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Article

Impact of climate change on Chinese college students' consumption behavior: A case study of Jilin University

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Abstract: This study investigates the impact of climate change on the consumption behavior of Chinese college students, especially their daily expenses. Using a survey method, data were collected and analyzed to understand the correlation between climate change awareness and consumption choices among students at Jilin University. The findings indicate that over 70% of respondents believe climate change significantly affects their daily lives and consumption habits. Particularly, changes in transportation choices were most prominent, with 68% of students opting for greener travel options. However, less willingness was observed in reducing online shopping or paying carbon taxes. These insights highlight the need for tailored educational interventions to enhance climate change awareness and promote sustainable consumption practices among college students.

Keywords: climate change; consumption behavior; Chinese colleague students; sustainable consumption; environmental awareness

1. Introduction

In recent years, the frequency of climate change and extreme weather events has become a focal point of global concern. On 20 January 2021, the first day of his presidency, Joe Biden signed 17 executive orders, including the re-entry of the United States into the Paris Agreement. Signed on 12 December 2015 and effective from 4 November 2016, the Paris Agreement is a milestone international legal text addressing climate change. It follows the Kyoto Protocol as the second legally binding international climate agreement. The United States' return to the Paris Agreement reflects the international community's emphasis on climate change, a significant non-traditional security issue affecting various aspects of human life.

To mitigate and avoid the risks climate change poses to human society, international cooperation is imperative. The global framework for addressing climate change has steadily improved. In 1988, the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) jointly established the Intergovernmental Panel on Climate Change (IPCC) to provide objective and reliable scientific information for decision-makers and other scientific fields globally. Subsequent milestones include the 1992 Earth Summit's United Nations Framework Convention on Climate Change (UNFCCC), the 1997 Kyoto Protocol, and the 2015 Paris Agreement, showcasing the international community's determination to combat global climate change. Furthermore, sovereign nations have implemented numerous measures to promote emission reductions and climate governance. For example, during the Climate Ambition Summit in December 2020, UK Prime Minister Boris Johnson announced the cessation of direct support for overseas fossil fuel projects [1],

and in January 2021, President Biden's administration rejoined the Paris Agreement and revoked the Keystone XL pipeline permit. China has also been proactive in addressing climate change, as highlighted in the 2017 report of the 19th National Congress of the Communist Party of China. The report emphasized the necessity of building an ecological civilization and pursuing green development to contribute to global ecological security. At the Climate Ambition Summit in December 2020, China reaffirmed its support for the Paris Agreement, pledging to reduce carbon dioxide emissions per unit of its Gross Domestic Product (GDP) by over 65% from 2005 levels by 2030 and achieve carbon neutrality before 2060 [2].

Encouraged by national policies, concepts like "low-carbon economy," "low-carbon development," "low-carbon life," and "low-carbon campus" have emerged. China has enacted laws and policies to promote low-carbon lifestyles and green living, which are crucial given its population of over 1.4 billion as of 2019. Fostering green consumption and low-carbon habits among the populace can significantly impact both national and global climate governance.

Addressing climate change is a long-term, arduous task that requires sustained effort and accumulation. Targeting key groups for breakthroughs is a viable strategy. According to the National Bureau of Statistics, there were over 28.31 million students enrolled in higher education institutions in China in 2018, making them a pivotal group for shaping future consumption trends [3]. Enhancing college students' awareness of green consumption and guiding their behavior can foster a low-carbon, environmentally friendly consumption trend across society, contributing green wisdom to building a prosperous, democratic, civilized, harmonious, and beautiful socialist modern country. Therefore, educating college students about climate change is crucial for sustainable development and improving national climate change response capabilities. Research on contemporary college students' green consumption behavior is increasingly important. In order to explore the influence of climate change on college students' consumption behavior through their awareness of climate change, the impact on their low-carbon consumption behavior, and intervention strategies to guide them, this study follows the basic logic of Marxist epistemology, collecting questionnaires on the consumption status of students at Jilin University, analyzing the result, and drawing conclusions finally.

2. Literature review

Domestic and international scholars have focused on the unique group of college students in climate change studies. However, research directly addressing "the impact of climate change on college students' consumption behavior" is scarce. Studies primarily concentrate on "college students' awareness of climate change" and "intervention strategies to guide low-carbon consumption among college students." According to Marxist dialectical materialism epistemology, awareness influences practice, and practice is the goal and ultimate destination of awareness. College students' awareness of climate change affects their consumption behavior, and guiding them towards low-carbon consumption is the objective of studying the impact of climate change on their behavior.

2.1. College students' awareness of climate change

Empirical research on college students' awareness of climate change typically involves surveys to collect data samples and analyze the findings. For example, Pan et al. [4] surveyed undergraduates at Nanjing Agricultural University, assessing their awareness of climate change, attitudes towards actions, and willingness to act. They found significant awareness of the relationship between climate change and agriculture but noted variations across different aspects of climate change awareness and among students of different grades and majors. Individual students exhibited varied attitudes towards participation in climate change actions, with overall awareness and participation attitudes showing a weak correlation with grade levels. The study suggested enhancing climate change education in higher agricultural education institutions by introducing relevant courses.

Huang's [5] survey revealed that although college students were highly concerned about climate change, their understanding was superficial. While they were willing to contribute to mitigating climate change, actual implementation was limited, reflecting a "gap between knowledge and action." This discrepancy was attributed to a lack of systematic climate change education, prompting suggestions for improving students' awareness and behavioral capabilities regarding climate change. Chen and Xie's [6] study at Nanjing University of Information Science and Technology used questionnaires to survey 6643 students, analyzing the data with SPSS18.0 software. The binary logistic regression results indicated that students' awareness of the severity of climate change-induced environmental deterioration significantly influenced their willingness to act. They concluded that students with greater knowledge about climate change were more willing to take action, highlighting the importance of understanding the negative impacts of climate change in studying its influence on students' consumption behavior.

Internationally, Wachholz et al. [7] conducted a survey of freshmen and seniors at a university, exploring their awareness and attitudes towards climate change, intentions to reduce personal greenhouse gas emissions, and satisfaction with current climate change education. The majority acknowledged climate change as real and human-induced, expressing concern about its impacts. However, there were misconceptions about its basic causes and consequences, suggesting a need for higher education to enhance climate change education. Panno et al. [8] investigated the relationship between climate change perception and responsible environmental behavior, emphasizing the link between individual thinking styles and environmental awareness. Grothmann and Patt [9] developed the Model of Private Proactive Adaptation to Climate Change (MPPACC), exploring its effectiveness in explaining adaptive behaviors in German cities and Zimbabwean rural areas and discussing the feasibility of promoting adaptation through external interventions.

Overall, both Chinese and overseas scholars have conducted extensive research on college students' awareness of climate change, often supported by empirical studies. These studies indicate that there is still room for improvement in students' awareness, which influences their environmental actions. Guiding students towards low-carbon, environmentally friendly behavior can begin with enhancing their awareness, with higher education playing a crucial role.

2.2. Impact of climate change on college students' low-carbon consumption behavior

Scientific advancements and evidence increasingly support the view that "climate change is a scientific issue," not a "false proposition," and that human activities, particularly since the Industrial Revolution, have exacerbated climate change. Changing human behavior to mitigate or improve climate change is a common global challenge. The "low-carbon consumption" model has emerged, aiming to fundamentally reduce carbon emissions and promote sustainable development. College students, as a special group, have significant influence on society and the potential to become role models for low-carbon consumption. Domestic and international scholars have researched the impact of climate change on their behavior.

Li and Ma [10] surveyed MBA students at Northwestern Polytechnical University, using questionnaires, factor analysis, and regression analysis. They found that highly educated youth are more likely to be green consumers, willing to pay higher prices for green products. This aligns with Zhao et al.'s [11] study on students' willingness to pay for carbon-labeled food, indicating that students are willing to accept a premium for such products. Wang [12] highlighted the issue of energy utilization in universities, noting prevalent wasteful practices like leaving lights and water running, using disposable utensils, and food wastage. Zhu and Zhang's [13] survey of 120 students from several universities in Nanjing and Yangzhou found that students lacked sufficient attention to environmental and sustainable development issues, exhibiting poor consumption habits such as excessive consumption, conspicuous consumption, one-time use, and convenience consumption, leading to significant pollution and waste.

Internationally, Toma et al. [14] studied energy consumption among students at the University of Bucharest, noting the need for students to recognize their residential electricity consumption's impact on the grid and participate in creating sustainable local energy communities. This mirrors Liu's [15] findings on electricity waste in Chinese universities, suggesting designing responsive systems to improve classroom utilization and promote low-carbon campuses.

In summary, research on college students' consumption habits reveals widespread deficiencies in low-carbon consumption, with students showing potential to be role models but low-carbon consumption not yet mainstream. Their consumption habits require further improvement.

2.3. Intervention strategies to guide low-carbon consumption among college students

Given the importance of college students' low-carbon consumption behavior for societal low-carbon development, guiding them towards such practices is essential. Domestic and international scholars have explored various strategies, focusing on internal factors (cultivating climate crisis awareness and environmental consciousness) and external factors (school, corporate, and government policy interventions).

Cultivating climate crisis awareness is crucial for guiding low-carbon consumption. Educational institutions play a significant role. For example, Sinatra et

al. [16] designed an experiment where students read a persuasive article on human-induced climate change, leading to statistically significant changes in their attitudes and willingness to act. Liu [17] emphasized the importance of incorporating environmental management courses into all university curricula and suggested campus activities and technical measures to promote low-carbon behavior. Family influence is also significant, with environmentally conscious families better able to guide students' low-carbon habits [3]. Schools, as core institutions, can utilize various means to encourage low-carbon practices. Successful examples include the "Environmental Learning Institute" at universities, encouraging students to participate in environmental protection and volunteering activities. Schools can also adopt low-carbon construction and green campus projects. Corporate and governmental policies are also critical. Integrating government regulation with corporate social responsibility can lead to broader changes in consumption behavior. For example, initiatives like carbon labeling and carbon credits can incentivize low-carbon practices [18].

In conclusion, the theoretical foundation and empirical studies suggest that climate change awareness and targeted interventions can significantly influence college students' consumption behavior. Comprehensive strategies involving education, institutional policies, and broader societal measures are essential for promoting low-carbon consumption among students.

3. Methodology

Despite the geographical dispersion and varied living and learning environments of Chinese college students across China, this demographic exhibit notable similarities. For instance, students within the same academic year are generally of similar age, and teaching methodologies are consistent across institutions. Furthermore, universities often enroll students from diverse provinces, making it feasible to conduct a representative study within a single university.

This study was conducted at Jilin University in northeast China using an online questionnaire targeted at undergraduate, master's, and doctoral students. The questionnaire design drew on the New Ecological Paradigm scale developed by Cotton et al. [19]. The questionnaire was refined to address the specific focus areas and characteristics of this study's target population. It included objective questions such as single-choice, multiple-choice, and Likert scale items, as well as subjective questions like fill-in-the-blank and open-ended responses. To accommodate both domestic and international students, the questionnaire was bilingual in Chinese and English. To protect respondents' privacy, all questionnaires were anonymous.

Survey design

The questionnaire design (see Appendix) was informed by the New Ecological Paradigm scale by Professor Debby Cotton from Plymouth Marjon University, covering four main areas: sample characteristics, knowledge, attitudes, and actions. Fifteen questions were developed, including two on sample characteristics (see **Table 1**), two on knowledge (see **Table 2**), five on attitudes, five on actions, and one screening question for effective responses.

Table 1. Sample characteristics.

Question	Result
What is your gender?	Male
	48.48%
What is your academic year?	Freshman
	7.58%

Knowledge-Related Questions:

Table 2. Knowledge-related questions.

Question	Options	Results
Are you aware of climate change?	Very aware	Very aware
	4.55%	51.52%
Through which medium do you mainly learn about climate change?	School education	Discussion with friends and family
	22.73%	6.06%

Attitude-related questions:

1) Do you think climate change impacts the daily lives of college students?
2) Do you think climate change affects the consumption behavior of college students?
3) In what ways do you believe climate change influences the consumption behavior of college students?
4) Do you think it is necessary to offer courses on low-carbon consumption concepts in universities?
5) Have you ever attended a course on low-carbon consumption concepts during your university studies? If so, did it benefit you?

Action-related questions

6) What methods do you think can be used to instill low-carbon consumption concepts in college students?
7) Which of the following low-carbon consumption practices are you willing to adopt? (Multiple choices allowed)
8) If you notice behaviors around you that contradict low-carbon consumption principles, what would you do?
9) On 1 January 2021, the "Plastic Straw Ban" was officially implemented, prohibiting the use of non-degradable disposable plastic tableware in the catering industry. What is your opinion on this regulation and the introduction of alternatives like "paper straws" and "wooden spoons"?
10) What suggestions do you have for guiding college students towards low-carbon consumption?

After collecting questionnaires, we confirmed the number of questionnaires, sorted out and counted the questionnaire responses, and removed the invalid data. We then classified the available data by type of problem for subsequent data analysis. Finally, the proportion is calculated according to the results of various types of questions.

4. Data analysis and results

This survey collected a total of 70 questionnaires, with 66 valid and 4 invalid responses, resulting in an effective response rate of 94.3%, which meets statistical requirements. The selection of respondents was random, comprising 63 undergraduates (5 freshmen, 9 sophomores, 42 juniors, 7 seniors), 2 master's students, and 1 doctoral student.

4.1. Awareness and understanding of climate change among college students

Awareness influences practice and affects decision-making. College students' perception of the climate crisis and awareness of low-carbon consumption significantly impact their behavior. The influence of climate change on students' consumption behavior heavily relies on their awareness and understanding of the climate crisis. Therefore, promoting low-carbon consumption on campuses requires a high level of awareness and rational understanding of the current climate situation among students. This study designed four questions to assess students' awareness and understanding of climate change, considering their perception of environmental changes and extreme weather phenomena. **Table 3** is based on our collected results from interviewees, which show students' awareness and understanding of the climate change issue. The following part will introduce more detail about the results and findings.

Table 3. Awareness and understanding on climate change.

Awareness		**Supportive policies for public low-carbon consumption**		**Understanding**	
Non-low-carbon consumption behaviors	69.7%	Support	69.69%	Fairly knowledgeable	51.52%
Promoting low-carbon consumption concepts	24.24%	Opposition	25.76%	Not very knowledgeable	43.94%
Others	6.06%	Strong opposition	4.55%	Very knowledgeable	4.54%

From the perspective of awareness, it can be further divided into attitudes toward non-low carbon consumption behaviors and attitudes toward promoting low carbon consumption concepts. According to the survey data, 69.7% of respondents would choose to remain silent and reflect on the behavior of others violating low-carbon principles, 24.24% would dissuade others and try to influence them towards low-carbon consumption through their actions, and only one person would join others in violating low-carbon principles. However, attitudes toward supportive policies for public low-carbon consumption were less consistent. 69.69% supported such policies, while 25.76% viewed the "plastic straw ban" as more detrimental than beneficial. Two students expressed strong opposition to paper straws, citing significant functional and sensory drawbacks.

Thus, students at Jilin University exhibit a certain level of awareness regarding the severe consequences of climate change and generally recognize and support appropriate consumption concepts to combat it. However, the attitudes expressed in some responses suggest that overall awareness is still at a lower stage, characterized by insensitivity to current climate deterioration and a low level of proactive

engagement. Without heightened awareness, students will struggle to genuinely practice low-carbon consumption principles.

From the understanding perspective, it can be further divided into the level of understanding of the current state of climate change and the methods of understanding it. The results show that 51.52% of respondents consider themselves fairly knowledgeable about climate change, 43.94% are not very knowledgeable, a small number claim to be very knowledgeable, and none consider themselves completely uninformed. Analysis of student demographics reveals that freshmen, sophomores, master's, and doctoral students generally rate their understanding highly, while more than half of juniors and seniors feel their understanding is insufficient. In terms of information sources, freshmen, master's, and doctoral students primarily use the internet and school education, with school education being more significant than in other years. Sophomores, juniors, and seniors also rely on discussions with friends and family and print media.

These findings indicate significant differences in the self-perceived understanding of climate change and preferred information sources among students of different academic years. These differences may correlate with education levels, suggesting that intervention strategies should be tailored to the educational backgrounds and preferences of different student groups to enhance their understanding and promote low-carbon consumption behavior.

4.2. Impact of climate change on low-carbon consumption behavior of college students

The impact of climate change on students extends beyond psychological awareness to manifest in specific behavioral changes. To verify whether climate change influences students' consumption choices, the study analyzed the relationship between the two through four questionnaire items. The results provide theoretical support for proposing recommendations to promote low-carbon consumption among students.

First, the influence of climate change on students' daily lives and consumption choices shows a consistent trend. Over 70% believe that climate change significantly impacts life and consumption on campus (both questions scored a mode of 7 on the Likert scale, indicating a high level of impact).

Second, climate change prompts students to engage in low-carbon consumption behaviors across clothing, food, housing, and transportation, though the extent varies. The survey indicates that changes in transportation behavior are most significant, with 68% willing to adopt green travel options to combat climate change. Additionally, nearly half support considering energy consumption as an important factor when purchasing products.

However, there are less optimistic aspects: only 36% believe that understanding climate change effectively promotes energy and water conservation, and although students recognize the benefits of low-carbon products, they are reluctant to restrict their choices significantly. Only 8% are willing to pay a carbon tax, and just 12% believe reducing online shopping can effectively contribute to environmental efforts.

Lastly, acceptance of specific low-carbon consumption methods varies. Over

60% are willing to sacrifice some personal satisfaction in clothing, utilities, and transportation for low-carbon consumption, but only 19.7% are willing to make dietary compromises. Some explicitly oppose replacing meat with soy products, indicating a need for nuanced evaluations of low-carbon methods to ensure practicality and acceptance.

4.3. Coping strategies and recommendations

The analysis of survey results highlights the positive impact of awareness and understanding of climate change on promoting low-carbon consumption among students. To externalize internal awareness and understanding, it is essential to deepen students' comprehension of climate change through diverse and enriched educational channels, catering to different student groups' characteristics and preferences.

Universities are uniquely positioned to educate all students on the importance and methods of low-carbon consumption through coursework. This study designed questions on the necessity and expectations of such courses. Results show 71.21% support the idea, though only 33.33% have received relevant training, predominantly favoring practical, life-related content. All surveyed freshmen had no course exposure, while most master's and doctoral students had received relevant education.

These findings suggest two main deficiencies: limited accessibility of low-carbon consumption courses and delayed course offerings mainly to upperclassmen. To ensure comprehensive and deep understanding among all students, courses should be compulsory, preferably integrated into the freshman curriculum as foundational courses.

Additionally, this study collected open-ended responses for broader suggestions, such as reducing unnecessary purchases, setting credit or item exchange rewards for low-carbon behaviors, and installing low-carbon consumption reminders on campus. Effective low-carbon consumption among students requires a multifaceted approach involving self-awareness, educational curriculum, campus culture, and supportive policies.

5. Conclusion and discussion

This study, using Jilin University in China as an example, investigates college students' awareness and understanding of climate change, their consumption concepts and behaviors, and the correlation between these factors. From a theoretical perspective, it is clear that awareness and cognition are prerequisites for behavior and significantly influence students' willingness to adopt low-carbon consumption practices. This understanding can effectively promote the implementation of low-carbon consumption concepts in university settings.

Additionally, given that school education is a primary means of helping students develop low-carbon consumption views, this research examines the current status of low-carbon consumption knowledge courses within the university education system. It also assesses students' understanding and satisfaction regarding the purpose and significance of these courses. Based on the survey results, feasible strategies and recommendations for students' specific consumption behaviors in response to climate change are proposed:

5.1. Current awareness and understanding of climate change among college students

- High Level of Awareness: College students generally exhibit a high level of concern about recent climate changes, make relatively accurate judgments, and possess rational cognition.
- Understanding the Current Situation: Students have a certain degree of understanding of the current state of climate change, its causes, and its negative impacts. This may be related to the higher educational level and cultural literacy of the student group. However, the overall level of understanding and cognition remains low, and the knowledge system lacks comprehensiveness.
- Education Background Impact: Graduate students (master's and doctoral) generally have a higher level of understanding of climate change compared to undergraduates, indicating that the higher the education level, the greater the awareness and more rational the cognition of climate change.

5.2. Impact of climate change on college students' low-carbon consumption behavior

- Correlation with Awareness: There is a correlation between students' willingness to choose low-carbon consumption and their understanding of climate change. The higher the level of understanding, the more inclined they are to accept low-carbon consumption.
- Behavioral Variations: Students' low-carbon consumption behaviors are evident in clothing, food, housing, and transportation. However, their willingness to adopt low-carbon practices varies across these aspects. Most students are willing to practice low-carbon principles in clothing and daily necessities, but fewer are willing to do so in food consumption. Therefore, promoting low-carbon consumption should balance pros and cons, encouraging thrift in clothing and daily use while avoiding dogmatic approaches that force compromises in food consumption.

5.3. Guiding college students to establish low-carbon consumption concepts

- Role of Educational Courses: School courses related to climate change are not only crucial for enhancing students' awareness and understanding of the issue but also for formalizing their cognition of low-carbon consumption concepts.
- Broad Implementation: Establishing low-carbon consumption views through school education is essential for the widespread adoption of low-carbon consumption concepts within campuses.
- Collaborative Efforts: Promoting low-carbon consumption concepts and encouraging low-carbon consumption behaviors in universities require the collaboration of students, educational departments, campus management, and national education policymakers. It is the result of comprehensive efforts from multiple sectors.

In a nutshell, this research highlights the importance of increasing students' awareness and understanding of climate change as a foundation for promoting low-

carbon consumption behaviors. It also emphasizes the critical role of education and the need for a multi-faceted approach to achieve widespread adoption of low-carbon consumption practices in university settings. However, there are still shortcomings in the article. One is the lack of using quantitative methods in the data analysis part, which makes the illustration seem unconvincing. The other is that the paper does not use any social psychological theories or hypotheses about behavioral factors, which leads to a lack of scientific and theoretical depth. The authors will take them into account for the future study.

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Appendix

Survey questionnaire a questionnaire survey on the impact of climate change on college students' consumption behavior

Dear friends,

Greetings! We are undergraduate students from Jilin University. It has been a while since we left campus; how have you been spending your time? As the Spring Festival approaches, we take this opportunity to extend our sincere regards to you. It is widely recognized that climate change profoundly affects our daily lives. In order to gain deeper insights into the impact of climate change on college students' consumption behavior, we are conducting a survey titled "The Impact of Climate Change on College Students' Consumption Behavior" using Jilin University as a sample. Our questionnaire will be completed anonymously, and we assure you that your personal information, preferences, and responses will remain confidential. The data collected will be used solely for the purposes of concluding and analyzing this survey report. We sincerely appreciate your assistance and hope that, together, we can contribute to global climate governance.

- Your Gender (Select one)
  - A. Male B. Female
- Your Grade Level (Select one)
  - A. Freshman B. Sophomore C. Junior D. Senior E. Graduate student F. Doctoral student
- How much do you know about climate change? (Select one)
  - A. A lot B. Quite a bit C. Not much D. Nothing
- How do you learn about climate change? (Select one)
  - A. School education B. From friends and relatives C. Newspaper and magazine D. From the Internet
- Do you think climate change affects college students' daily life? If yes, please rate the extent of its impact (Scale of 1 to 10).
- Do you think climate change affects college students' consumption behavior? If yes, please rate the extent of its impact (Scale of 1 to 10).
- In what aspects of college students' life do you think climate change affects consumption behavior? (Select all that apply)
  - A. Reduce the purchase of high-energy-consuming products B. Increase the purchase of environmentally friendly products C. Be more thrifty in daily life (e.g., buy fewer new clothes) D. Change dietary habits (e.g., less meat, more vegetables) E. Change means of transportation (e.g., use green transport) F. Save electricity G. Save water H. Buy products with a carbon tax I. Reduce online shopping J. Other changes (please specify)
- Do you think it is necessary to introduce courses promoting the concept of low-carbon consumption in universities? (Select one)
  - A. Yes B. No C. Not sure
- Have you attended any courses promoting low-carbon consumption during your university studies? If yes, has it been beneficial? If so, why? (Select all that apply)
- If you are answering this questionnaire seriously, please choose A. (Select one)
  - A. Global warming B. Rise of sea levels C. Destruction of the ozone layer D. Sharp decline in biodiversity
- How can college students establish a concept of low-carbon consumption? (Select all that apply)
  - A. Offering courses or lectures B. Carrying out low-carbon consumption activities (e.g., clothing recycling) C. Organizing low-carbon environmental knowledge quiz contests D. Other methods (please specify)
- Among the ways of low-carbon consumption listed below, which ones are you willing to accept? (Select all that apply)
- If you find others' behaviors contrary to the concept of low-carbon consumption, what would you do? (Select one)

- What do you think about the restaurant industry's ban on non-degradable disposable plastic utensils from 1 January 2021, and their replacement with degradable alternatives like paper straws and wooden spoons? (Select one)
- What suggestions do you have for guiding college students to engage in low-carbon consumption? (Open-ended)

Note: The original survey was conducted online via software and in Chinese, this is only a translation for the survey content.

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Article

An analysis of the social, psychological, and legal aspects of Hamster Kombat coin

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Abstract: The paper aims to examine and analyze the social, psychological, and legal implications of a fictional currency known as the Hamster Kombat coin. It explores topics such as the impact of virtual currency on society, the potential for fraud or misuse, and the legal framework surrounding the use and regulation of virtual currencies. Additionally, the paper discusses the ethical considerations associated with using digital currency in a virtual world. In this paper, a qualitative research method has been employed. Qualitative methods involve the use of research techniques that focus on understanding the underlying reasons, motivations, and perceptions of individuals regarding the Hamster Kombat coin. This approach includes gathering information through interviews, surveys, observations, and other qualitative data collection methods to gain insights into how people perceive and interact with the coin within both social and legal contexts. By utilizing this approach, researchers can explore the intricacies and nuances of the subject matter, thereby providing a deeper understanding of the social and legal implications associated with the Hamster Kombat coin. The results are categorized into three sections: social, psychological, and legal. The social findings indicate that the Hamster Kombat coin may foster community among individuals interested in hamsters or cryptocurrency. This could lead to the formation of online forums, social media groups, and other avenues for interaction. Additionally, the Hamster Kombat coin may serve as an educational tool, helping newcomers understand hamsters, cryptocurrency, and investment strategies. The psychological findings reveal that various factors, both negative and positive, can significantly impact human experiences, such as heightened feelings of excitement and anticipation, as well as financial stress. The legal findings suggest that specific regulations governing cryptocurrency investments, trading, and offerings may vary by country or region. Investors must be aware of these regulations to ensure compliance. Furthermore, as with any investment opportunity, there is a risk of fraud or scams associated with the Hamster Kombat coin. Therefore, investors should exercise caution and conduct thorough research before committing to cryptocurrency investments. Finally, profits generated from investing in Hamster Kombat coins may be subject to taxation in certain jurisdictions. Investors are advised to consult with a tax professional to fully understand the tax implications of their investments. The contribution of this paper lies in its examination of the social and legal implications of a specific cryptocurrency known as the Hamster Kombat coin. The paper likely explores how this coin fits into the broader cryptocurrency landscape and its impact on users, as well as the legal framework surrounding cryptocurrencies. Additionally, it may investigate the potential societal implications of utilizing such a coin in the market. Overall, this paper illuminates an important aspect of the cryptocurrency world and offers valuable insights for researchers, policymakers, and cryptocurrency enthusiasts.

Keywords: cryptocurrency; coin; token; Hamster Kombat; social and legal threat
JEL Codes: E2; K0

1. Introduction

The year 2023 was characterized by the rise of artificial intelligence; however, 2024 seems poised to witness a surge in Telegram mini-games that incorporate "tap-to-earn" and "play-to-earn" mechanics.

Globally, over 1 billion individuals utilize Telegram for instant messaging. Consider the potential of Telegram to onboard newcomers to cryptocurrency within its ecosystem. This familiarity, combined with the fact that these games require no financial investment, reduces the barrier for newcomers to the crypto space, enabling them to engage in crypto games on Telegram without the necessity of acclimating to a new platform.

Furthermore, the opportunity to earn through gaming has rekindled interest among former users and attracted individuals with no prior knowledge of cryptocurrencies [1]. The gameplay mechanics of tap-to-earn games typically adhere to a similar pattern:

- Players earn coins by tapping the screen.
- They can increase the effectiveness of their taps, elevate energy levels, and accelerate the speed of energy recovery.
- Completing in-game tasks rewards players with various bonuses.
- Daily boosts are employed to improve the overall gameplay experience.

It all began with Notcoin. Since its inception, the cryptocurrency Notcoin has rapidly gained immense popularity, attracting millions of individuals to the Web3 space through its engaging tap-to-earn gameplay mechanics. This surge in interest ultimately led to Notcoin's listing and provided real monetary value to its players. Now, numerous developers, from large corporations to smaller teams, are striving to replicate Notcoin's success by creating their engaging mini-applications.

Currently, the most popular game in this genre seems to be Hamster Kombat, where players earn coins by tapping on a hamster within a Telegram-based mini-app. Players accumulate points that can be used to develop a fictional cryptocurrency exchange managed by a "hamster CEO. This process involves implementing various strategies, such as enabling margin trading, listing new meme coins, and enforcing anti-money laundering policies. Successfully executing these strategies increases the players' rate of point earnings.

With a player base exceeding 31 million, Hamster Kombat stands out as one of the many successful games in this thriving genre.

This paper aims to provide a comprehensive analysis of the social and legal aspects of Hamster Kombat Coin, exploring how this emerging cryptocurrency is shaping our understanding of money, value, and ownership in the digital age. By examining the social impact of Hamster Kombat Coin on communities and individuals, as well as the legal implications of its use and regulation, we can gain deeper insights into the broader consequences of this new form of currency. Through a combination of theoretical analysis, case studies, and empirical research, this paper will delve into the various ways in which Hamster Kombat Coin is reshaping our economic and social landscape. By critically examining the social and legal dimensions of this cryptocurrency, we can better understand its potential benefits and risks, as well as its implications for society as a whole.

This exploration of Hamster Kombat Coin is not merely a case study of the absurdities within the cryptocurrency market; rather, it serves as a critical examination of the intricate web of social, psychological, and legal considerations that emerge when technology intersects with entertainment, finance, and our collective values. It is a journey into the heart of the "hamster in the room symbol of the rapid evolution of our digital landscape and the pressing need for ethical and responsible innovation.

Overall, this paper aims to contribute to the ongoing discourse regarding the role of cryptocurrency in our increasingly digital world, illuminating the intricate interplay between technology, society, and law in the context of the Hamster Kombat coin. Through a comprehensive exploration of these issues, we aspire to offer valuable insights into the broader implications of this emerging form of currency.

The contribution of this paper lies in its examination of the social and legal implications of a specific cryptocurrency known as the Hamster Kombat coin. The paper likely explores how this coin fits into the broader cryptocurrency landscape and its impact on users, as well as the legal framework surrounding cryptocurrencies. Additionally, it may investigate the potential societal implications of utilizing such a coin in the market. Overall, this paper illuminates an important aspect of the cryptocurrency world and offers valuable insights for researchers, policymakers, and cryptocurrency enthusiasts.

The remainder of the paper is organized as follows:

Part 2 is dedicated to the literature review. Part 3 focuses on the methodology. In Part 4, we examine Hamster Kombat from social, psychological, and legal perspectives. Part 5 presents the findings and results. Finally, the last section provides the conclusion and remarks.

2. Literature review

2.1. The history of cryptocurrency

The history of cryptocurrency is a captivating journey that dates back to the early days of digital currency experimentation. This literature review will provide an overview of the key milestones and developments in the evolution of cryptocurrency, highlighting the significant events, technologies, and trends that have shaped the landscape of digital currency over the years [2].

2.1.1. Early beginnings

The concept of digital currency can be traced back to the 1980s and 1990s, during which various attempts were made to create digital cash systems. One of the earliest examples is DigiCash, founded by David Chaum in 1989, which aimed to provide secure and anonymous electronic transactions. However, DigiCash ultimately failed due to regulatory challenges and a lack of widespread adoption.

2.1.2. Bitcoin and the emergence of cryptocurrency

The pivotal moment in the history of cryptocurrency occurred in 2008 with the publication of a whitepaper titled "Bitcoin: A Peer-to-Peer Electronic Cash System" by an anonymous individual or group using the pseudonym Satoshi Nakamoto. This whitepaper introduced the concept of a decentralized digital currency based on blockchain technology, with Bitcoin serving as its inaugural implementation.

2.1.3. The rise of altcoins

Following the success of Bitcoin, a wave of alternative cryptocurrencies, commonly referred to as altcoins, emerged in the early 2010s. Litecoin, launched in 2011 by Charlie Lee, was among the first altcoins to gain significant traction. Other notable altcoins include Ethereum, Ripple, and Dash, each of which offers unique features and use cases.

2.1.4. Initial coin offerings (ICOs)

The popularity of cryptocurrencies has led to the emergence of Initial Coin Offerings (ICOs) as a fundraising method for blockchain projects. ICOs enable startups to raise capital by issuing their tokens, which are often built on established blockchain platforms such as Ethereum. While ICOs offer a novel approach for projects to secure funding, they have also encountered regulatory scrutiny due to concerns regarding fraud and investor protection.

2.1.5. Regulatory challenges

As cryptocurrencies gained mainstream attention, regulators worldwide began to grapple with how to regulate this emerging asset class. Countries such as China imposed bans on cryptocurrency trading, while others established frameworks to regulate exchanges and Initial Coin Offerings (ICOs). The regulatory landscape for cryptocurrencies remains complex and continually evolving, with ongoing debates about how to balance innovation with investor protection.

2.1.6. Institutional adoption

In recent years, there has been a growing trend toward the institutional adoption of cryptocurrencies. Major financial institutions and corporations have begun to explore blockchain technology and digital assets as integral components of their business strategies. This trend has enhanced the legitimacy and credibility of the cryptocurrency market, paving the way for mainstream acceptance.

2.1.7. DeFi and NFTs

The emergence of Decentralized Finance (DeFi) and Non-Fungible Tokens (NFTs) marks the latest evolution in the cryptocurrency landscape. DeFi platforms facilitate decentralized lending, borrowing, and trading of digital assets, while NFTs enable the creation and exchange of unique digital items, such as art and collectibles. These advancements have ignited new waves of innovation and investment within the cryptocurrency ecosystem.

In conclusion, the history of cryptocurrency is a narrative of innovation, disruption, and adaptation. From the inception of Bitcoin to the contemporary era of decentralized finance (DeFi) and non-fungible tokens (NFTs), the evolution of digital currency has transformed our understanding of money, value, and ownership. As we continue to navigate the complexities of this rapidly changing landscape, it is crucial to reflect on the lessons learned from the past and consider how to effectively harness the potential of cryptocurrency for a more inclusive and equitable financial future.

As a summary, **Figure 1** is depicted.

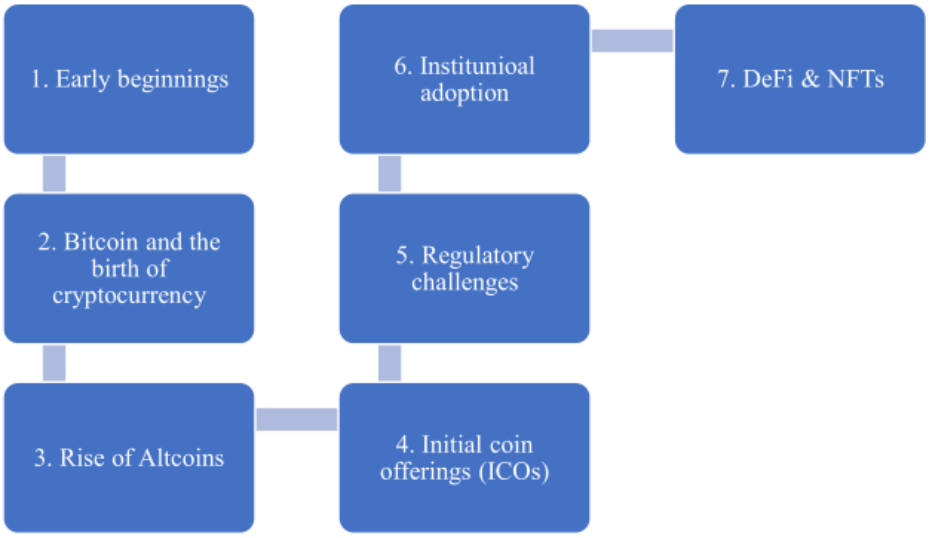

Figure 1. The history of cryptocurrency.

2.2. The history of Telegram-based crypto

Telegram has played a significant role in the cryptocurrency space, particularly as a platform for communication, community building, and information sharing within the crypto community. Here are some key points in the history of Telegram's involvement with cryptocurrency [3]:

1) ICO and TON: In 2018, Telegram conducted one of the largest initial coin offerings (ICOs) in history, raising approximately $1.7 billion for its Telegram Open Network (TON) project. TON aimed to establish a blockchain platform featuring its native cryptocurrency, known as Gram. However, the project encountered regulatory challenges and was ultimately abandoned by Telegram in 2020.
2) Crypto Communities: Telegram has become a popular platform for cryptocurrency-related communities and groups. Numerous cryptocurrency projects, both established and emerging, maintain official or unofficial channels on Telegram to engage with their communities, provide updates, and offer support.
3) Pump-and-Dump Groups: Unfortunately, Telegram has also been linked to pump-and-dump schemes in the cryptocurrency sector. Certain groups on the platform have been known to coordinate efforts to artificially inflate the prices of specific cryptocurrencies before selling off their holdings for profit, resulting in substantial losses for unsuspecting investors.
4) Information Sharing: Telegram has become a popular platform for disseminating news, analysis, and trading tips related to cryptocurrencies. Many cryptocurrency enthusiasts and traders utilize Telegram channels and groups to discuss market trends, share insights, and exchange information about various digital assets.

It is important to recognize that while Telegram has served as a valuable tool for numerous cryptocurrency projects and communities, it has also become a breeding ground for scams, misinformation, and illicit activities within the crypto space. As with any online platform, users should exercise caution and conduct thorough research before engaging with cryptocurrency-related content on Telegram.

The results of this section are summarized in **Figure 2**.

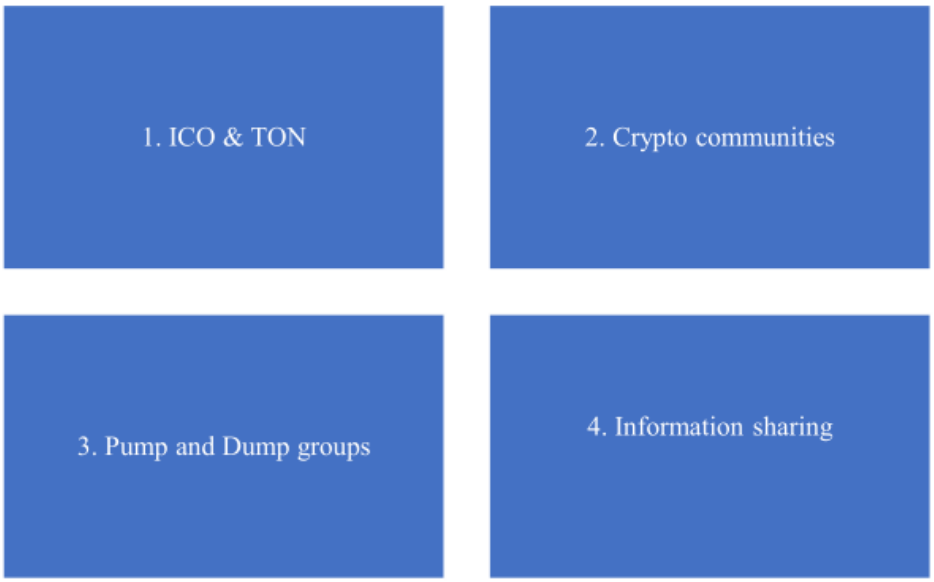

Figure 2. The history of Telegram-based crypto.

3. Methodology

In this paper, a qualitative research method has been employed. Qualitative methods involve utilizing research techniques that aim to understand the underlying reasons, motivations, and perceptions of individuals concerning the Hamster Kombat coin. This approach includes gathering information through interviews, surveys, observations, and other qualitative data collection methods to gain insights into how people perceive and interact with the coin within both social and legal contexts.

To conduct an effective interview about the identification of different aspects of "Hamster Kombat," the interviewees should possess certain characteristics and backgrounds, such as familiarity with the game, gaming experience, analytical skills, community engagement, diverse perspectives, and experts in the desired fields, including psychology, social, and legal.

Interview and survey questions are about issues like how do you think people generally perceive coins compared to paper money or digital currency? Do you think this perception affects how people interact with coins in social settings? How about in a legal context? Are there specific laws or regulations that govern the use of coins? And so on.

Additional details regarding the methodology are provided below [4]:

- Content Analysis: This research will incorporate a content analysis of online discussions, social media platforms, and official communication channels related to Hamster Kombat Coin. This method will facilitate the identification of themes, patterns, and sentiments within the community, thereby providing a deeper understanding of the social dynamics of the project.
- Review of Legal Documents and Regulatory Frameworks: The methodology will include a comprehensive review of legal documents, regulatory guidelines, and compliance requirements pertinent to the development, marketing, and regulatory adherence of Hamster Kombat Coin. This component aims to analyze the legal

considerations and implications associated with the cryptocurrency project.

- Data Analysis: The data analysis procedures will involve synthesizing findings from interview transcripts, identifying themes in online discussions, and analyzing legal documents to gain a comprehensive understanding of the social and legal aspects of Hamster Kombat Coin.

Overall, the qualitative research methodology employed in this study aims to deliver a comprehensive analysis of the social and legal dimensions of the cryptocurrency project. This is achieved by utilizing qualitative research methods to collect and analyze rich, contextual data from various sources.

4. Analysis of the impacts of Hamster Kombat coin on human life

4.1. Social impacts of Hamster Kombat on human life

The social impact of Hamster Kombat Coin is a fascinating and complex issue that extends far beyond mere entertainment. The cryptocurrency's unique premise, which involves pitting hamsters against one another in virtual combat, raises critical questions about how technology shapes our social fabric, influences our values, and challenges the boundaries of acceptable entertainment [5].

4.1.1. Potential positive impacts

- Community Formation: Hamster Kombat Coin has the potential to cultivate a strong sense of community among its supporters, uniting individuals who share a distinct interest in the project, whether for entertainment, investment, or philosophical engagement. This community could facilitate online discussions, organize meetups, and host social events, thereby fostering genuine connections and friendships in the real world.
- Conversation Starter: The absurdity and controversy surrounding Hamster Kombat Coin could ignite engaging discussions about the ethics of animal welfare, the impact of technology on entertainment, and the increasing role of cryptocurrency in society. Such conversations may foster a deeper understanding and awareness of these intricate issues, encouraging constructive debate and critical reflection.
- Technological Innovation: The development of Hamster Kombat Coin has the potential to advance blockchain technology, paving the way for innovative applications across various sectors. This progress could result in the creation of new jobs, stimulate economic growth, and contribute to overall advancements in the digital economy.

4.1.2. Potential negative impacts

- Polarization and Conflict: The controversial nature of Hamster Kombat Coin may lead to polarization and conflict within society. It has the potential to exacerbate existing societal divisions rooted in ideologies, ethical perspectives, and cultural sensitivities related to animal welfare and entertainment.
- Erosion of Empathy: Frequent exposure to simulated animal cruelty may desensitize individuals to real-world suffering, resulting in a decline in empathy and compassion towards animals. This desensitization could have significant implications for animal welfare activism and the overall treatment of animals in

society.

- Normalizing Violence: The normalization of virtual violence against animals may subtly influence societal attitudes toward violence in general. This phenomenon could contribute to desensitization to violence against humans and foster a greater acceptance of aggressive behavior.
- Financial Exploitation: The potential for financial gains associated with cryptocurrency may lead to increased exploitation of vulnerable individuals, particularly those seeking quick profits or attempting to escape financial hardship. This situation could exacerbate existing economic inequality and create new opportunities for financial scams and fraud.

4.1.3. Important considerations

- Context and Culture: The social impact of Hamster Kombat Coin is likely to vary based on the cultural context and societal norms of different regions and communities. What may be perceived as humorous or harmless in one context could be deemed highly offensive or problematic in another.
- Responsible Development: The developers of Hamster Kombat Coin have a responsibility to ensure that their project is developed and implemented responsibly and ethically. This includes addressing potential harms, fostering open dialogue with stakeholders, and promoting transparency and accountability throughout the project.

The social impacts of Hamster Kombat Coin are complex and continually evolving. While there is potential for positive social outcomes, such as community building and the stimulation of critical discussions, it is essential to acknowledge and address the potential negative consequences, including the desensitization of individuals to animal suffering and the normalization of violence. The project's long-term impact on society will ultimately depend on how its developers, users, and the broader public engage with it and navigate the ethical and social complexities it presents.

The details are summarized in **Figure 3**.

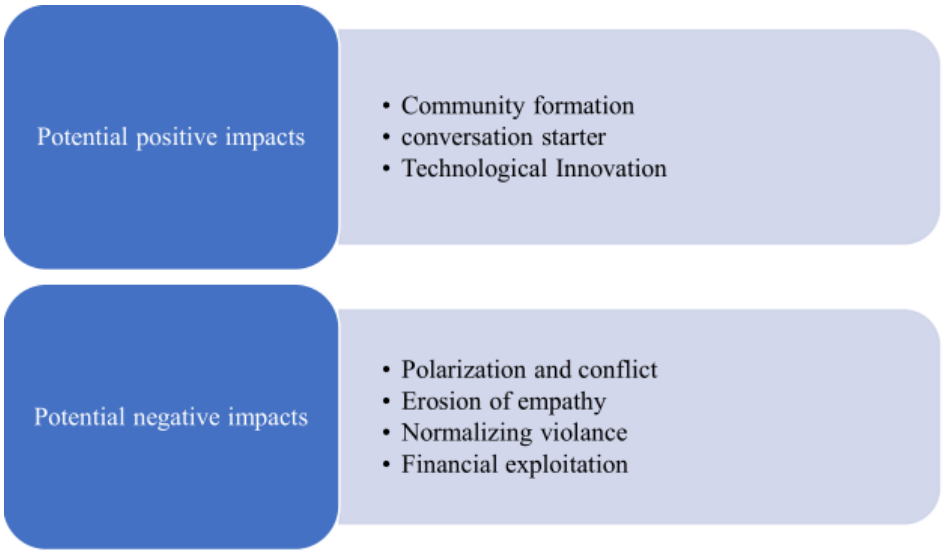

Figure 3. Social impacts of Hamster Kombat on human life.

4.2. Psychological impacts of Hamster Kombat coin on human life

While the concept of Hamster Kombat Coin may appear to be lighthearted entertainment, its psychological impacts on human life are far from trivial. It is essential to consider the potential ramifications—both positive and negative—of this unique cryptocurrency [6].

Increased Feelings of Excitement and Anticipation: The concept of the Hamster Kombat coin can evoke heightened feelings of excitement and anticipation as individuals eagerly await the outcomes of their investments in the coin.

The fear of missing out (FOMO) on potential gains or opportunities can lead individuals to make impulsive decisions and investments in the Hamster Kombat coin, resulting in a tumultuous emotional experience and increased stress.

- Financial Stress: The volatility of the Hamster Kombat coin can result in considerable financial stress for individuals who have made substantial investments in it. The unpredictability of the market and the possibility of losses can significantly impact one's mental health.
- Obsessive Thoughts and Behaviors: The continuous monitoring of a coin's value and fluctuations can result in obsessive thoughts and behaviors as individuals become preoccupied with checking their investments and making decisions based on market conditions.
- Relationship Strain: The financial implications of investing in Hamster Kombat Coin can create strain in relationships, especially if one partner is significantly invested in the coin while the other is not. Disagreements regarding financial decisions and investments may lead to conflict and tension within the relationship.
- Emotional Rollercoaster: The highs and lows of investing in Hamster Kombat Coin can evoke a wide range of emotions, from euphoria to despair. This emotional volatility can significantly impact one's mental well-being and overall quality of life.

Overall, the psychological impacts of the Hamster Kombat coin on human life can be substantial, resulting in heightened stress, anxiety, and emotional turmoil for individuals invested in this cryptocurrency. It is essential for individuals to remain aware of their mental health and seek support when necessary while navigating the complexities of cryptocurrency investments.

Figure 4 summarizes the results.

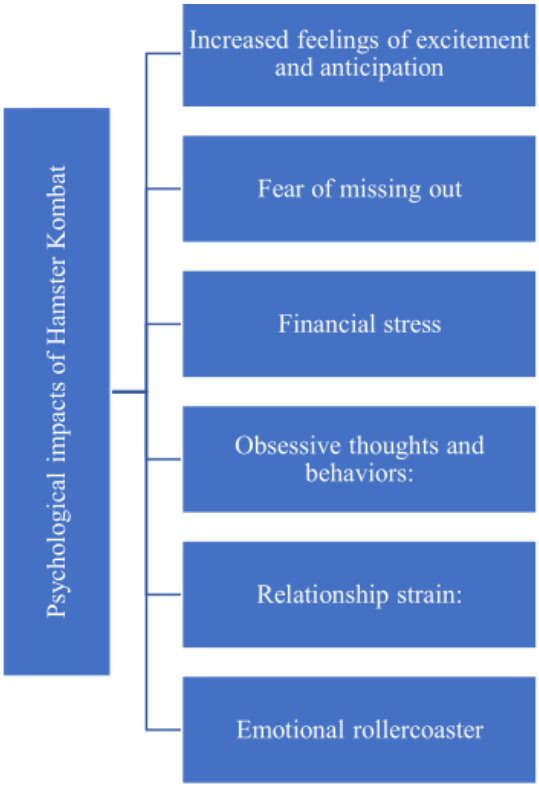

Figure 4. Psychological impacts of Hamster Kombat coin on human life.

4.3. Legal impacts of Hamster Kombat coin on human life

- Regulatory Compliance: As with any cryptocurrency or token project, the developers of Hamster Kombat Coin must ensure compliance with all relevant laws and regulations. This includes obtaining the necessary licenses and registrations, as well as adhering to anti-money laundering (AML) and know-your-customer (KYC) requirements [7].
- Intellectual Property Rights: The developers of Hamster Kombat Coin should consider any intellectual property rights, such as trademarks or copyrights, that may be associated with the project. They must ensure that they have obtained the necessary permissions and licenses to utilize any third-party intellectual property.
- Consumer Protection: The developers of Hamster Kombat Coin should take into account consumer protection laws and regulations. This includes providing clear and accurate information to users regarding the risks associated with investing in the coin. Additionally, they must implement robust security measures to safeguard user data and funds.
- Taxation: Developers of the Hamster Kombat coin should be aware of the tax implications associated with launching and trading the coin. They should consult with tax professionals to ensure compliance with all relevant tax laws and regulations.
- Liability: The developers of Hamster Kombat Coin should also consider potential liability issues, including the risk of lawsuits from investors or other third parties. They should take proactive measures to protect themselves from potential legal disputes, such as implementing appropriate disclaimers and terms of service agreements.

The summary of the results is presented in **Figure 5**.

Figure 5. Legal impacts of Hamster Kombat coin on human life.

Key jurisdictions and their regulatory stances

Cryptocurrency investments are subject to a variety of legal landscapes across different jurisdictions. These variations significantly impact how cryptocurrencies are classified, traded, taxed, and regulated. Here's an overview of some key jurisdictions and their regulatory stances:

1) United States

Regulatory Bodies: The Securities and Exchange Commission (SEC) oversees securities, while the Commodity Futures Trading Commission (CFTC) regulates derivatives.

Classification: Cryptocurrencies can be classified as securities, commodities, or currencies depending on the characteristics of individual assets.

Taxation: The IRS treats cryptocurrencies as property, subjecting them to capital gains tax.

State Regulations: Individual states may have their own laws, such as New York's BitLicense, which imposes strict regulatory requirements on cryptocurrency businesses.

2) European Union

Regulatory Framework: The EU is working on a comprehensive regulatory framework known as the Markets in Crypto-Assets Regulation (MiCA), which aims to create a unified approach across member states.

Classification: Cryptocurrencies may be treated as financial instruments, assets, or means of payment depending on their specific use case.

Anti-Money Laundering (AML): The EU has stringent AML directives that apply to cryptocurrency exchanges and wallet providers.

3) United Kingdom

Regulatory Authority: The Financial Conduct Authority (FCA) regulates cryptocurrency businesses.

Consumer Protection: The FCA has issued warnings about the risks of investing in cryptocurrencies and has proposed regulations to enhance consumer protections.

Taxation: HM Revenue and Customs (HMRC) treats cryptocurrencies as assets and applies capital gains tax when they are sold or exchanged.

4) Canada

Regulatory Framework: The Canadian Securities Administrators (CSA) provide guidance on the classification of cryptocurrencies as securities.

Taxation: The Canada Revenue Agency (CRA) treats cryptocurrencies as a commodity for tax purposes, imposing goods and services tax (GST) on their sale.

Licensing: Certain provinces, like Ontario, require cryptocurrency exchanges to register with securities regulators.

5) Asia-Pacific

China has taken a strict stance by banning all cryptocurrency transactions and Initial Coin Offerings (ICOs). The government promotes its own digital currency, the digital yuan.

Japan recognizes Bitcoin and other cryptocurrencies as legal property under their Payment Services Act. Cryptocurrencies are regulated, and exchanges must register with the Financial Services Agency (FSA).

South Korea regulates cryptocurrencies and requires exchanges to comply with AML and Know Your Customer (KYC) regulations.

6) Australia

Regulatory Authority: The Australian Securities and Investments Commission (ASIC) regulates cryptocurrency exchanges.

Taxation: The Australian Taxation Office (ATO) treats cryptocurrency as property and applies capital gains tax to profits made from sales.

Licensing: Cryptocurrency exchanges must register with the Australian Transaction Reports and Analysis Centre (AUSTRAC).

7) Middle East

United Arab Emirates (UAE): Offers a favorable environment for cryptocurrency through free zones like Dubai Multi Commodities Centre (DMCC), which have tailored regulations for crypto businesses.

Saudi Arabia has taken a cautious approach, allowing some blockchain initiatives while regulating cryptocurrencies.

5. Ways to deal with the negative effects of Hamster Kombat coin on human life

5.1. Solutions for negative social effects

Dealing with the negative social effects of Hamster Kombat Coin (or any cryptocurrency) on human life requires a multifaceted approach. Here are several potential strategies to address these issues [8]:

- Education and Awareness: Raising awareness about the risks and potential drawbacks of investing in cryptocurrencies can empower individuals to make more informed decisions. This includes comprehending the speculative nature of these investments and recognizing the potential for substantial financial loss.
- Regulation and Oversight: Government agencies can establish regulations to safeguard consumers and investors from fraudulent or misleading cryptocurrency

schemes. Effective oversight can help prevent market manipulation and promote transparency.

- Financial Literacy Programs: Promoting financial literacy empowers individuals to make informed financial decisions, including understanding the risks associated with cryptocurrency investments.
- Consumer Protection Measures: Providing consumers with clear information about the risks and volatility associated with cryptocurrencies can help safeguard them from making uninformed investment decisions.
- Support for Mental Health: Volatile investments can significantly impact individuals' mental health, especially when they incur substantial financial losses. Access to mental health support and resources can assist individuals in coping with the stress and anxiety associated with these losses.
- Promotion of Diversified Investments: Encouraging individuals to diversify their investment portfolios beyond cryptocurrencies can help mitigate the impact of substantial losses in any single asset class.
- Transparent Communication from Cryptocurrency Creators: Promoting transparency and responsible communication among cryptocurrency creators can help manage expectations and mitigate excessive speculation.

Remember that each of these measures presents its own set of challenges and may necessitate collaborative efforts from a variety of stakeholders, including governments, financial institutions, educators, mental health professionals, and cryptocurrency communities.

The summary of the solutions presented in this section is displayed in **Figure 6**.

Solutions	Education and awareness
	Regulation and oversight
	Financial literacy programs
	Consumer protection measures
	Support for mental health
	Promotion and diversified investments
	Transparent communication from cryptocurrency creators

Figure 6. Solutions for negative social effects.

5.2. Solutions for negative psychological effects

Dealing with the negative psychological effects of participating in volatile ventures, such as "Hamster Kombat Coin, can be challenging. Here are several strategies to mitigate the adverse impact:

- Limit Exposure: If the fluctuations of these investments are causing distress,

consider reducing your exposure to market news and price monitoring. Constantly checking values can lead to unnecessary stress [6].

- Seek Support: Discuss your concerns with friends, family, or a financial advisor. Having a support system can help alleviate anxiety and provide valuable perspective.
- Focus on Long-Term Goals: remind yourself of the reasons behind your initial investment. If it aligns with your long-term financial objectives, short-term volatility may have a diminished impact.
- Diversify Investments: Consider diversifying your investment portfolio to mitigate the impact of volatility associated with any single asset.
- Practice Mindfulness: Engage in activities that promote mindfulness and alleviate stress, such as meditation, yoga, or deep breathing exercises.
- Educate Yourself: Enhance your understanding of the market and investment strategies to feel more empowered and in control of your decisions.
- Set realistic expectations: recognize that all investments carry a certain degree of risk. Establishing realistic expectations can help mitigate disappointment during market downturns.
- Professional Help: If the negative psychological effects are significant, consider seeking guidance from a mental health professional. They can offer strategies for managing stress and anxiety associated with financial issues.

Remember, the value of any investment, particularly volatile ones, can fluctuate significantly, which may not be suitable for everyone. It is essential to evaluate your risk tolerance and ascertain whether such investments align with your financial objectives and emotional well-being.

The summary of the solutions presented in this section is displayed in **Figure 7**.

Solutions	Limit exposure
	Seek support
	Focus on long-term goals
	Diversify investments
	Practice mindfulness
	Educate yoursrlf
	Self-realistic expectations
	Professional help

Figure 7. Solutions for negative psychological effects.

5.3. Solutions for negative legal effects

Dealing with the negative legal implications of Hamster Kombat Coin or any cryptocurrency on human life primarily involves understanding and navigating the legal and regulatory landscape surrounding cryptocurrencies. Here are some general

guidelines to consider [9]:

- Compliance and Regulation: Ensure adherence to current financial regulations and laws governing cryptocurrencies. Consult legal counsel to comprehend and comply with any regulatory requirements specific to Hamster Kombat Coin and its operations. This may involve aspects of securities law, tax law, and anti-money laundering regulations.
- Transparency and due diligence: Maintain transparency in all operations associated with the Hamster Kombat Coin. Furthermore, conduct thorough due diligence on all aspects of the coin's usage and its impact on human life to ensure both legality and ethical integrity.
- Legal Consultation: Seek legal advice from professionals who specialize in cryptocurrency and blockchain technology. They can guide how to address any adverse legal implications and minimize potential liabilities.
- Community Engagement and Education: Actively engage with the community impacted by Hamster Kombat Coin and provide education regarding its role, rights, and responsibilities. Promote a culture of compliance and ethical behavior within the community.
- Risk Mitigation: Implement risk management strategies to minimize potential legal repercussions. This may involve establishing safeguards against fraud, theft, and market manipulation.
- Advocacy and lobbying: Engage in advocacy initiatives to influence cryptocurrency-related regulations and promote a legal framework that balances innovation with consumer protection.

Always stay informed about legal developments and adjust strategies as needed to comply with evolving regulations and best practices.

The summary of the solutions presented in this section is displayed in **Figure 8**.

Solutions	Compliance and regulation
	Transparency and due diligence
	Legal consultation
	Community engagement and education
	Risk mitigation
	Advocacy and lobbying
	Transparent communication from cryptocurrency creators

Figure 8. Solutions for negative legal effects.

6. Strengths and weaknesses, opportunities and threats (SWOT) analysis of Hamster Kombat on human life

SWOT analysis is a strategic planning tool utilized to identify an organization's strengths, weaknesses, opportunities, and threats.

- Strengths: Internal factors that provide an organization with a competitive advantage over others.
- Weaknesses: Internal factors that put the organization at a disadvantage compared to its competitors.
- Opportunities refer to external factors that provide the organization with the potential to improve or expand.
- Threats: External factors that may pose challenges to the organization.

SWOT analysis is commonly employed to evaluate a business venture, product, project, or even an individual. It aids in developing a strategy that aligns strengths with opportunities, addresses weaknesses, and mitigates threats [10].

We have conducted a SWOT analysis focusing on the social, psychological, and legal aspects of the "Hamster Kombat" coin and its impact on human life.

6.1. Strengths

- Social Engagement: The coin has the potential to cultivate a community of like-minded individuals who are passionate about hamsters and gaming, thereby promoting social interaction and fostering a sense of belonging.
- Psychological Entertainment: It can provide a source of entertainment and stress relief for individuals seeking a lighthearted distraction, potentially enhancing their mental well-being.
- Legal Compliance: If the coin complies with applicable regulations and laws, it can offer a secure and legitimate avenue for investment and participation.

6.2. Weaknesses

- Social Division: Over-investment in the coin by certain individuals may create divisions within social circles, resulting in tensions and conflicts.
- Psychological Impact: Addiction and compulsive behaviors associated with coin trading and gaming can have detrimental psychological effects on vulnerable individuals.
- Legal Risk: If the legal status of the coin is uncertain, it may pose legal risks for participants and result in regulatory consequences.

6.3. Opportunities

- Social Connection: The coin has the potential to create opportunities for social events and gatherings centered around a common interest in hamsters and gaming.
- Psychological: When used in moderation, the coin can provide relaxation and enjoyment, contributing to positive mental well-being.
- Legal Framework: By adhering to legal and regulatory frameworks, the coin can increase its credibility and appeal to a wider audience.

6.4. Threats

- Social Buzz and FOMO: The hype surrounding the coin might create social pressure and a fear of missing out (FOMO), which could lead individuals to make quick and risky financial decisions.
- Psychological Stress: Significant volatility and market changes might cause stress and emotional strain for participants, particularly if they invest more than they can afford to lose.
- Legal Ambiguity: Legal issues and regulatory backlash could threaten the coin's legitimacy and operation, affecting both investors and the development team.

In conclusion, the "Hamster Kombat" coin could have both positive and negative impacts on social, psychological, and legal aspects of human life, contingent on its management and regulation.

The summary of the SWOT results is shown in **Figure 9** below:

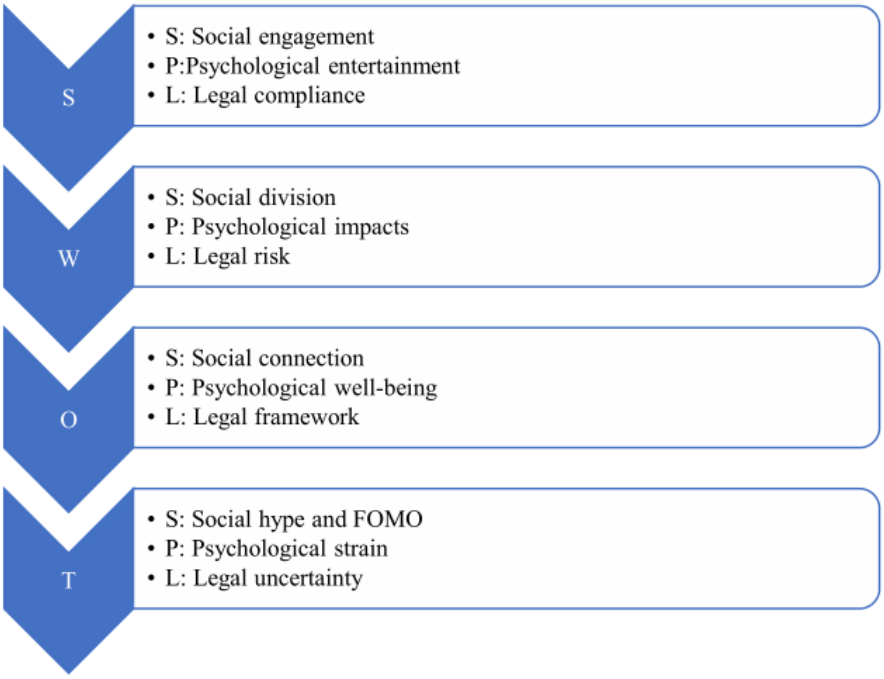

Figure 9. SWOT analysis of Hamster Kombat on human life.

7. Case study about the influence of Hamster Kombat coin in a real-world scenario

The Hamster Kombat coin, a cryptocurrency that gained traction in niche gaming communities, offers distinct examples of how it can impact various realms, such as gaming economies, user engagement, and community building. Here are several case studies that illustrate its influence in real-world scenarios:

Case Study 1: Gaming Economy Enhancement:

Scenario: The launch of Hamster Kombat as an in-game currency in a popular multiplayer online battle arena (MOBA) game.

Impact: By incorporating Hamster Kombat coins into the game, developers enabled players to purchase unique in-game items, skins, and upgrades using the cryptocurrency. A significant impact was observed:

Increased Revenue: The game reported a 40% increase in revenue within the first month of integrating Hamster Kombat coins, as players were attracted to exclusive items.

User Engagement: Players spent more time in-game, with average session durations increasing by 25%, driven by new activities tied to the use of Hamster Kombat coins.

Case Study 2: Community Development and Player Retention:

Scenario: A dedicated online community and gaming platform adopted Hamster Kombat coins for rewards and loyalty programs.

Impact: By rewarding engagement with Hamster Kombat coins, the platform experienced:

Higher Retention Rates: Player retention rates rose by 30% as users were motivated to stay engaged to earn coins through participation in tournaments and community events.

Enhanced Community Interaction: Forums and Discord channels saw a surge in conversations, with players sharing strategies on earning more coins and enhancing their gaming experience, fostering a sense of belonging and community.

Case Study 3: Innovation in Fundraising:

Scenario: A developer team sought to fund a new expansion for a popular hamster-themed mobile game by leveraging Hamster Kombat coins for crowdfunding.

Impact: By allowing fans and players to invest in the project using Hamster Kombat coins:

Successful Campaign Launch: The crowdfunding campaign raised over $150,000 within weeks, primarily due to players willing to invest in the future of the game, feeling empowered by their financial stake in the game's success.

Long-Term Player Involvement: Investors received exclusive content and early access, fostering a deeper bond between the players and developers and leading to sustained interest in the game.

Case Study 4: Charity Events and Social Good:

Scenario: An annual charity gaming event incorporated Hamster Kombat coins into its fundraising efforts, allowing participants to donate coins to various charitable causes.

Impact: This event showcased the potential for cryptocurrency in philanthropy.

Fundraising Success: The event raised over $200,000 through the donation of Hamster Kombat coins, utilizing blockchain transparency to show participants the direct impact of their contributions.

Community Mobilization: Engagement levels surged as participants were motivated not only by their love for gaming but also by contributing to a cause, exemplifying how cryptocurrency can bridge the gap between entertainment and altruism.

8. Comparative analysis of virtual currencies

The landscape of gaming and crypto is rapidly evolving, with numerous platforms like Notcoin, Blum, Tapswap, Musk Empire, and Catizen offering experiences similar to Hamster Kombat. Whether it is through apps, bots, coins, or

mini-games, these platforms have intelligently provided new frontiers for both gamers and crypto enthusiasts. As the market burgeons, these innovative platforms will undoubtedly take center stage in shaping the future of gaming and digital currencies.

In this part, we have tried to explore and compare apps, bots, coins, and games like Hamster Kombat, including Notcoin, Blum, Tapswap, Musk Empire, and Catizen. **Table 1** presents some information about each mentioned alternative:

Table 1. Hamster Kombat alternatives.

Alternatives	Description	Apps	Bots	Coins	Games
Notcoin	Overview	Just like Hamster Kombat, this particular application is where gaming and crypto rewards meet; in here, users get to earn Notcoins by fulfilling some challenges and participating in any other in-app activity.	The Notcoin bot provides users with automated trading and gaming options within their Telegram group, much like Hamster Kombat.	Notcoin is the native crypto of the Notcoin platform, used for rewarding players and facilitating in-app transactions.	Notcoin offers a range of mini-games within its Telegram app, rewarding players with Notcoins for their participation.
	Features	The app offers a variety of mini-games and a user-friendly interface, among others.	It offers real-time trading signals, game alerts, and reward tracking, making it an essential tool for gamers and traders alike.	It offers high liquidity, trading opportunities, and integration with various gaming activities.	The games are diverse, engaging, and integrated with the Notcoin ecosystem for seamless rewards.
Blum	Overview	Blum is a gaming app that incorporates blockchain technology, thereby enabling gamers to earn crypto by simply playing games.	Blum bot integrates with popular messaging platforms to facilitate gaming and crypto transactions.	Blum Coin is the currency of the Blum platform, earned through gameplay and used for in-game purchases.	Blum features mini-games within its Telegram app, allowing players to earn Blum Coins through gameplay.
	Features	To cater to the game's interest in competition, it offers tournaments, leaderboards, and other plenty of opportunities for players to win and trade their crypto winnings.	It provides game notifications, reward updates, and transaction tracking, enhancing the overall gaming experience.	It provides stability, trading potential, and a secure way to reward players for their achievements.	The games are competitive, fun, and designed to enhance the overall user experience.
Tapswap	Overview	This app is a decentralized gaming app that rewards its players with crypto tokens whenever they play games.	Tapswap bot offers automated trading and game management features, similar to Hamster Kombat's bot functionalities.	Tapswap Coin is the native token of Tapswap, used for rewards and trading within the platform.	Tapswap includes a variety of mini-games in its Telegram app, offering Tapswap Coins as rewards.
	Features	A marketplace to trade the earned tokens, and game modes for various genres of player preferences.	It includes trade execution, game updates, and a reward system that keeps players informed and engaged.	It offers seamless integration with the app's marketplace, high liquidity, and potential for value appreciation.	The games are interactive, rewarding, and fully integrated with the Tapswap platform.

Table 1. (*Continued*).

Alternatives	Description	Apps	Bots	Coins	Games
Musk empire	Overview	Musk Empire combines adventure gaming with crypto rewards. Players get on quests and can earn crypto by finishing the assigned mission.	The Musk Empire bot automates game alerts and crypto rewards within their community channels.	Musk Coin is the crypto of Musk Empire, earned through missions and adventures.	Musk Empire provides mini-games within its Telegram app, rewarding players with Musk Coins for completing missions.
	Features	Offers an enormous game world with deep immersion, heavy storytelling, along with a unique reward system in place for in-game achievements.	It provides mission updates, reward notifications, and community engagement tools, making it a vital part of the Musk Empire ecosystem.	It provides a rewarding experience for players, with opportunities for trading and in-game purchases.	The games are adventurous, immersive, and tied to the platform's reward system.
Catizen	Overview	Catizen is a social-driven mobile gaming application wherein users are rewarded with native cryptocurrencies if they socially engage within the app or are playing games on the platform.	Catizen bot enhances the gaming experience by offering automated notifications and crypto reward management.	Catizen Coin is the native currency of the Catizen platform, used to reward player engagement and in-game activities.	Catizen offers mini-games within its Telegram app, where players can earn Catizen Coins through various activities.
	Features	It has social utilities, mini-games, and a vibrant community—all wrapped into one awesome platform for gaming and earning.	It includes social interaction features, game alerts, and reward tracking, keeping players connected and motivated.	It offers social interaction rewards, trading potential, and integration with various app features.	The games are social, engaging, and connected to the Catizen community and reward system.

So far, we have tried to identify Hamster Kombat's competitors and get to know their features. Now we decide to compare Hamster Kombat from different aspects with its competitors in **Table 2**.

Table 2. Comparison to other clicker games.

Point of view	Descriptions
Traditional clicker games	Traditional clicker games like Cookie Clicker, AdVenture Capitalist, and Clicker Heroes focus on simple mechanics where players click to earn resources and automate processes to increase efficiency over time. These games are praised for their relaxing and addictive nature, providing a straightforward and enjoyable experience. However, they do not offer any real-world financial incentives, which is a significant differentiator for Hamster Kombat.
Educational and thematic clicker games	Some clicker games incorporate educational content or thematic elements to enhance the gameplay experience. For instance, Cell to Singularity combines clicker mechanics with educational content about human evolution, offering a learning experience alongside gameplay. Games like Forager and Plantera incorporate more active gameplay elements, such as combat and base-building, providing a richer and more diverse gaming experience compared to the straightforward tapping in Hamster Kombat.
Other crypto clicker games	There are other clicker games that integrate cryptocurrency, but they often face challenges that Hamster Kombat has managed to navigate successfully. For example, TapSwap, another Telegram-based clicker game, allows players to earn cryptocurrency but has experienced technical difficulties due to high user traffic. Notcoin and similar games offer play-to-earn mechanics but may not have the same level of community engagement or unique features as Hamster Kombat.

As a conclusion, Hamster Kombat stands out in the clicker game genre due to its integration with cryptocurrency, large community, and unique gameplay features. While traditional clicker games offer a relaxing and addictive experience, Hamster Kombat adds a layer of financial incentive and social engagement that appeals to a different audience. The game's accessibility through Telegram and its strong social

media presence further enhance its appeal. However, potential players should be aware of the risks and concerns associated with crypto-based games.

9. Conclusion and remarks

This examination has explored the various facets related to Hamster Kombat Coin, uncovering insights into its social, psychological, and legal dimensions. Socially, this phenomenon has fostered communities and interactions among enthusiasts, creating a distinct subculture focused on digital assets. Psychologically, the allure of such tokens lies in their gamified elements and potential financial gains, tapping into fundamental human motivations of competition and reward-seeking behavior. Legally, the rise of these digital tokens raises critical questions about regulatory frameworks and consumer protection, highlighting the need for adaptable legal structures in response to evolving technologies.

Furthermore, the study emphasizes the broader implications of digital currencies in modern society, demonstrating how blockchain technology innovations can redefine traditional concepts of value and ownership. As Hamster Kombat Coin continues to develop, further research will be essential in comprehending its long-term societal impacts and guiding responsible governance practices.

In summary, while Hamster Kombat Coin may appear niche, its analysis reveals broader insights into the intersection of digital culture, psychology, and law, showcasing the transformative potential of decentralized technologies in our increasingly connected world.

To sum up, “An Analysis of the Social, Psychological, and Legal Aspects of Hamster Kombat Coin” uncovers a multifaceted interaction of elements affecting this distinct cryptocurrency. From a social perspective, the meme culture associated with Hamster Kombat Coin showcases the strength of community involvement and how niche markets can thrive on collective enthusiasm. Psychologically, the attraction of gaming components and the novelty of merging entertainment with financial investment can boost user participation, often blending the lines between gaming and serious investment.

Legally, the rise of such cryptocurrencies brings forth critical questions about regulation, consumer protection, and how digital assets should be categorized. As regulators continue to address the ramifications of digital currencies, establishing clear legal guidelines will be crucial to protect investors and maintain market integrity.

In essence, the case of Hamster Kombat Coin offers an engaging example of modern cryptocurrency trends, emphasizing the importance of ongoing discussions among social, psychological, and legal experts to effectively navigate this ever-changing landscape. As the environment around digital currencies keeps evolving, insights drawn from this analysis will be key to comprehending future developments in the cryptocurrency realm.

For future research, the following recommendations are made:

- Longitudinal Study: Implement a longitudinal study to observe the societal impact of Hamster Kombat Coin (HKC) over an extended period. This should include monitoring shifts in public perception, adoption rates, and regulatory actions.

- Cross-Cultural Analysis: Examine the reception and ramifications of HKC within different cultural settings. Analyze how social, psychological, and legal factors differ across various regions.
- Impact on Mental Health: Investigate the psychological consequences of engaging in HKC markets for individuals, with a focus on addictive behaviors, anxiety, and financial stress.
- Regulatory Frameworks: Evaluate the evolving legal structures surrounding cryptocurrencies and their implications for HKC. This may involve case studies on regulatory actions and their effectiveness.
- Market Dynamics: Research the economic and behavioral characteristics of HKC trading, including market manipulation, investor sentiment, and volatility.
- Ethical Considerations: Examine the ethical issues associated with promoting HKC, such as consumer protection, fairness, and transparency.

Additionally, future recommendations are provided:

- Educational Campaigns: Create educational initiatives to raise public awareness about the risks and benefits of participating in HKC markets. This could help reduce psychological harm and enhance decision-making abilities.
- Policy Advocacy: Support regulatory frameworks that balance innovation with consumer protection. Collaborate with policymakers to develop guidelines that address the unique challenges posed by HKC.
- Psychological Support: Offer mental health resources and support services for individuals impacted by HKC trading, focusing on addiction prevention and financial well-being.
- Transparency Initiatives: Urge HKC developers and platforms to improve transparency in operations, disclosures, and risk communication to users.
- Research Collaboration: Promote interdisciplinary collaboration among social scientists, psychologists, legal experts, economists, and technologists to study HKC comprehensively from various perspectives.
- Community Engagement: Foster open discussions between HKC developers, regulators, investors, and the general public to address concerns and build trust.

By prioritizing these research directions and adopting these recommendations, stakeholders can enhance their understanding of the social, psychological, and legal impacts of Hamster Kombat Coin. This will ultimately lead to more effective policies and practices within the evolving cryptocurrency landscape.

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Article

Attitudes of consumers towards ethical buying and fair trade in Slovakia

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Abstract: Nowadays, more and more consumers have an increased interest in the field of ethics and social responsibility, which they present in connection with the companies they buy from. The attitude towards ethical shopping becomes particularly important in the context of sustainable development and environmental protection. Slovakia, as a member of the European Union, is not left out of this trend. In the contribution, we focus on the attitude of consumers in Slovakia towards ethical shopping through an applied questionnaire inquiry. Ethical shopping is the way consumers think when choosing products, considering the conditions under which products are produced, distributed, and disposed. When choosing products, consumers consider not only the impact of these products on the environment but also whether adequate working conditions were observed during their production. We obtained data on the attitudes of consumers in Slovakia through a survey, using the questionnaire method. The survey focused on selected areas of ethical shopping, with a special focus on fair trade and its knowledge among consumers in Slovakia. Based on the results of the survey, we suggest ways to educate as well as motivate consumers in Slovakia to realize ethical buying to a greater extent.

Keywords: correlation analysis; ethics; consumer behaviour; marketing survey; sustainability

1. Introduction

Plenty of related terms are used to define the growing ethical consumer movement, such as green consumerism, eco-consumerism, conscious consumption, sustainable consumption, and socially responsible consumption [1]. Ethical consumerism can be manifested in various types of ethical consumption behaviors (the buying of ethical product options, consumer preferences for more ethical brands, or types of ethically questionable consumption practices [2–5]. Ethical consumerism may be presented in the form of anti-consumption or boycotting behaviors [6] or in charitable giving [7]. Sustainable consumption is considered one of the main prerequisites for sustainable development [8]. It is possible that ethical consumption as part of sustainable consumption represents a response to concerns related to the field of ordinary and mass consumption associated with self-interest and effective utility [9]. The United Nations 2030 Agenda and Sustainable Development Goals point to the need to deal with the unprecedented environmental crisis, protect human rights, and promote equality. Therefore, it is important to open a discussion about consumer literacy in relation to the social and environmental aspects of consumption [10]. Conventional consumption practices are often blamed for significant ecological and social negative impacts such as climate change and inequality [11,12]. Concerns about conventional consumption have led many people to rethink the consequences of their everyday behaviors and choices [13]. Inclusive partnerships built upon a shared vision and shared goals for sustainability that place people and the planet at the centre,

are needed at global, regional, national, and local levels [14]. Fair Trade constitutes a social-business initiative that plays a crucial role in the transition towards sustainability and a sustainable market economy, countering the major challenges of the 21st century [15].

Fair Trade is "a trading partnership based on dialogue, transparency, and respect that seeks greater equity in international trade. It contributes to sustainable development by offering better trading conditions and securing the rights of marginalized producers and workers" [16]. There are strong indications that many consumers are switching towards more socially and environmentally responsible products and services, reflecting a shift in consumer values that is indicated in several countries [17]. The turn towards sustainability is becoming more critical in every sector; the trend of ethical consumerism is undeniable, but consumers' lifestyles and behaviors have been slow to transform [18]. Even though consumers are ethically concerned, they rarely transform their intentions into a green purchasing behaviour [19].

In connection with ethical shopping and ethical consumption, we often come across the term Fair Trade. Fair trade can be understood as a global movement of association and commercial cooperation based on communication, transparency, and respect that seeks greater equity in international trade, contributing to sustainability in the best conditions of trade and the guarantee of rights of involved groups [20]. Marketing can communicate within the company and with consumers to make better environmental choices and therefore have a positive impact, but marketing communication of sustainability at different levels can very easily turn into greenwashing or misleading messages towards customers about the positive environmental impact of a selected product or activity of a company or organization [21,22].

The aim of Fair Trade is to increase the satisfaction of stakeholders that primarily include producers, employees, consumers, as well as representatives of various environment-focused groups, etc. Ethical consumption fulfills the goals related to consumers, environmental protection, and fair treatment of human resources also through Fair Trade [23]. The Fair Trade is generally considered a tool associated with development. It is also considered a part of "new globalisation", changing patterns of international trade and the processes of corporate expansion that have historically overcome global ecological and social conditions [24]. Fair Trade presents a strong contrast to the conventional rational economic model of global trade, which focuses on maximum return for institutional buyers of commodities through a power imbalance in favour of purchasers. Some retailers have even developed their own product lines [25,26]. However, for a successful inclusion on the market, sellers need to differentiate the features of Fair Trade goods from the conventional ones [27]. The ethical dimension of such differentiation reduces the pressure on the price competitiveness of even homogeneous products, and the higher retail prices caused by the higher incomes for producers in the developing world are generally classified as having a higher value [26,28,29]. The higher value perceived by consumers is also connected with a feeling of buying a kind of premium product [30]. Such products are also perceived by the consumer as having a higher price. The customer is willing to pay for such products in part. The dependence of consumers on the purchase and price

of Fair Trade products depends on the perceived level of respect for producer rights and trust in social responsibility [31]. A broadened education and distribution channel of Fair Trade has extended beyond the circle of social activists to conscious consumers because it offers ethical consumption and enhances social entrepreneurship to bring about radical institutional change through social activism, marketing, and ethics [32]. Such social responsibility as well as the positive reputation of sellers are important factors in gaining consumer interest [33–36]. Therefore, socially responsible retailers must be transparent with their customers and build positive relationships with society [37–39]. In recent decades, Fair Trade research has developed rapidly as it provides sellers with the opportunity to monetize products. The concept and implementation of Fair Trade represent an innovation in the business model of sellers to help maintain a competitive advantage in a rapidly changing economic situation by improving their ability to create value [34,40–42].

On the other hand, Fair Trade offers a new attitude towards the producer-consumer relationship, which connects production and consumption via an innovative supply chain model. This model distributes its economic benefits more fairly among all stakeholders [24]. Fair trade successfully supports significant changes, which is also possible thanks to the fact that it involves people from all over the world in making decisions about these changes and their implementation in practice. It's a global movement made up of a diverse network of manufacturers, companies, shoppers, advocates, and organizations that put people and the planet first. Thanks to Fair Trade, there is an improvement in the employment opportunities of women and children, especially from developing countries where insufficient working conditions have been recorded. Fair Trade enables people to make the right decisions regardless of gender, status, position in society, or position in the world [20]. Fair trade is one of the most far-reaching and well-known ethical consumerism movements. It aims to put social justice at the heart of global supply chains [43]. Fair Trade is extremely important because it can have a positive impact on the market in terms of sustainable transformation [15,44].

Over the last period, within the framework of the solved issue, attention has been paid to sustainable purchase intentions [44], determinants of consumers' intention to buy Fair Trade products from the perspective of gender [45,46], drivers of consumer's willingness to pay for Fair Trade products [47–49], the promotion of Fair Trade buying behavior [50], ethical identity, social image, and sustainability, and a sociopsychological framework of ethical consumers' attitude-behavior gaps [51].

In Slovakia, only marginal studies are devoted to this issue. They rather focus on research and cross-generational analysis in shaping sustainable food markets [52], corporate social responsibility and application of its principles in chosen transnational corporations based in Slovakia and its impact on their international marketing management [53], case for developing and implementing a Fair Trade regime and participation in EU activities [54], and other studies examining the marginal impact of Fair Trade [55–57]. In view of the above, we can conclude that currently considerable attention is paid to the investigation of the attitudes of consumers towards ethical buying and Fair Trade from the point of view of various determinants and drivers. In Slovakia, attention is paid to this issue only marginally, focusing on the international level. No study examines the issue from the point of view of the general determinants

of gender and education at the level of Slovakia. Therefore, this contribution focuses on the evaluation of attitudes of consumers towards ethical buying and Fair Trade in Slovakia. Since sustainability, the issue of corporate social responsibility, and environmental protection are becoming more and more relevant, we decided to deal with them as a part of our survey, which is aimed at monitoring the attitude of consumers in Slovakia towards ethical shopping and its individual aspects.

2. Materials and methods

Considering the need to solve global ethical issues including rogue states, child labor, migration, climate change, global trade, and many others, we focused on the knowledge of consumers in Slovakia not only in the field of ethical shopping and the concept of Fair Trade, but we were also interested in the extent to which they actively participate in solving selected ethical aspects in shopping.

The survey was applied from 1 February 2024 to 15 May 2024 by means of a questionnaire. The survey was realized by the combined method—many questionnaires were sent online, and part of the survey was carried out by personal inquiries.

The questionnaire consisted of 16 questions, including 4 questions related to demographic data of the respondents (gender, age, education, income) and 12 questions that were aimed at monitoring various aspects of ethical buying, including knowledge about Fair Trade and its importance (the knowledge of consumers in Slovakia related to the concepts of ethical shopping, ethical consumption, interest in ethical products, and obstacles that limit consumers in Slovakia in purchasing ethical products). To increase the validity of the survey, we conducted a pre-survey on a sample of 70 respondents, so we found out whether the wording of the questions was chosen appropriately.

Before conducting the survey itself, we calculated the required sample of respondents.

Sample size calculation:

$$n = \frac{\left(z^2 \times \mathrm{p} \times (1-\mathrm{p})\right)+e^2}{\mathrm{e}^2+ z^2 \times \mathrm{p} \times \frac{(1-p)}{N}} = \frac{\left(95^2 \times 50 \times (1-50)\right)+6^2}{6^2+ 95^2 \times 50 \times \frac{(1-50)}{5\,424\,687}} = 268$$

where:

population size (N)—5 424 687.

Margin of Error (e)—6%.

Variance (p)—50%.

Confidence level (z)—95%.

Sample size—268 [58].

274 respondents took part in the survey, which fulfilled the minimum size regarding the required number of respondents, with a set confidence level of 95%, a margin of error of 6%, and a variance of 50%.

As part of the research, research objectives and hypotheses were determined, which were tested using the student's test. The mutual relation among independent variables and individual responses was analysed by the correlation coefficient. It is used to measure the strength of a relationship between two variables. We interpret the

values of the correlation coefficient according to Chráska [59]. He describes their dependence as follows: values from 0.9 to 1 (−0.9 to −1) are considered to be very highly dependent, so there is a very strong interdependence among the variables. Values from 0.7 to 0.9 (−0.7 to −0) are highly dependent, and from 0.4 to 0.7 (−0.7 to 0.4) are moderately dependent, from 0.2–0.4 (−0.4 to −0.2) are with low dependence. Values from the interval 0–0.2 (−0.2–0.0) are considered to be weak (without dependence). The entire methodological research process is shown in **Table 1**.

Table1. Methodological research procedure.

Methodology procedure		**Characteristic**
Primary research method		**Questionnaire inquiry**
Research time		**1 February 2024 to 15 May 2024**
Method of inquiry		**Combined method**
Questionnaire	Demographic issues	4
	Research questions	12
Survey validation	pre-survey	a sample of 70 respondents
Survey	Sample size calculation	268
	Sample size real	274
H1	Goal	The goal is to find out whether the gender of the respondents affects their experience (knowledge) with the concept of Fair Trade
	Research question	Does the gender of the respondents influence their experience (knowledge) with the concept of Fair Trade
	Hypothesis	There is a statistical dependence between the gender of the respondents and their experience (knowledge) with the concept of Fair Trade.
H2	Goal	The aim is to find out whether the respondents' education affects their experience (knowledge) with the concept of Fair Trade
	Research question	Does the respondents' education influence their experience (knowledge) with the concept of Fair Trade
	Hypothesis	There is a statistical dependence between respondents' education and their experience (knowledge) with the concept of Fair Trade.
File normality testing		*F*-test
Hypothesis testing		Student's *t*-test
Testing the strength of a relationship		Pearson correlation coefficient

3. Results

The knowledge of consumers in Slovakia about the concept of ethical shopping is at the required level, and in most cases, they correctly interpret it as buying products that have been produced regarding environmental and social aspects, but the actual implementation of ethical shopping in practice is already at a much lower level. Up to 64% of respondents carry out ethical shopping only in exceptional cases, and these cases concern the purchase of products such as food, clothes, and cosmetics. 18% of respondents are not interested in the ethical aspects of products at all.

Consumers primarily associate the motives for purchasing ethical products with the expected benefits in the area of health and the higher quality of ethical products compared to other products. Respondents generally perceive the level of ethical shopping as very low. The main reasons for the lack of interest in ethical shopping

include low awareness of what ethical shopping represents, the assumed high price of ethical products, and their weak offer on store counters.

The survey was also aimed at searching for dependence between selected demographic variables (gender and achieved education of respondents) and their experience with selected aspects of ethical buying, including knowing the Fair Trade and its concept.

The first hypothesis assumes the dependence between the gender of respondents and their experience (knowledge) with the Fair Trade concept as the inevitable part of ethical buying (see **Table 2**).

Table 2. Testing the dependence between gender and knowledge of the Fair Trade concept.

H1	**Gender**	**Positive answer**	**Not sure**	**Negative answer**	**Total amount**
Absolute frequency	Male	47	58	26	131
Relative frequency		36 %	44 %	20 %	100 %
Absolute frequency	Female	49	64	30	143
Relative frequency		34 %	45 %	21%	100 %
Total amount		96	122	56	274
F-test				0.467764	
F critical value				0.819182	
Assessment of the normality of variables by *F*-test				The hypothesis of equality of variances is accepted	
Hypothesis testing *t*-Test for difference of variances				The test for inequality of variances is valid	
Area minus				−1.9647	
Area plus				1.9647	
t Stat				−6.20161	
Hypothesis testing *t*-test for equality of variances				We reject the hypothesis of equality of variances	
Pearson correlation coefficient				0.0187659	
Strength of relationship—Pearson correlation				weak positive	

Based on the statistical evaluation of the established hypothesis—there is no statistical dependence between gender and knowledge of the Fair Trade concept—this hypothesis is rejected. Even though the normality of the data distribution was confirmed, the *t*-test did not confirm the dependence between the investigated variables since the *t*-Stat value (−6.20161) is not between the evaluation areas, which means that the *t*-Stat test statistic does not lie in the area of acceptance of the null hypothesis, which is the interval −1.9647 to 1.9647. The strength of the relationship between the investigated variables is moderately positive (0.0187659). We can assume that men as well as women have known (or not known) this term, so belonging to a certain gender does not affect the closer knowledge of this issue.

The next hypothesis tested dependence between the achieved education of respondents and their experience (knowledge) with the Fair Trade concept (see **Table 3**).

Table 3. Testing the dependence between education and knowledge of the Fair Trade concept.

H2	**Achieved education**	**Positive answer**	**Not sure**	**Negative answer**	**Total amount**
Absolute frequency	Basic education	5	0	0	5
Relative frequency		100 %	0 %	0 %	100 %
Absolute frequency	Secondary education	43	55	13	111
Relative frequency		38.7 %	49.6 %	11.7 %	100 %
Absolute frequency	University education	48	67	43	158
Relative frequency		30.4 %	42.4 %	27.2 %	100 %
Total amount		96	122	56	274
F-test				1.23312	
F critical value				1.22073	
Assessment of the normality of variables by *F*-test				The hypothesis of equality of variances is no accepted	
Hypothesis testing *t*-Test for difference of variances				The test for inequality of variances is valid	
Area minus				−1.9647	
Area plus				1.9647	
t Stat				12.87967	
Hypothesis testing *t*-test for equality of variances				We reject the hypothesis of equality of variances	
Pearson correlation coefficient				0.0209773626	
Strength of relationship—Pearson correlation				weak positive	

Based on the statistical evaluation of the established hypothesis—there is no statistical dependence between gender and knowledge of the Fair Trade concept—this hypothesis is rejected. The normality of the distribution of the data was not confirmed by the *t*-test, and the dependence between the investigated variables was not confirmed either, since the *t*-Stat value (12.87967) is not between the assessment areas, which means that the *t*-Stat test statistic does not lie in the area of acceptance of the null hypothesis, which is interval −1.9647 to 1.9647. The strength of the relationship between the investigated variables is weakly positive (0.0209773626).

There is only a weak dependence between monitored variables, so we can assume that achieved education influences the knowledge of Fair Trade to a low extent. When implementing steps leading to increasing literacy in the field of ethical consumption and various areas related to it (including Fair Trade), all consumers in Slovakia may meet this concept, provided that such activities are applied with regard to a specific target group and its preferences associated with possibilities to increase consumer literacy.

Consumers in Slovakia have some awareness of ethical shopping and issues associated with it, but it is important to provide them with more information so that they can base their purchasing decisions on detailed information, such as whether the products were produced under conditions that take into account adequate working conditions, as well as information on the impact the very production and consumption of these products on the environment.

4. Discussion

Ethical consumerism can be seen as an awareness of how much influence one's own consumption can have in the social and environmental spheres. Many consumers want products that are consistent with their own values, so they look for information about the conditions under which the products they buy are produced, transported, and liquidated. However, understanding and spreading the meaning of ethical shopping habits vary from country to country, and various factors are responsible for different attitudes towards ethical shopping. Knowing these factors becomes the subject of many studies because their knowledge allows the elimination of obstacles that negatively influence consumers when buying ethical products [60].

The results of our survey point to the fact that consumers in Slovakia know the main idea of ethical shopping, but they lack more detailed information about the availability of ethical products and their labelling. To make ethical purchases, it is necessary to raise their awareness, regardless of gender or level of education, as the results of the survey show little or no influence of the mentioned demographic factors on the knowledge and choice of products that can be considered ethical. This category also includes products with the Fair Trade label. In the survey, although most consumers have the correct knowledge of what the given term means, in some cases their awareness is wrong. In addition, even knowledge of terms related to ethical shopping does not mean that consumers will choose ethical products when making their purchases, because they are limited by low awareness of ethical shopping, and another limiting factor is the higher price with which consumers in Slovakia associate ethical products. The primary step leading to the higher motivation of consumers to make ethical purchases is an increase of awareness of ethical consumption, which we propose to address as part of education at elementary levels as well as secondary schools. It is also necessary to provide information to older generations of consumers in ways that we consider more effective in relation to this age category (e.g., by broadcasting educational programs on television). We also suggest the use of social networks because they seem to be effective when targeting the desired group of consumers, which increases the effectiveness of the promotion and its desired result. When raising consumer awareness and literacy about ethical shopping, it is necessary to consider the appropriateness of the communication channels used and the quality of the provided information. As it is reported by authors [61–64], the quality of information and the reliability of information sources affect the degree of their acceptance by consumers. Enterprises are primarily responsible for the sufficiency and quality of information. As reported by Wei et al. [65], consumers associate incomplete information with a higher risk that they place on themselves when making purchasing decisions. It is necessary for businesses to determine whether they provide enough relevant information to consumers. Even if consumers think that it is useless to have much information, businesses should actively provide some official, professional, and authoritative information, because based on it we can infer the level of professionalism and honesty of businesses. Moreover, the more complex information, the higher the avoidance tendency, which may cause individuals individuals process information in an inappropriate way [66]. Information is also a significant source for producers and sellers because information about consumers and their preferences is also beneficial

for managers, as it allows them to better understand consumers and, consequently, can make their marketing activities more efficient [67].

In the approach to ethical shopping, a survey conducted by Deng, who asked more than 1000 respondents in a two-stage study, found that there is a large gap between purchasing intention and purchasing reality. The findings show that the purchase of ethical products is influenced by many factors, including personal characteristics, ethical awareness, economic rationality, purchasing inertia, cynicism, and ethical cognitive efforts, but also situational factors. They all have an impact on the purchasing intention with which we approach selecting the ethical products and how their final selection looks like [68].

Compared to previous quantitative studies, a qualitative study dealing with the attitude of consumers towards ethical shopping was conducted by Rabeson et al. [69]. Based on interviews with French consumers, they found that time, money, and pleasure are the most important factors negatively affecting ethical shopping for couples.

It is highly likely that this ethical shopping trend has growing potential. As it is stated by Šálková et al. [60], an increasing number of consumers consider ethical, environmental, and social aspects of products. The real interest in ethical products in Slovakia is also at a low level. Both surveys identified the same factors that cause low interest in ethical products. The results of the survey conducted on respondents in the Czech Republic revealed that, especially the poor availability of ethical products in the sales network, lack of interest in ethical products, and higher prices are the most important reasons for not buying ethical products. The survey conducted by Nayak et al. [61] also emphasizes the importance of price when considering the purchase of ethical products. He states that consideration of price sensitivity is therefore also crucial for retail managers, whose pricing strategies can influence consumers' ethical purchasing decisions [70].

Attitudes towards ethical buying are also important for companies. Companies can increase their attractiveness in the eyes of ethically oriented consumers and, at the same time, contribute to a more sustainable society by addressing the discomfort, ambiguity, and negative emotions resulting from their own unethical behavior [71]. From the point of view of promoting ethical consumption, understanding its driving forces and obstacles is crucial for companies and their managers, because taking them into account can improve strategies to promote ethical consumption and influence the target market more effectively [72].

5. Conclusion

It is not possible to generalise the results of our survey. The results presented in this paper consider the conditions and buying preferences of Slovak residents. It is highly probable that specific case studies in other countries can present diverse results because of various cultural conditions that result in specific purchase decisions. Cultural and regional factors can have a significant impact on consumer decision-making processes. Values, traditions, and social norms can also influence how individuals perceive ethical issues and accept ethical products. Therefore, it is necessary for each country, in order to participate in the global effort related to

sustainability, to carry out its own surveys in the field of ethical consumerism and, based on the findings of the surveys and taking into account social, economic, and cultural specificities, determine the most suitable procedures that could effectively motivate consumers to become more ethical in making their purchasing decisions.

Considering the expectations associated with the concept of sustainability, which are associated with the need to ensure adequate living standards not only for current but also future generations, societies primarily focus on activities that monitor impacts in both the environmental and social areas. Many businesses are under scrutiny to see if their activities meet the requirements, taking into account the elimination of negative impacts in the aforementioned areas.

Not only companies but also consumers themselves can contribute to sustainability by considering the ethical aspects of products in their purchasing decisions. To be able to make the right decisions, it is important for consumers to know which products support sustainability and vice versa, which products do not meet the required standards, and not to include such products in their purchases.

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Article

Enterprise digital transformation, accounting information comparability and corporate innovation

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Abstract: In the evolving digital landscape, the digital shift within corporations is pivotal for fostering innovation and elevating competitiveness. This study investigates the impact of digital transformation on enterprise innovation, utilizing a dataset of A-share listed firms from 2010 to 2020. To address sample self-selection, the Propensity Score Matching (PSM) method is employed, dividing enterprises into experimental and control groups based on their level of digital transformation. Additionally, to mitigate endogeneity concerns, all explanatory variables are lagged by one period. The study employs benchmark regression analysis, considering control variables and fixed effects for year and industry, to examine the relationship between digital transformation and innovation. The study constructs models to evaluate the mediating role of accounting information comparability in the relationship between digital transformation and innovation. Notably, a strong positive link is observed between a company's digital evolution and its innovation capacities, suggesting that this evolution substantially augments innovation. Moreover, the consistency of accounting data further amplifies this effect. Such insights offer strategic guidance for companies aiming to bolster innovation amid their digital journey and underscore the necessity for consistent accounting data.

Keywords: digital transformation; accounting information comparability; innovation

1. Introduction

With the development of the global economy, innovation has become the key to high-quality development of enterprises. Innovation, defined as the process of translating ideas into value-creating goods and services, enables firms to stay ahead in the market and adapt to technological changes. However, innovation activities require large investments and long research and development cycles, which make the risk of innovation investment increase. Against this background, the era of digital economy brings us a new opportunity: digital transformation [1]. The Chinese government attaches great importance to this, setting clear goals for digital transformation and introducing a series of policies to promote its realization. In addition, the state has been increasing its investment in major projects such as "East Counts, West Counts" [2] and encouraging all industries to deeply integrate digital technologies to achieve high-quality economic development. **Figure 1** shows that with the development of the digital economy in recent years, the number of patents representing enterprise innovation has steadily increased.

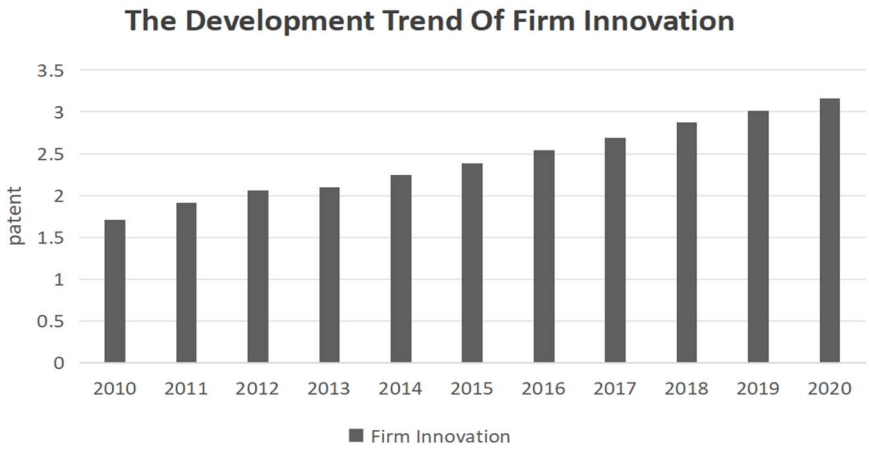

Figure 1. Chart of the development trend of firm innovation.

Digital transformation has become a critical factor in driving enterprise innovation in the contemporary business landscape. Defined as the comprehensive integration of digital technologies into all facets of an organization, digital transformation reshapes how companies operate and deliver value. It involves the adoption of cutting-edge technologies such as artificial intelligence and big data analytics, fostering an environment that promotes continuous innovation and improved business processes. By embracing digital transformation, firms can enhance their innovation capabilities and leverage more comparable and transparent financial information, thereby driving sustainable growth and competitiveness in the digital age. Numerous studies have explored the multifaceted impacts of digitalization on various aspects of business operations, providing valuable insights into how digital transformation can foster innovation and improve overall firm performance. For instance, digital transformation can significantly enhance the efficiency and effectiveness of business processes, leading to increased innovation capabilities [3]. Moreover, the integration of digital technologies can facilitate better decision-making and more agile responses to market changes, further driving innovation [4]. Besides, digital transformation enables more efficient processes, better decision-making, and the creation of new products and services [5], and studies have identified the importance of cultivating a digital culture within organizations to fully leverage the benefits of digital transformation. A digital culture encourages experimentation, agility, and continuous learning, which are critical for innovation [6]. However, the role of regulatory environments in shaping the effectiveness of digital transformation efforts and subsequent innovation is not well explored. Regulatory support and constraints can significantly influence how digital transformation initiatives are implemented and their outcomes [7], but subsequent innovation has not been proven.

Innovation, as the core driving force of enterprise development, has been studied in depth by many scholars. Schumpeter made an in-depth discussion on enterprise innovation at the beginning of the last century and pointed out that enterprise innovation covers many aspects such as systems, technology, markets, and management. In recent years, many scholars have explored the influencing factors of corporate innovation from different perspectives, including the internal shareholding structure and scale of the enterprise, as well as the external financing environment and macro policies. However, relatively few studies have focused on how digital

transformation affects corporate innovation. Although some scholars have explored this issue from the perspectives of talent effects, dynamic capabilities, and knowledge management, it is clear that this is not enough. So, this paper aims to explore the following key research questions: What is the impact of digital transformation on enterprise innovation? How does accounting information comparability mediate the relationship between digital transformation and enterprise innovation? What are the differences in the impact of digital transformation on innovation across various industries and firm sizes? What are the potential endogeneity issues in studying the relationship between digital transformation and enterprise innovation, and how can they be addressed?

Accounting information comparability also plays a crucial role in this context, as it enables stakeholders to make more informed decisions, thereby enhancing the overall impact of digital transformation on innovation [8]. Studies have shown that greater comparability of financial statements can lead to more efficient capital allocation and reduced information asymmetry [9]. With the support of digital technology, companies can collect, integrate, and analyze data more effectively, thus improving the comparability of their accounting information. And highly comparable accounting information can not only help firms better assess the effectiveness of their innovation strategies but also provide external investors with more accurate and reliable information, thus reducing the risk of innovation investment. Therefore, the purpose of this paper is to explore how firms' digital transformation can promote firm innovation by affecting the comparability of accounting information.

The marginal contributions of this paper are mainly in the following aspects: first, we explore how firms' digital transformation affects firms' innovation from the perspective of accounting information comparability, which provides new perspectives and theoretical support to the existing literature. Second, we provide insights into the mechanisms of how digital transformation and comparability of accounting information work together on firm innovation. Finally, we also explore how to further improve the comparability of firms' accounting information in the digital economy to better support firm innovation.

2. Theoretical analysis and research hypotheses

2.1. Enterprise digital transformation and enterprise innovation

With the rapid development of the digital economy, enterprises are in urgent need of transformation, especially digital transformation, in order to maintain their competitive position. Digital transformation not only means the upgrading of technology but also the overall change of enterprise culture, management mode, and business model. The relationship between digital transformation and innovation has been a focal point of contemporary research, with numerous studies examining how digital technologies impact enterprise innovation capabilities. The existing literature provides robust evidence of the positive impact of digital transformation on innovation, emphasizing the importance of digital culture, financial transparency, and industry-specific strategies. However, there are still several areas that require further exploration, such as the long-term effects of digital transformation, its impact on SMEs, the influence of regulatory environments, and the mediating and moderating

factors involved. Addressing these gaps will provide a more comprehensive understanding of how digital transformation can drive sustainable innovation across various contexts.

First, the institutional innovation aspect. Digital transformation requires enterprises to form a new set of institutional logic internally to adapt to the external digital economic environment [10]. This institutional innovation can help enterprises better adapt to the external environment, improve their responsiveness and flexibility, and thus promote innovation. Second, technological innovation aspect: digital technologies, such as big data, cloud computing, artificial intelligence, etc., provide powerful tools and means for enterprises to develop and innovate their products and services more quickly and accurately [11]. Third, market innovation aspect: digital transformation enables enterprises to better understand market demand and respond more quickly to market changes, thus promoting market innovation. Fourth, management innovation: digital transformation promotes the flattening of enterprise management, enabling enterprises to better stimulate the innovation potential of employees and improve their innovation efficiency [12]. In summary, we believe that digital transformation can promote enterprise innovation in many ways.

2.2. Enterprise digital transformation, accounting information comparability, and enterprise innovation

In today's digital era, businesses are undergoing swift transformations. The digital shift has revolutionized corporate operations and significantly altered their information management and dissemination methods. Through the lens of digital tech and accounting data management, the integration of advancements like big data, cloud solutions, and AI enables firms to handle diverse accounting data with increased precision and speed. This elevates the reliability and comprehensiveness of accounting details, expediting their release to satisfy the immediate informational requirements of investors and other concerned parties. In terms of transparency and trust, tools like blockchain amplify the clarity of accounting data, offering stakeholders a clearer glimpse into the company's genuine operational status, which in turn fosters increased confidence. Thus, a firm's digital transition can enhance the comparability of its accounting details.

And regarding the impact of accounting information comparability on enterprise innovation, it can be analyzed from four aspects: the basis of innovation decision-making, the convenience of financing, risk management and innovation, and stakeholder participation. First, highly comparable accounting information provides firms with important feedback about their innovation strategies. Firms are able to use this information to clearly understand which innovation projects or strategies are successful and which need to be adjusted or abandoned so that they can allocate resources more precisely [13]. Second, financing is key in innovation activities. Highly comparable accounting information can better demonstrate a firm's operating conditions and potential growth, attracting the attention of investors and financial institutions. This will help firms obtain financing more easily to support their innovation projects. Third, when firms' accounting information is highly comparable, they can perform risk assessment more effectively. This risk assessment can help firms

better manage the risks associated with innovation, thus encouraging bolder attempts at innovation [14]. Fourth, highly comparable accounting information can also facilitate the engagement of stakeholders, such as suppliers, customers, and partners. When these stakeholders are able to better understand a firm's operations, they may be more willing to participate in and support the firm's innovation programs. In summary, we argue that digital transformation can further promote firm innovation by improving the comparability of accounting information. This paper proposes the following hypotheses:

H1: Digital transformation can significantly enhance corporate innovation.

H2: Accounting information comparability plays a pivotal intermediary role in the influence of enterprise digital transition on business innovation.

3. Research design

3.1. Sample source

This study examines A-share listed firms between 2010 and 2020. Companies in the financial and insurance sectors were omitted, as were ST and *ST-designated firms. Additionally, entities without the necessary data were disregarded. After this screening process, we were left with a total of 20,093 sample data points. To ensure the robustness of the study, all continuous variables were adjusted at both the top and bottom 1% to minimize the effects of outliers. All requisite data for this research was derived from the Wind database.

3.2. Model construction

3.2.1. Model construction

To evaluate the influence of digital transformation on business innovation and the intermediary role of accounting information comparability, this study formulates a specific model. Detailed definitions of the variables can be found in **Table 1**:

$$Patent_{i,t} = \alpha_0 + \alpha_1 DCG_{i,t} + \alpha_2 Controls_{i,t} + Industry + Year + \xi_{i,t} \quad (1)$$

$$Comp_{i,t} = \alpha_0 + \alpha_1 DCG_{i,t} + \alpha_2 Controls_{i,t} + Industry + Year + \xi_{i,t} \quad (2)$$

In this framework, the term 'Controls' encompasses all control variables. The 'Year' and 'Industry' variables indicate the respective fixed effects for time and sector. Meanwhile, and ξ is the random error term.

3.2.2. Definition of variables

Explained variable: firm innovation (innovation). Enterprise innovation can be measured from two dimensions: one is based on innovation output, usually using indicators such as the number of patent applications and authorizations [15]; the other is based on innovation input to assess the innovation activity of enterprises. In this study, we choose the method of innovation output and use the number of patent applications as a metric, based on the study of Kong et al. [16]. This method is adopted because, on the one hand, invention patents better reflect the scientific and technological innovation capability of enterprises compared with R&D inputs [16]; on the other hand, the number of patent applications is more stable than the number of

patents granted, which may be affected by a variety of factors [17]. In order to eliminate data skewness, we take the logarithm of all patent values after adding 1 to get three variables: Patent, Patent1, and Patent2, which represent the total innovation quantity, innovation quality, and innovation quantity of enterprises, respectively.

Explanatory variable: Enterprise Digital Transformation Intensity (DCG). Domestic research often gauges a firm's digital transformation progression by counting digital-related terms in annual reports, a method detailed by Wu et al. [18]. Using this approach, we tallied the occurrences of such terms in the annual reports of listed firms. These reports contain detailed disclosures about the companies' strategic initiatives, investments, and implementations related to digital technologies. A systematic keyword search is conducted within the annual reports to identify relevant mentions of digital transformation activities. Keywords include terms such as "digital strategy," "IT investment," "digitalization," "innovation through technology," "big data," "cloud computing," "artificial intelligence," and "Internet of Things (IoT)." To address data skewness, we incremented the frequency count by one and then applied a logarithmic transformation, resulting in the DCG variable that represents the company's digital transformation level.

Mediating variable: accounting information comparability (Comp). Accounting information comparability is concerned with the consistency of the accounting system, ensuring that different economic operations are consistent when translated into accounting information. In short, financial statements are more comparable when firms apply similar accounting treatments to similar economic operations. To measure this comparability, we refer to the approach of De Franco et al. [19]. First, we conduct a regression analysis based on Equation (3) using firms' data for the 16 quarters prior to period t, where $\text{Earning}_{i,t}$ represents the ratio of a firm's quarterly profit to its opening market capitalization, and $\text{Return}_{i,t}$ denotes the quarterly stock return. If firms i and j are assumed to have the same economic operations, then based on the estimation of Equation (3), we can use Equations (4) and (5) to predict their expected surpluses. Further, we calculate the difference between the expected surpluses of the two firms and take the opposite of the average of their absolute values so that we obtain the comparability of accounting information between firms i and j as shown in Equation (5). In order to obtain the comparability of accounting information for a particular company, we match it with other companies in the same industry. Finally, we rank the comparability of each pair of firms and take the average value of the comparability of the firm with all other firms in its industry (Comp) as the measure of the comparability of accounting information of that firm. Theoretically, the larger this value is, the more comparable the firm's accounting information is.

$$\text{Earning}_{i,t} = \alpha_i + \beta_i \text{Return}_{i,t} + \varepsilon \tag{3}$$

$$E(\text{Earning})_{i,i,t} = \alpha_i + \beta_i \text{Return}_{i,t} \tag{4}$$

$$E(\text{Earning})_{i,j,t} = \alpha_i + \beta_i \text{Return}_{i,t} \tag{5}$$

$$\text{Comp}_{i,j,t} = -1/16 \times \sum_{t}^{t=15} |E(\text{Earning})_{i,i,t} - E(\text{Earning})_{i,j,t}| \tag{6}$$

Control Variables: This study incorporates several control variables: the company's scale (Size), leverage ratio (Lev), total asset returns (ROA), operational income growth rate (Growth), board member count (Board), proportion of independent directors (Indep), the largest shareholder's ownership percentage (Top1), equity balance level (Balance), and ownership configuration (SOE). The paper concludes by also controlling for year effects and fixed effects. This is shown in **Table 1**:

Table 1. Table of control variable definitions.

Variable Name	Variable Symbol	Variable Definition
Enterprise Size	Size	Taking the natural logarithm of total business assets
Gearing Ratio	Lev	Total liabilities/total assets
Return on Total Assets	ROA	Net profit/total assets
Operating Revenue Growth Rate	Growth	(Current Operating Income − Previous Operating Income)/Previous Operating Income
Number of Directors	Board	Number of Board of Directors
Proportion of Independent Directors	Indep	Number of independent directors/total number of board members
Shareholding ratio of the largest shareholder	Top1	Number of shares held by the first largest shareholder/total number of shares
Shareholding checks and balances	Balance	Total percentage of shares held by the second to fifth largest shareholder/percentage of shares held by the first largest shareholder
Ownership Structure	SOE	If the enterprise is a state-owned enterprise, take 1, otherwise take 0

3.2.3. Variable descriptive statistics

Table 2 presents the descriptive statistics of the studied variables. As evident in **Table 2**, the average values for corporate innovation are 2.589, 1.785, and 2.076 with variations in innovation levels across firms. The mean and standard deviation for digital transformation (DCG) are 1.412 and 1.416, highlighting considerable dispersion. This diversity in the sample data confirms its suitability for statistical analysis.

Table 2. Descriptive statistics of variables.

Variable	*N*	Mean	Std Dev	Min	Max
Patent	20,093	2.589	1.712	0	7.18
Patent1	20,093	1.785	1.503	0	6.531
Patent2	20,093	2.076	1.640	0	6.332
DCG	20,093	1.412	1.416	0	4.934
Comp	20,093	−0.009	0.007	−0.039	0.003
Size	20,093	22.38	1.302	19.52	26.21
Lev	20,093	0.467	0.209	0.0668	0.961
ROA	20,093	0.0323	0.0683	−0.289	0.217
Growth	20,093	0.179	0.564	−0.632	4.124
Board	20,093	8.687	1.720	5	15
Indep	20,093	0.3749	0.0538	0.3333	0.5714
Top1	20,093	0.3400	0.1464	0.0923	0.7365
Balance	20,093	0.0066	0.0057	0.0002	0.0255
SOE	20,093	0.465	0.499	0	1

4. Empirical results and analysis

4.1. Benchmark regression analysis

The regression analysis of Equation (1) in **Table 3** reveals that the correlation coefficients of enterprise innovation indicators Patent, Patent1, and Patent23 with the DCG of the enterprise's degree of digital transformation are 0.269, 0.285, and 0.215, respectively, which implies that when the degree of digital transformation of the enterprise is increased by 10%, the innovation level of the enterprise is correspondingly increased by 2.69%, 2.85%, and 2.15%, and the level of digital transformation of the enterprise is increased by 2.69%, 2.85%, and 2.15%, 2.85%, and 2.15%, respectively. This result clearly indicates that there is a significant positive correlation between firms' digital transformation and their level of innovation, and this correlation is validated at the 1% level of statistical significance. It can be seen that the higher the degree of digital transformation, the more significant is its positive contribution to corporate innovation, thus confirming the H1 hypothesis.

Table 3. Benchmark regression results.

Variable	Equation (1)			Equation (2)
	Patent	Patent1	Patent2	Comp
DCG	0.269***	0.285***	0.215***	0.023***
	(29.987)	(32.350)	(22.175)	(8.295)
Constant	−75.093***	−59.717**	−61.193***	16.383***
	(−10.220)	(−8.228)	(−7.672)	(7.185)
Controls	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes
Observations	20,093	20,093	20,093	20,093
R-squared	0.103	0.105	0.116	0.280

Note: ***, **, and * denote significant at the 1%, 5%, and 10% levels, respectively, and *t*-values in parentheses are the same as below.

Meanwhile, the correlation coefficient between the degree of digital transformation (DCG) and the comparability of accounting information (Comp) is 0.023, which means that when the degree of digital transformation of enterprises increases by 10%, the comparability of accounting information can be increased by 0.23%. This further confirms that digital transformation has a significant positive impact on the comparability of accounting information, and this finding is solidly supported at the 1% level of statistical significance.

4.2. Robustness tests

4.2.1. Propensity score matching method (PSM)

To circumvent the problem of sample self-selection, this study applies the propensity score matching method (PSM). Based on the digital transformation level of enterprises, we regard the top 25% of enterprises as the experimental group with a high level of digital transformation and the rest as the control group. By introducing

the dummy variable DCG_dum, we assign a value of 1 to the experimental group (high level of digitalization) and a value of 0 to the control group (low level of digitalization). Meanwhile, considering the characteristics of the enterprises such as whether they are loss-making (Loss), two jobs in one (Dual), the nature of the property rights (Soe), and whether they are a Big 4 auditing firm (Big 4), we adopt the radius matching method for pairing, where the threshold value was set at 0.01, resulting in 10,824 valid samples. The results of parallel hypothesis testing for PSM revealed that before matching, the experimental group differed significantly from the control group on several characteristics. This implies that these characteristics may act as confounding variables. However, after matching, these differences were significantly reduced, indicating that the matching was successful and ensured the consistency between the experimental and control groups on the key features. This further demonstrates the effectiveness of PSM. Based on the screened sample, we further conducted a regression analysis of the relationship between the degree of digital transformation and firm innovation. As shown in columns (1), (2), and (3) of **Table 4**, the results of the analysis again support our initial hypothesis.

Table 4. Robustness test results.

Variable	(1)	(2)	(3)	(4)	(5)	(6)
	Patent	**Patent1**	**Patent2**	**Patent**	**Patent1**	**Patent2**
DCG	0.312***	0.328***	0.237***	0.225***	0.226***	0.148***
	(24.292)	(26.377)	(16.519)	(25.754)	(28.768)	(17.910)
Constant	−59.117***	−39.842***	−51.937***	−63.317***	−37.071***	−55.646***
	(−5.073)	(−3.418)	(−4.135)	(−8.793)	(−5.762)	(−7.880)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes	Yes	Yes
Observations	10,824	10,824	10,824	20,093	20,093	20,093
R-squared	0.085	0.083	0.080	0.251	0.231	0.210

4.2.2. Lagged explanatory variables

In response to the above conclusions about how the degree of digital transformation of firms affects firm innovation, there may be questions. In particular, there may be certain omitted variables that affect both firm digital transformation and firm innovation, thus biasing the findings. Furthermore, given that innovation is a time-intensive process, the issue of endogeneity here cannot be ignored.

To address these issues, this paper refers to an approach of lagging all explanatory variables by one period, which can alleviate the potential endogeneity problem. As shown in columns (7), (8), and (9) of **Table 4**, even after accounting for these lags, every 1% increase in the degree of digital transformation (DCG) increases Patent, Patent1, and Patent2, 3 by 0.225%, 0.226%, and 0.148%, respectively. These results still hold at the 1% level of significance, thus reconfirming the validity of hypothesis H1.

4.2.3. Conclusions and insights

This research distinctly underscores a notable positive linkage between the extent of digital transformation and business innovation. As companies amplify their digital endeavors, they simultaneously bolster their innovative pursuits and proficiencies. This reiterates the indispensable nature of digital transformation in today's economic milieu for a company's enduring expansion and competitive edge. The research also highlights that digital transformation positively impacts the uniformity of accounting data. Crucially, this improved accounting data uniformity serves as a conduit linking digital transformation to enterprise innovation. Put differently, by refining the consistency of accounting details, digital transformation further amplifies a firm's innovative endeavors. However, there are some potential limitations related to the subjectivity of self-reported metrics about digital transformation. Self-reported measures, especially those derived from annual reports, are subject to the biases of the reporting firms. Companies may portray their digital transformation efforts more favorably to appeal to investors and stakeholders, potentially leading to an overestimation of their actual digital transformation intensity. This subjectivity can introduce systematic bias, making it challenging to accurately assess the true extent of digital transformation and its impact on innovation. Second, firms may vary in how they report and describe their digital transformation initiatives, leading to inconsistencies in the data collected. These differences can arise from varying levels of detail, terminology, and emphasis in the annual reports. Inconsistent reporting standards can compromise the comparability of digital transformation measures across different firms, potentially affecting the robustness of the study's conclusions. Self-reported measures also lack independent verification, meaning that the reported data on digital transformation may not always reflect actual practices and investments. Firms may exaggerate or underreport their digital activities due to strategic considerations or errors in reporting. Without external validation, the reliability of self-reported measures is questionable, which can affect the study's overall validity. While self-reported measures provide valuable insights into firms' digital transformation efforts, these potential limitations highlight the need for caution in interpreting the results. Future research could benefit from incorporating more objective measures of digital transformation, such as direct investment data, technology usage statistics, and third-party assessments, to complement self-reported information and provide a more comprehensive understanding of the phenomena under study.

This research emphasizes several practical implications for both business managers and policymakers, providing actionable insights that can guide strategic decisions and policy formulations to enhance enterprise innovation through digital transformation and improved accounting information comparability. Firstly, enterprises must delve deeper into digital transformation, recognizing it as more than just a technological shift—it's instrumental in spurring innovation and enhancing overall competitiveness. Managers should develop and implement comprehensive digital strategies that integrate these technologies into their core business processes to drive innovation and maintain competitive advantage. For optimal impact, this transformation should be in harmony with the firm's long-term objectives and strategies. Secondly, during this digital transition, the emphasis should be placed on refining the accuracy and consistency of accounting data. This approach serves the dual purpose of catering to external stakeholders' informational requirements while

solidifying the foundation for informed internal decisions. This can be achieved by adopting international accounting standards and leveraging advanced financial reporting tools. Lastly, in light of the importance attached to digital transformation and accounting data consistency, policymakers should design and implement incentives such as tax breaks, grants, and subsidies for businesses that invest in digital technologies and innovation. Additionally, creating innovation hubs and providing support for research and development can further spur digital adoption. Parallelly, policymakers should enforce and promote regulations that ensure high standards of financial reporting and transparency. This includes adopting international financial reporting standards and providing guidelines for consistent financial disclosures. In conclusion, for policymakers, the findings highlight the need to create a supportive regulatory and infrastructural environment that encourages digital adoption and fosters innovation across different industries. By implementing these practical recommendations, both managers and policymakers can drive sustainable economic growth and maintain competitive advantage in the digital era.

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Article

Solvency analysis of vanke real estate

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Abstract: The real estate industry has an important impact on the national economy and financial system. The implementation of various new policies, market competition, and economic development have drawn much attention to the solvency of the real estate industry, which is of great significance to the development trend and risk prevention of the entire real estate industry. Therefore, this paper analyzes the solvency of Vanke Real Estate and puts forward corresponding countermeasures, hoping to improve the solvency of Vanke Real Estate and provide certain reference value for the future development of the real estate industry. This paper first analyzes the solvency of Vanke real estate through short-term solvency and long-term solvency, and then analyzes the ranking of Vanke real estate's solvency in the real estate industry through factor analysis. In the process of analysis, typical problems existing in Vanke Real Estate are also found. After in-depth analysis of the reasons, it is found that Vanke Real Estate has inventory overhang, unreasonable capital structure, and insufficient industry competitiveness in terms of solvency and puts forward countermeasures such as strengthening inventory management, optimizing capital structure, and adjusting sales strategy.

Keywords: solvency; liability structure; ratio analysis; vanke real estate

1. Introduction

China's real estate market is one of the largest real estate markets in the world and has an important impact on both the national economy and the financial system. In recent years, although China's real estate market has experienced a rapid growth phase, it has also faced many challenges, such as over-investment, fluctuating house prices, market regulation, and other problems [1]. As one of the leading companies in China's real estate market, Vanke Real Estate occupies an important position in the industry [2]. Founded in 1984, the company has become one of the largest real estate developers in China after years of development, with its business covering real estate development, property management, architectural design, and other fields. Its performance in the real estate market not only directly affects the company's own development but also has a profound impact on the development of the entire industry [3].

With the continuous development and changes in China's real estate market, the importance of corporate solvency is becoming more and more prominent. Solvency analysis helps to assess the ability of enterprises to withstand uncertainties and risks, provides a basis for decision-making for enterprise managers, and also provides an important reference for investors to assess investment risks. From the perspective of the whole industry, the study of Vanke Real Estate's solvency also has far-reaching social significance. It not only reveals the internal operational efficiency and risk

control status of real estate enterprises but also helps to promote the real estate industry to develop in a more standardized and transparent direction [4]. By continuously improving the solvency of enterprises, real estate developers can enhance the confidence of the capital market, attract more investment, and promote the benign cycle of the real estate financial market. Therefore, an in-depth study of the solvency of Vanke Real Estate not only helps to understand the financial situation of the enterprise but also has important significance for the development trend and risk prevention of the whole real estate industry.

Solvency is one of the crucial financial indicators in the business activities of enterprises. With the intensification of market competition and the constant changes in the economic environment, enterprises are facing various risks and challenges, and maintaining good solvency is crucial to the survival and development of enterprises [5]. The liabilities of enterprises mainly come from the financing of creditors, including bank loans and bond issuance. The improvement of solvency can protect the interests of creditors and enhance their confidence in the enterprise. The good or bad debt servicing ability directly affects the financing ability of the enterprise, and having a good debt servicing ability can improve the negotiation position of the enterprise in the financing market and increase the choice of financing channels. The solvency of an enterprise is directly related to its image and credibility, and the credibility of an enterprise is built on the basis of a long-term stable repayment record and good credit, which affects the business cooperation and customer relationship. Only with good solvency can an enterprise's reputation and trust be enhanced.

Compared with previous studies, the research method of this paper introduces the factor analysis method in addition to the conventional short-term and long-term solvency analysis, aiming at a more comprehensive assessment of Vanke Real Estate's competitive position in the real estate industry. Through factor analysis, we were able to extract a number of key factors affecting Vanke's solvency and compare them with other major competitors in the industry to clarify Vanke's relative ranking.

In addition, we will also examine Vanke's industry performance in terms of liquidity, profitability, and asset management. This comprehensive analysis method can not only reveal Vanke's strengths and weaknesses in terms of solvency but also provide data support for its future strategic decisions. With an in-depth understanding of Vanke's relative position in the industry, we are better able to develop targeted improvement measures to help improve its overall financial health. Ultimately, this research will provide readers with a multi-dimensional perspective to help them understand Vanke's challenges and opportunities in a dynamic market environment.

In the field of financial management, solvency has always been the focus of attention of corporate management and investors [6]. This indicator is not only related to the short-term liquidity of enterprises but also an important yardstick to assess their long-term stability and sustainable development potential. Solvency has become a topic of discussion for many researchers, scholars, and policymakers, both in the domestic and international arenas. In China, researchers mainly analyze

in-depth financial statements of listed companies to grasp the financial status of real estate companies as well as key data such as asset status and liability status to measure their solvency. This approach relies on the statistical analysis of historical data and the accuracy of the firm's future cash flow projections. Although it is a more traditional research method, it still has an irreplaceable role in revealing the solvency of enterprises. In sharp contrast, foreign countries emphasize more on the accumulation of experience and case studies when analyzing the solvency of real estate. For example, some well-known international financial institutions will regularly issue reports on the solvency of the real estate industry, which are usually based on a large number of case studies and the opinions of industry experts, in order to provide more in-depth and practical advice for enterprises to learn from. Researchers have adopted rigorous theoretical frameworks and empirical research methods to carry out multi-faceted and in-depth studies centering on different changes in the market environment and the characteristics of the relevant industries [7]. They use a combination of quantitative and qualitative analysis to explore the various factors affecting the solvency of enterprises in an all-round way, from the macroeconomic environment to the microbusiness strategies. Through data analysis and theoretical application, researchers are able to analyze the reasons for the weakening of solvency from multiple dimensions and put forward practical countermeasures and suggestions for the problems found. These suggestions not only help enterprises optimize their internal management and improve their risk control ability, but also provide theoretical support for relevant government departments to formulate policies and jointly promote the healthy development of the whole society and economy.

The research question of this paper is how to choose a good method to evaluate the solvency of Vanke real estate. The analysis of Vanke Real Estate's solvency reveals the common problems of the real estate industry in solvency. Based on these findings, this paper puts forward a series of practical suggestions to help Vanke Real Estate improve its solvency. Through the multi-dimensional analysis method, the research of this paper deeply discusses the solvency of Vanke Real Estate and provides valuable insights and suggestions for the enterprise management and relevant investors, aiming at promoting Vanke Real Estate to maintain its sound financial position in the highly competitive real estate market. The common evaluation method is generally the combination of short-term solvency and long-term solvency. In this paper, the potential research method to solve the problem is to introduce the solvency ranking analysis of Vanke Real estate in the real estate industry. This approach not only makes a horizontal comparison of the solvency of Vanke's properties but also places it in the context of the entire industry, making the analysis more comprehensive and in-depth. In this way, we can identify the strengths and weaknesses of Vanke Real Estate in terms of its solvency to provide a more targeted analysis.

In this paper, the literature review and factor analysis methods were used in order to explore this topic in depth. In the process of writing this paper, I first screened the literature closely related to the topic of this research in the school library, which covered both Chinese and English literature over the past few years,

providing a broad knowledge background and a rich source of data for this paper. Subsequently, the data related to the solvency of Vanke Real Estate and other representative enterprises in the same industry were exhaustively collected and organized using the Cathay Pacific database. Through meticulous analysis and organization, a series of reliable data were obtained, which not only reflected the financial status of Vanke Real Estate but also revealed the financial performance of other companies in the industry, and then SPSS16.0 was used to carry out the factor analysis method to show more intuitively the solvency of Vanke Real Estate in the same industry, which laid a solid foundation for the research of this paper.

We expect this study to provide valuable lessons for other real estate companies. When facing similar solvency dilemmas, Vanke's research results can be used as a reference to help them optimize their financial management strategies and improve the efficiency of capital operations so as to occupy a favorable position in the fierce market competition. Through an in-depth analysis of Vanke Real Estate's debt-servicing strategy and its effectiveness, this paper hopes to reveal the risks that real estate companies may overlook in their pursuit of rapid growth and to provide practical guidance and suggestions for other companies in the same industry.

2. Methodology and concepts

2.1. Literature review

This paper provides a comprehensive literature review on the field of debt repayment, aiming to summarize and analyze the current status of Vanke Real Estate's debt repayment ability. Debt repayment has always been the top priority of the enterprise and has had extensive influence in various fields [8]. This review includes several key aspects, such as mode innovation, national policies, and future prospects [9].

In the review of the previous research on solvency by scholars, we can find that solvency has always been one of the most concerned company characteristics by academics and business people, which is also an aspect of the formulation of financial strategy [10]. How to scientifically evaluate solvency is very important. Solvency itself is a part of financial management, but as the evaluation of solvency becomes more and more important in enterprise management, scholars begin to try to carry out theoretical and empirical analysis from different theoretical bases [11]. In general, the research of foreign scholars on solvency mainly focuses on the empirical research of companies and then combines theoretical analysis with different theoretical bases. There are few empirical studies on solvency analysis by Chinese scholars, most of which focus on the impact and current limitations of solvency analysis on corporate value, and the conclusions are not consistent [12].

In the past century, the solvency analysis theory has been continuously developed and improved and has made great contributions to the financial management of enterprises. In particular, American economists and management experts have played a very important role in the theoretical and practical research of corporate solvency analysis. When companies began to pay attention to solvency, they began to pay attention to financial reports, and Costa was the leader [13].

Heidary discussed and compared 42 British companies reporting to the SEC (U.S. Securities and Exchange Commission) with 42 large American companies [14]. The content of the report of the British company is more detailed and richer, focusing on the analysis of risks and uncertainties and including more predictive information. The practice of the British company is more in line with the requirements of the SEC. The report analyzes solvency, risk uncertainty, and other financial information and contains more forward-looking information, which has more reference value and guiding significance. At this time, the necessity of solvency analysis and other financial information analysis is indirectly proposed [15].

At present, solvency analysis has been closely linked with enterprise evaluation. In China, there are many works introducing solvency and other financial information, but there are still a hundred schools of thought. Huang proposed the cash flow analysis earlier [16], and Guo proposed the trend analysis and forecast analysis on the basis of conventional analysis [17]. At present, more scholars "diagnose" enterprises by combining the analysis of debt capacity and other financial information with performance evaluation, such as Jiang [18] and Peng [19]. Most of these works involve three parts of traditional financial analysis: solvency analysis, operating capacity analysis, and profitability analysis. First of all, this paper determines the important position of Vanke Real Estate in the real estate industry and analyzes the solvency of Vanke Real Estate, which has strong practical significance and industry representation. After that, not only the short-term solvency analysis and long-term solvency analysis, but also the use of big data and intelligent technology to carry out comparative analysis between the same industry.

This paper analyzes the impact of national policies on the solvency of Vanke real estate. For example, China has issued three red-line policies in 2020, aiming to control the debt level of real estate enterprises and reduce systemic financial risks. Although the "three red lines" policy has to some extent controlled the debt level of real estate enterprises and reduced financial risks, it has also brought some challenges. For example, some enterprises are under financial pressure and need to ease their financial situation by means of price reduction and promotion, which may have a certain impact on market prices [20].

Finally, this paper discusses the prospect of the research on the solvency of enterprises in the future. The solvency will continue to play an important role, and a better analysis method should continue to be developed.

2.2. Concept

2.2.1. Liquidity ratio analysis

Solvency is the ability of a company to repay its long-term and short-term debts with its assets. Whether a company can develop healthily and sustainably depends on whether it has enough capital and whether it can pay off its debts in time [21]. Enterprise solvency is the main index reflecting the financial status and operating ability of the enterprise, which can help the decision makers of the enterprise to find the enterprise positioning and also can let the stakeholders better understand the enterprise. In modern enterprises, solvency is a very important index that can be used to measure a company's operation status, financial status, and strategy. The solvency

of a company is greatly affected in all aspects of its operation, investment, and financing.

2.2.2. Short-term solvency concepts

Short-term solvency analysis is also called liquidity analysis. Analyzing the short-term solvency of an enterprise can often provide investors and creditors with information related to the solvency of the enterprise, usually through the analysis of the current ratio, quick ratio, and cash ratio to determine the short-term solvency of an enterprise [22].

Current ratio = current assets/current liabilities. The higher the current ratio is, the better the liquidity of assets and the better the short-term solvency of the enterprise; on the contrary, the worse it is [23]. However, if the current ratio is too high, it may cause asset depreciation and make enterprises unable to invest, so enterprises should try to maintain the current ratio at a reasonable level [24].

Quick ratio = quick assets/current liabilities. Quick assets are the current assets after removing the poor liquidity and unstable inventory, so compared with the current ratio, it can more accurately reflect the short-term solvency of the enterprise [25]. When the quick ratio is less than 1, it indicates that the short-term solvency of the enterprise is poor; when the quick ratio is greater than 1, it represents that the enterprise has too many quick assets, which is not conducive to the enterprise to obtain the income, but the standard of the quick ratio is also according to the different enterprises, and there is a slight change [26].

Cash ratio = (cash + valuable securities)/current liabilities. However, in general, companies do not need to have sufficient monetary funds to ensure that they can repay their liabilities so that they can use cash more wisely to increase profits [27].

2.2.3. The concept of long-term solvency

Long-term solvency analysis refers to the analysis of the enterprise's ability to pay long-term debt principal and interest on time. Long-term solvency can effectively determine whether the enterprise is in financial difficulties and is the basis for evaluating the operating results of the enterprise as well as predicting the direction of the enterprise's future financing [28].

Assets-liability ratio = total liabilities/total assets. This index refers to the proportion of total liabilities in the total assets of the enterprise. This index reflects the proportion of the assets provided by the company's creditors in the company's total assets but also reflects the degree of risk of the enterprise's loans and the enterprise's ability to raise debt to operate [29].

Equity ratio = total liabilities/owners' equity. In a general sense, the equity ratio reflects the number of shares held by the company's shareholders and also provides a sideways view of the company's borrowing and operating conditions [30]. In general, a higher index means less solvency.

3. Solvency analysis of Vanke real estate

Despite its remarkable achievements in the real estate sector, Vanke Real Estate is facing challenges in various aspects, such as market fluctuations, policy adjustments, and fierce competition in the industry [31]. The regulatory policies

implemented by the PRC (People's Republic of China) government on the real estate market are constantly changing, and the market demand is becoming increasingly diversified and individualized, all of which have brought certain uncertainties to Vanke's development. At the same time, the competition in the international market has become increasingly fierce, requiring Vanke to continuously improve its competitiveness and innovation ability [32].

The solvency of Vanke Real Estate is a key indicator to assess its financial soundness and risk-taking ability [33]. Based on the financial statements of Vanke Real Estate from 2019 to 2023, the solvency status of Vanke Real Estate can be understood by analyzing its current ratio, quick ratio, cash ratio, gearing ratio, and equity ratio. Meanwhile, by comparing and analyzing Vanke Real Estate with other enterprises in the same industry through factor analysis, it can more accurately assess its solvency, which helps to formulate effective financial strategies to enhance the company's solvency and soundness [34].

3.1. Short-term solvency analysis

3.1.1. Liquidity ratio analysis

The current ratio reflects whether a company can cover its short-term debts in the short term. By collecting the current assets and current liabilities data from the company's financial statements, we can calculate and analyze the current ratio of Vanke Real Estate in the last five years. As shown in **Table 1**, the current ratio of Vanke Real Estate in recent years is greater than 1 but less than 2, which indicates that the company's solvency also has some problems. Of course, in the process of analysis, it is also necessary to consider the characteristics of the industry because the ideal value of the current ratio may be different for different industries. For example, in this paper, the real estate industry has a long construction period, and it can be seen from **Table 1** that Vanke Real Estate's current liabilities are larger, so the current ratio standard can be appropriately reduced. However, because the size of current assets is also larger, the current ratio of Vanke Real Estate in the past five years is greater than 1 but has not reached 2, indicating that Vanke Real Estate's current ratio still has a certain amount of room to rise. The current ratio of Vanke Real Estate shows an overall trend of growth, indicating that Vanke Real Estate is developing in a good direction as a whole.

Table 1. Vanke real estate current ratio in 2019–2023.

Particular year	2019	2020	2021	2022	2023
Current asset	14,389.89	15,473.87	16,002.68	14,153.56	11,502.60
Current liability	12,726.10	13,174.92	13,114.46	10,778.01	8,217.85
Current ratio (%)	113.07	117.45	122.02	131.32	139.97

Data source: 2019–2023 Vanke Real Estate Annual Report.

3.1.2. Quick ratio analysis

The quick ratio is a more restrictive form of the current ratio that excludes the effect of inventories on liquidity and focuses more on liquid assets. Quick assets usually include cash, short-term investments, and accounts receivable, but not

inventories. This is because inventories are not always quickly realized in the short term, so the quick ratio more accurately reflects the ability of a company to cope with sudden capital needs [35]. It is also important to analyze the quick ratio of Vanke Real Estate in detail. By analyzing the quick ratio, we can more comprehensively evaluate the company's ability to cope with unpredictable risks in the short term.

We can see from **Table 2** that Vanke Real Estate's quick ratio is less than 1 from 2019 to 2023, indicating that quick assets are less than current liabilities. The quick ratio of Vanke Real Estate has been slowly decreasing from 2019 to 2020, which is largely because China's real estate is close to saturation and most people's willingness to buy houses has been gradually weakened, especially in 2021. The quick ratio plummeted from 41.39% in 2020 to 17.98%, which is due to the impact of the New Crown Epidemic in 2020, and the people's purchasing power generally declined. It is not until 2022 that it rises again to 47.16%, in which changes in national policies and government support are key factors that help Vanke Real Estate's quick ratio rise.

Table 2. Vanke real estate quick ratio in 2019–2023.

Particular year	2019	2020	2021	2022	2023
Quick assets	5447.69	5453.24	2358.29	5083.00	4485.65
Current liability	12,726.10	13,174.92	13,114.46	10,778.01	8,217.85
Quick ratio (%)	42.81	41.39	17.98	47.16	54.58

Data source: 2019–2023 Vanke Real Estate Annual Report.

3.1.3. Cash ratio analysis

Usually, we think that the cash ratio can more accurately reflect the ability of the enterprise to directly repay current liabilities; this ratio is more appropriate between 20% and 30%. In this case, the enterprise only needs to use part of the inventory, accounts receivable, and other assets, plus part of the cash can repay current liabilities; this time, there will not appear too many idle funds and will not appear the situation of a cash shortage [36].

From **Table 3**, we can see that from 2019 to 2023, the cash ratio of Vanke Real Estate is lower than 20%, and there is even a decrease in the cash ratio in 2021 and 2023, which indicates that Vanke Real Estate does not have a strong ability to repay its current liabilities directly, and there is a great possibility that Vanke Real Estate will not be able to repay its short-term borrowings in time. The low cash ratio represents less cash that can be liquid, but at the same time, the amount of current liabilities of Vanke Real Estate is still large, which also shows that Vanke Real Estate does not utilize the current liabilities well. In this situation, if no effective measures are taken to optimize the capital structure or improve the financial position, it may lead the company into more complicated financial difficulties. Therefore, the management of Vanke Real Estate must improve the efficiency of capital utilization, rationally plan the debt repayment schedule, as well as enhance the solvency of the enterprise.

Table 3. Vanke real estate cash ratios in 2019–2023.

Particular year	2019	2020	2021	2022	2023
Cash	1661.94	1952.30	1493.52	1372.07	998.13
Current liability	12,726.10	13,174.92	13,114.46	10,778.01	8217.85
Cash ratio (%)	13.06	14.82	11.39	12.73	12.14

Data source: 2019–2023 Vanke Real Estate Annual Report.

3.2. Long-term solvency analysis

Long-term solvency is one of the most important indicators to assess the financial stability and sustainability of a company. In this paper, we will conduct an in-depth analysis of Vanke Real Estate's long-term solvency, including gearing ratio, equity ratio, and other aspects. Through these analyses, we will be able to gain a comprehensive understanding of the company's performance in long-term debt management, providing valuable references and suggestions for investors and managers. H2: The digital economy drives the transformation and upgrading of the manufacturing industry by improving the resource allocation ability of manufacturing enterprises.

3.2.1. Asset-liability ratio analysis

From **Table 4**, it can be seen that the gearing ratio of Vanke Real Estate reached 84.35% in 2019, and in 2020, it is still higher than 80%, although it decreases. In recent years, China's land resources have been relatively scarce; however, Vanke Real Estate continues to carry out land development projects and increased a large number of long-term loans to maintain the operation of the enterprise, which also led to the company's debt level continuing to increase. 2020, under the influence of the policy of the "Three Red Lines", the company's gearing ratio gradually declined, and the long-term debt servicing ability was guaranteed, but overall, the gearing ratio reached 84.35% in 2019, although it decreased but was still higher than 80%. In 2020, under the influence of the "Three Red Lines" policy, the company's gearing ratio will gradually decrease, and its long-term solvency will be guaranteed, but overall, the gearing ratio is still at a high level.

Table 4. Vanke real estate gearing metrics, 2019–2023 (100Million).

Particular year	2019	2020	2021	2022	2023
Total assets	17,299.29	18,691.77	19,386.38	17,571.24	15,048.50
Total liability	14,593.50	15,193.32	15,458.65	13,521.32	11,019.16
Gearing	84.35	81.28	79.74	76.95	73.22

Data source: 2019–2023 Vanke Real Estate Annual Report.

3.2.2. Analysis of equity ratios

The equity ratio is used to reflect the stability of the basic financing structure of the enterprise and can also be used to measure the degree of protection of creditors' rights and interests in the event of bankruptcy. According to traditional theory, an equity ratio of 100% is appropriate, which means that the capital of the shareholders of the enterprise is sufficient to repay the capital provided by the debtors, and the solvency of the enterprise is also high.

As can be seen from **Table 5**, the equity ratio of Vanke Real Estate is at a high level, which is not lower than 270% from 2019 to 2023 and even reaches 539% in 2019. In 2020–2023 it starts to decrease year by year, but it is still some distance away from 100%. This shows that Vanke Real Estate's main source of funding is debt rather than through shareholders' contributions, so although it can reduce financial costs, it increases long-term liabilities, which leads to the elevation of its debt level, reduces the long-term solvency of Vanke Real Estate, and increases the possibility of Vanke Real Estate's default on debt repayment, which adds a certain degree of difficulty to the repayment of debt in the future, and at the same time, there is a certain probability that it will reduce the credibility of the enterprise.

Table 5. Vanke real estate equity ratio metrics in 2019–2023 (100 Million).

Particular year	2019	2020	2021	2022	2023
Shareholders' equity	2705.79	3498.44	3927.72	4056.36	4029.33
Total liability	14,593.50	15,193.32	15,458.65	13,521.32	11,019.16
Equity ratio	539.34	434.29	393.58	333.34	273.47

Data source: 2019-2023 Vanke Real Estate Annual Report.

3.3. Comparative analysis with other enterprises in the same industry

The real estate industry, as a key economic field, has experienced changes from the big rise to the fall of the house price in recent years. Through the comparative analysis with other enterprises in the same industry, we can understand the positioning and competitive advantages of Vanke Real Estate in the industry and find out the existing problems and the space for improvement to guide the future development strategy and decision-making.

The principle of factor analysis is to convert raw indicators with strong correlations into factors that are independent of each other. What needs to be tested before conducting factor analysis is whether there is a strong correlation between the original indicators. In this paper, SPSS16.0 is used to convert 6 economic indicators: x1-current ratio; x2-current ratio; x3-cash ratio; x4-gear balance ratio; x5-working capital; and x6-equity multiplier. Bartlett's test was obtained after processing, and the F-value was equal to 672.765, the F-value was significant, and the significance was less than 0.005, which indicated that the data taken satisfied the normal overall distribution: the KMO value was equal to 0.666 in **Table 6**, which was greater than 0.5 indicating that the correlation between the variables can be explained by the other variables, and therefore it is suitable to do the factor analysis.

Table 6. KMO and bartlett's test table.

KMO Quantity of Sample Suitability		0.666
Bartlett's test of sphericity	Approximate chi-square (math.)	672.765
	(number of) Degrees of freedom (physics)	15
	Significance	0.000

Using statistical software SPSS16.0 to conduct factor analysis of the six financial indicators, the root of the characteristics and the degree of variance explained to the eigenvalue is greater than 1 as the standard selection of the main factor, so the selection of the two main factors, the use of the two main factors instead of the original six factors of the cumulative contribution rate of 67.073% in **Table 7**. At the same time, it can also be seen from the gravel in **Figure 1**. The eigenvalue of factor 1 is around 2.7, the eigenvalue of factor 2 is around 1.4, and the eigenvalues of the rest of the factors are less than or equal to 1, especially factor 6, whose eigenvalue is only around 0.1, from which it can be concluded that factor 1 and factor 2, that is, the solvency and the operating ability, can be analyzed as the extracted factors.

Table 7. Total variance explained.

	Initial eigenvalue			**Extract the sum of the squares of the loads**		
Ingredient	**Total**	**Percentage of variance**	**Cumulative %**	**Total**	**Percentage of variance**	**Cumulative %**
1	2.692	44.872	44.872	2.692	44.872	44.872
2	1.332	22.200	67.073	1.332	22.200	67.073
3	0.998	16.629	83.701			
4	0.528	8.796	92.498			
5	0.361	6.018	98.515			
6	0.089	1.485	100.000			

Extraction method: principal component analysis.

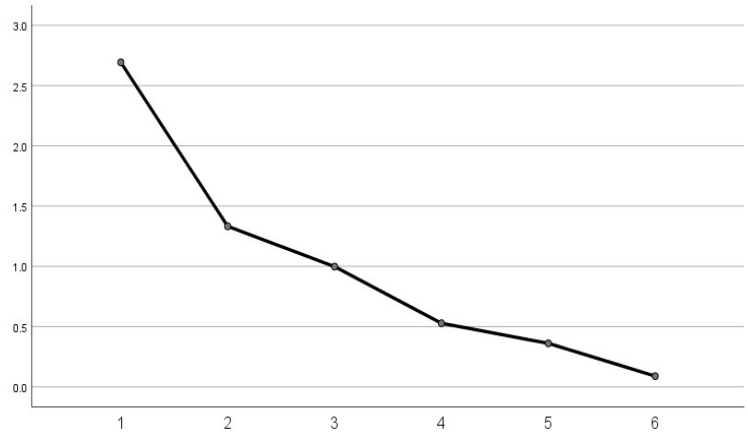

Figure 1. Gravel diagram.

From the comprehensive ranking, Vanke Real Estate is ranked 23rd among 42 enterprises in **Table 8**, which is in the middle position. Vanke Real Estate's operating ability is ahead, but its debt serviceability is behind, which indicates that the enterprise faces a large debt service risk and especially needs to strengthen its financial risk control. From the individual ranking, although Vanke Real Estate's operating ability is outstanding, its debt servicing ability is poor, which indicates that Vanke Real Estate is still in the growth stage and may have a faster development trend in the future, and it should have a balanced development of all aspects of its financial ability, which is beneficial to the long-term development of the enterprise.

Strong operating ability shows that the enterprise can meet the short-term demand, but it does not represent the long-term development of the enterprise. The solvency of Vanke Real Estate is weak, even if the operating capacity is strong, but still may not be able to achieve long-term stable development because the selection of this table is the listed companies in the ability of the real estate company, so after comprehensive consideration, Vanke Real Estate is currently in the real estate industry as a whole in the front-end, but solvency compared with other enterprises in the industry there are still some shortcomings, which need to be further improved and strengthened by the company. This requires the company to further improve and strengthen.

Table 8. Comprehensive ranking of enterprises.

Stock code	Company abbreviation	Solvency	Operating ability	*F*
000002	Vanke A	23	2	23
000004	Shenzhen Zhenye A	31	32	31
000005	brand new	1	40	1
000006	beautiful ecology	13	16	13
000007	Shenzhen Property A	35	21	35
000010	Shahe Shares	20	12	20
000011	FCFA	17	13	17
000012	Grand Hyatt City (hotel chain)	10	41	10
000014	Shenzanda A	14	28	14
000016	Hualian Holdings	28	11	28
000017	China Continent Holdings Limited	42	17	42
000018	China Aviation Shanda (abbr.)	33	3	33
000019	Northern International	11	22	11
000020	OCTA	5	31	5
000021	Tianjian Group	7	29	7
000023	Financial Street	29	5	29
000025	Shandong Road and Bridge	32	20	32
000026	Yudai (or central Chongqing) district of Chongqing municipality, formerly in Sichuan	30	15	30
000027	Rongan Real Estate	16	26	16
000028	Guangyu Development	2	33	2
000029	Zhongtian Financial	34	14	34
000030	Rheinland Sports	9	35	9
000031	I love my house.	25	4	25
000032	Guangdong Hongyuan A	27	7	27
000034	Sunshine Shares	26	8	26
000035	Aoyuan Meigu	21	27	21
000036	HNA Investment	36	42	36
000037	Xinhua News Agency	19	36	19

Table 8. (*Continued*).

Stock code	Company abbreviation	Solvency	Operating ability	*F*
000038	High-tech development	41	19	41
000040	Shunfa Hengye (1946), PRC politician and diplomat	4	30	4
000042	Jinke Co.	22	9	22
000043	Wonderful Homes	18	25	18
000045	Rongfeng Holdings	40	23	40
000046	Sunshine City	39	1	39
000048	Cameron Technology Corporation (Taiwan)	37	6	37
000049	Suning Global (PRC media company)	8	18	8
000050	Xinneng Taishan (city in Shandong)	24	24	24
000055	Thai Harvest Group	3	34	3
000056	China Communications Land (CCL), China's largest real estate developer	38	10	38
000058	China Wuyi	6	37	6
000059	Finance and Trust Development	15	39	15
000060	Impressions of San Xiang Xiang	12	38	12

4. Analysis of problems in Vanke real estate's solvency

With the continuous development of China's real estate market, the solvency of real estate enterprises has become a crucial aspect of financial management. In this context, it is crucial to conduct a comprehensive and in-depth analysis of the solvency of Vanke Real Estate, an industry leader, to reveal the existing problems. In this paper, the problems of Vanke Real Estate's solvency are explained in detail, mainly including the backlog of inventory, unreasonable capital structure, and the lack of competitiveness of Vanke Real Estate's industry.

4.1. Inventory backlog

In the past five years, Vanke real estate has been greater than 1 in the current ratio, but the quick ratio is less than 50% and has a large portion of the inventory backlog; even in 2021, it reached 17.98%. On the one hand, due to the saturation of China's real estate volume in recent years, the state's control over the real estate industry is more stringent, so it is much more difficult to obtain land, and the available profit is also reduced, which also directly leads to the longer time to pay off the debt of Vanke Real Estate. The pressure becomes bigger. On the other hand, Vanke Real Estate showed a high degree of caution in the face of the uncertainty of today's market by making provision for inventory impairment to ensure that the value of inventory on its balance sheet could truly reflect the current market conditions and the actual operating results of the company.

4.2. Inadequate capital structure

The irrationality of capital structure is also a significant problem facing the solvency of Vanke Real Estate. The capital structure of an enterprise is directly related to its long-term solvency and financial stability. If the capital structure is unreasonable, over-reliance on debt financing, or other imbalances exist, it may increase the financial risk of the enterprise and reduce its solvency. The solution to this problem requires an in-depth analysis of the company's capital structure, including the composition of the balance sheet, the ratio of debt and equity, the maturity of debt, and interest rates. By adjusting the capital structure and optimizing the company's financial position, it can improve its long-term solvency and reduce financial risks.

4.3. Lack of competitiveness in the industry

Compared with other enterprises in the same industry, the solvency of Vanke Real Estate is in the middle position, and there is a deficiency compared with enterprises in the same position, such as Joy City and Guangyu Development, which is mainly due to the lack of competitiveness of Vanke Real Estate in the industry. The real estate industry itself does not have strong liquidity; it is also sensitive to political development characteristics, making Vanke real estate easy to face greater liquidity risk. The real estate industry in which Vanke Real Estate is located has always been highly competitive, with greater pressure to compete for market share. In the case of fierce competition in the industry, the market position of the enterprise may also change, and the enterprise faces the pressure of losing market share well more intense competition, which tends to weaken the solvency of the enterprise. Competition in the real estate industry often involves product quality, price, marketing, and other aspects. If the enterprise cannot occupy a favorable position in this fierce competition, it may face the risk of a decline in sales and profits, which will lead to a decline in solvency.

Taken together, Vanke Real Estate's problems in solvency mainly include the lack of a reasonable short-term debt repayment plan, unreasonable capital structure, and insufficient competitiveness in the industry. In response to these problems, the enterprise needs to formulate a scientific financial plan, optimize its capital structure, and enhance its competitiveness to ensure that it maintains a sound financial position and sustained development in the ever-changing market environment. These efforts not only help to improve the solvency of enterprises but also help to cope with the various challenges of the external environment and maintain the sustainable development of enterprises.

4.4. Discussion

In recent years, the state has strictly regulated the real estate market, and the financing of the company has been well controlled. However, in China, real estate companies still mainly rely on debt financing for their operations [37]. As the leader of the real estate industry, Vanke Group's solvency index plays a good role as a model in the industry, which can reflect the common problems in the industry more precisely. In this paper, through the short-term solvency, long-term solvency, and

comparative analysis of Vanke Real Estate, we get that Vanke Real Estate has the problems of inventory backlog, unreasonable capital structure, and insufficient competitiveness in the industry, which requires Vanke Real Estate to improve its solvency by strengthening the inventory management, optimizing the capital structure, and adjusting the sales strategy. Under the current social situation, in-depth understanding of the solvency of enterprises can not only help enterprises reasonably plan the future development trend but also enable suppliers, consumers, and other stakeholders to have a clearer understanding of enterprises and help them make reasonable decisions. Although the solvency of Vanke Real Estate is in the middle level of the industry, the enterprise itself is located at the front end of the real estate industry, which means that Vanke Real Estate should be more demanding on itself to improve its solvency to the upstream level of the real estate industry. Due to the fact that it is difficult to study the solvency of real estate enterprises, coupled with the fact that the development of China's capital market is relatively late, the theoretical study of enterprise solvency is still not perfect [38]. Therefore, this paper only takes Vanke as a typical case, and it is expected to be able to optimize the solvency of China's listed companies to provide reference and reference [39]. It is also hoped that there will be studies to make up for this deficit in the future.

5. Countermeasures to improve the solvency of vanke real estate

With the fluctuation of the real estate market and the change in the economic environment, improving the solvency of the enterprise has become an important task that Vanke Real Estate must face. To effectively resolve the challenges faced, this paper will deeply discuss countermeasures such as formulating a reasonable short-term debt repayment plan, optimizing capital structure, and adjusting sales strategy to provide comprehensive and in-depth guidance for improving the solvency of Vanke Real Estate.

5.1. Enhance inventory management and rationalize planning

To improve the economic efficiency of enterprises, it is necessary to strengthen the work of inventory management. The real estate market itself is a large inventory market; the high price of real estate has led to a reduction in the amount of people buying; at the same time, the hands of the enterprise inventory will be more, so in the real estate enterprise, inventory management is particularly important. Inventory liquidity is weak but also reflects the difficulty of realizing, and the degree of realizing exactly in a certain aspect represents the enterprise's solvency [40]. The use of scientific data analysis and supply chain optimization strategies enables inventory to be classified, inventoried, and its demand forecast. Therefore, on this basis, a reasonable procurement plan and storage program are designed to ensure the effective use of inventory and prevent excess or shortage. This will not only reduce costs but also increase customer satisfaction and market share.

5.2. Optimize capital structure and reduce financial risk

The rationality of the capital structure is directly related to the long-term solvency and financial stability of the company. To optimize the capital structure, it

is necessary to analyze the company's financial situation in depth, including the proportion of debt, the term of debt, and interest rates. With the help of the financial professional team, an accurate risk assessment is carried out to find out the existing problems and potential risk points [41]. Secondly, diversified financing channels can be considered to reduce the reliance on a single source of financing, including bank loans, bond issuance, equity financing, and other methods. By reasonably matching these financing methods, the financing cost can be reduced and the financial pressure can be alleviated. In addition, enterprises can also optimize internal capital operations, improve asset turnover, reduce the time of capital occupation, and increase the efficiency of the use of the enterprise's funds. This helps to improve the profitability of the enterprise, thus improving the capital structure and reducing financial risks.

5.3. Adjusting sales strategies to improve core competitiveness

Adjustment of sales strategy is crucial to improving the core competitiveness of enterprises. Firstly, competitiveness can be improved through product differentiation by gaining a deeper understanding of the needs of target customers, launching products in line with market trends and consumer tastes, and increasing the added value of products [42]. This helps to increase sales price and profitability. Secondly, it is recommended to strengthen marketing efforts to increase brand awareness, attract more customers, and expand sales through more effective marketing, advertising, and promotional activities. This can be done by cooperating with internet platforms and adopting new media, such as social media, for advertising to increase brand exposure. Thirdly, enterprises should establish good cooperative relationships with the upstream and downstream of the supply chain to optimize resource allocation and reduce production costs. By improving production efficiency and optimizing supply chain management, the enterprise can achieve cost control while maintaining product quality, thus improving its core competitiveness and enhancing the solvency of Vanke Real Estate.

6. Conclusion

In recent years, the state has strictly regulated the real estate market, and the financing of the company has been well controlled. However, in China, real estate companies still mainly rely on debt financing for their operations. As the leader of the real estate industry, Vanke Group's solvency index plays a good role as a model in the industry, which can reflect the common problems in the industry more precisely. Through short-term solvency, long-term solvency, and comparative analysis, it is clear that Vanke Real Estate faces issues such as inventory backlog, irrational capital structure, and insufficient industry competitiveness. To improve its solvency, Vanke must strengthen inventory management, optimize its capital structure, and adjust its sales strategy. Although the company ranks at the middle level in terms of solvency, its prominent position in the real estate industry demands a higher standard. Due to the relatively late development of China's capital market and the complexity of studying the solvency of real estate enterprises, this paper only

uses Vanke as a typical case. It is expected to provide useful references to optimize the solvency of China's listed companies.

This paper enriches the study of solvency in real estate enterprises, particularly in the context of Vanke Real Estate. By applying factor analysis and comparing it with other enterprises in the same industry, the paper provides a detailed examination of Vanke's short-term and long-term solvency. Furthermore, it bridges gaps in the literature by identifying solvency risks unique to China's real estate market while highlighting Vanke's response to market regulation and financial management. The study offers new insights into the dynamics of solvency in a highly competitive and regulated market, expanding the theoretical discourse on real estate finance.

The findings of this study are not only significant for Vanke Real Estate but also have broader implications for other real estate enterprises. Strengthening inventory management, optimizing capital structure, and adjusting sales strategies are actionable insights that can improve the solvency and financial health of firms. For managers and financial decision-makers, the study provides a roadmap for mitigating solvency risks, especially in markets with high regulation and competition. Additionally, this research can assist government regulators in understanding how real estate firms manage debt and the impact of policy changes on their solvency.

Future research could extend the analysis by considering the impact of external factors such as macroeconomic shifts, interest rate changes, and government regulations on the solvency of real estate firms. Comparative studies between different regions or countries with varying levels of market maturity and regulation would also be beneficial. Furthermore, integrating qualitative analysis such as management strategies and leadership decisions could provide a more holistic understanding of how firms navigate solvency challenges. Another area for exploration is the role of digital transformation in optimizing financial management and enhancing the solvency of real estate enterprises.

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Article

Detecting financial statements fraud: Evidence from listed companies in China

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Abstract: Financial statement fraud is the deliberate misrepresentation of a company's financial statements. Financial statement fraud has been a global concern since it not only harms the investors and creditors but also undermine the public confidence of the capital market. Based on the fact that a common incentive for companies to manipulate financial statement is a decline in the company's financial prospects, this paper applies the mixture hazard early warning model to identify the key impacting financial characteristics in detecting the financial statement fraud for listed companies in China. We find that in the construction industry the warning sign of suspcious business practices is a falling return on assets, while in the real estate industry the financial red flag is an increase in the inventory level. The estimation results indicate that the financial characteristics may have different implications in different industries in detecting financial statement fraud. This research has shed light on setting specific financial characteristics for fraud monitoring and detecting by the regulators.

Keywords: financial statement fraud; listed companies in china; mixture hazard model

1. Introduction

Financial fraud has been a global concern for the public, the press, and regulators because of its rapidly increasing adverse impacts not only on individual investors but the overall economic stability. The Federal Trade Commission reported that the U.S. consumers lost more than US$5.8 billion to fraud in 2021, an increase of more than 70% over 2020[1]. Among various types of financial frauds and scams, including Ponzi-schemes, credit card fraud, ecommerce fraud, imposter scam, and phishing, financial statement fraud in particular has received considerable attention from many organizations across industries and countries. Financial statement fraud directly harms the investors and creditors of the issuer of a fraudulent financial report, bringing related parties lost all or part of the investments if such fraud results in a bankruptcy or near failure. The Association of Certified Fraud Examiners (ACFE) reported that financial statement fraud had been the most costly form of occupational fraud, causing a median loss of around US$1 million [1]. Financial statement fraud may also impact heavily on the public trust in the integrity of the financial reporting mechanism, threaten to undermine the confidence of the capital market, and even lead up to massive devastation to the whole financial system. For example, the notorious Enron debacle[2] and Tyco International scandal[3], among others, significantly dampened the confidence of the investors and resulted in large-scale reputational damage in financial markets. In severe cases, such as the mortgage fraud of Fannie Mae and Freddie Mac[4] and the collapse of the Lehman Brothers[5], securities fraud affected not only the U.S. stock market but triggered the global financial crisis in 2008.

The American Institute of Certified Public Accountants concisely defines the financial

statement fraud as the intentional misstatements or omissions in financial statements. Similarly, the ACFE defines fraud, in general, as any activity that relies on deception in order to achieve a gain, and financial statement fraud, in particular, as the deliberate misrepresentation of the financial condition of an enterprise accomplished through the intentional misstatement or omission of amounts or disclosures in the financial statements to deceive financial statement users. Despite minor variations in its definition, financial statement fraud in practice is a white-collar crime perpetrated by management insiders, usually involving overstating assets, revenues, and profits and understating liabilities, expenses, and losses. For instance, Enron's leadership cooked the books by using special purpose vehicles (SPVs) to hide its debts and liabilities from investors, creditors and regulators. When Enron declared bankruptcy in October 2001, its shareholders lost US$74 billion and its employees lost their jobs and billions of dollars in pension benefits, ranking it the largest bankruptcy reorganization at that time. Comparably, the Securities and Exchange Commission (SEC) charged six former top executives of Fannie Mae and Freddie Mac with securities fraud in December 2011, alleging they knew and approved misleading statements claiming the companies had minimal holdings of higher-risk mortgage loans, including subprime loans between December 2006 and August 2008. Actually, Fannie Mae's loan products included more than US$43 billion of Expanded Approval (EA) loans towards borrowers with weaker credit histories. Meanwhile, Freddie Mac's subprime exposure was about US$141 billion on 31 December 2006, accounting for 10% of its portfolio, and grew to approximately US$244 billion on 30 June 2008, or 14% of its portfolio[6]. In an extreme case, Lehman Brothers hided over US$50 billion of its bad assets by employing an accounting trick known as the "Repo 105"[7] to lower its leverage level and maintained the AAA status until it crashed on 15 September 2008.

Recently, the Theranos fraud represented a significant scandal in the world of technology startups, touching upon issues of technological innovation, business ethics, and regulation. Theranos, founded by Elizabeth Holmes in 2003, soared to a $10 billion valuation by promising revolutionary blood tests. However, these claims were exposed as fraudulent in 2015, triggering legal and financial turmoil. Holmes and former president Sunny Balwani faced SEC fraud charges in 2018, ultimately leading to Holmes's conviction and 11-year prison sentence in 2022. This is not an isolated case. FTX Trading Ltd., colloquially known as FTX, imploded spectacularly in 2022, brought down by the colossal fraud orchestrated by its founder, Sam Bankman-Fried. Established in 2019, FTX had risen to prominence as a leading cryptocurrency exchange and crypto hedge fund, boasting over a million users at its peak. Prior to its downfall, FTX stood as the third-largest cryptocurrency exchange globally, facilitating a staggering US$10 billion in active trading volume during 2021, underscoring its formidable position in the digital asset landscape.

The pervasiveness of financial statement fraud is not limited to the U.S., but a widespread problem all over the world. In Europe, the implosion of Germany's Wirecard[8] had turned out to be one of Europe's biggest financial scandals. In June 2020, Wirecard dramatically announced a "missing" of 1.9 billion euros in cash. The company committed a few days later that the 1.9 billion euros amount likely did not exist and filled for bankruptcy on 25 June 2020. In Japan, the Olympus scandal was surfaced by its former president and chief executive officer Michael Woodford on 14 October 2011, that the company had been implicated in loss-concealing arrangments for two decades. Six former executives of Olympus (except the whistleblower Michael Woodford) were charged in a fine of US$529 million and sentenced years in prison for their roles in a US$1.7 billion cover-up since the 1990s. Coincidentally, the Toshiba accounting scandal revealed in 2015 was tied to unscrupulous accounting practices, such as booking future profits early, pushing back losses, and pushing back charges. The company had overstated profits by US$1.2 billion over the previous seven years.

In the modern global economic system, no country is immune from financial state fraud, and China is no exception. Since the establishment of the Shanghai Stock Exchange (SSE) and the Shenzhen Stock Exchange (SZSE) in the end of 1990, the domestic Chinese stock market[9] has expanded rapidly with China's runaway economic growth in the last three decades. Based on data from the China Securities Regulatory Commission (CSRC), **Figure 1** provides a development trend of the Chinese stock market in the recent years. As of the end of 2020, there were 4154 companies listed on the SSE and the SZSE, with an average increase of 8% year-on-year over the past 5 years. The total market capitalization combining the SSE and the SZSE reached US$12.2 trillion in 2020, ranking the Chinese mainland stock market the second largest stock market by country or region in the world, trailing only the U.S. equity markets. However, the development of China's stock market is accompanied by a proliferation of fraudulent activities. From the earliest case of Shenzhen Yuanye[10] in the 1990s, to the Yinguangxia[11] scandal in the 2000s, and the infamous LeEco[12] scam in recent years, the scale and scope of accounting frauds are both expanding fast with the expansion of China's capital market.

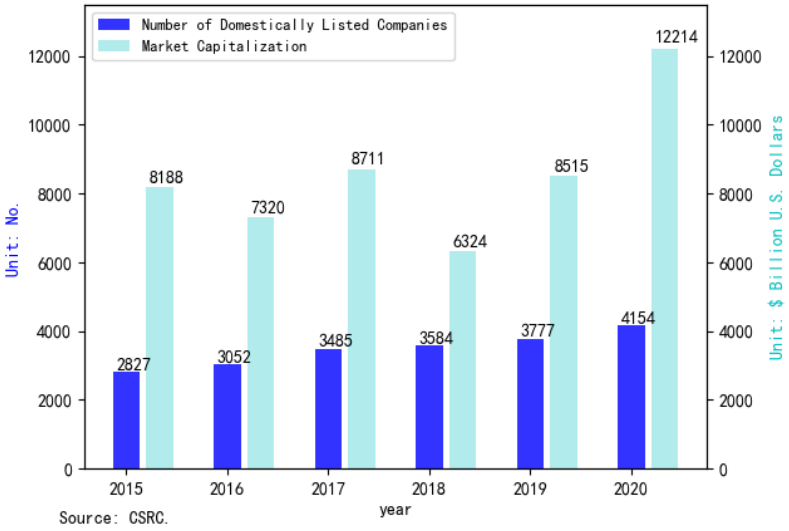

Figure 1. Market size of companies listed on the SSE and the SZSE (2015–2020).

With the prevalence of corporate fraud and malfeasance comes the public outcry for regulation and reforms. In the U.S., the financial reporting scandals of Enron and Worldcom[13] gave rise to the Sarbanes-Oxley (SOX) Act of 2002, a federal law that expanded reporting requirement for all the U.S. public company boards, management, and public accounting firms to ensure that companies report their financials honestly. In China, the CSRC, the main regulator of the securities industry, has been constantly committed to cracking down on stock market manipulation to protect investors, especially the medium and small shareholders. **Figure 2** presents the CSRC actions against securities violations in 2015–2020. Although the new investigation cases were approximately 300 cases in each year, the proportion of disclosure violation cases is steadily increasing per year. In 2020, the CSRC received 435 valid tips on illegal activities and misconducts, newly launched 353 investigations, and opened 282 cases. Among the 282 new investigations in 2020, 82 cases were related to material disclosure violations, which is a dramatic increase from the 42 cases of disclosure violations in 2015. It shed light on that information disclosure violation is becoming one of the most common types of financial statement fraud in China[14].

Earlier this year, China's regulatory authorities accused Evergrande and its founder, Xu Jiayin, of allegedly inflating revenues by a staggering US$78 billion, making it the center piece

of the country's largest financial fraud case. Xu Jiayin, the founder and chairman of the Evergrande Group, was subsequently fined 47million yuan (approximately US$6.5 million) for the overstatement and other alleged infractions. Furthermore, PwC China, the auditing firm that had approved Evergrande's financial statements, has come under fire. Despite Evergrande's inflation of its mainland revenues by nearly 80 billion in the two years preceding its 2021 default, PwC China failed to uncover the discrepancies. In response, Chinese authorities imposed a six−month ban on PwC China and levied a fine of 441 million yuan (approximately US$62 million), citing staff members' concealment or even condoning of fraud in their audit failures related to the collapsed property developer.

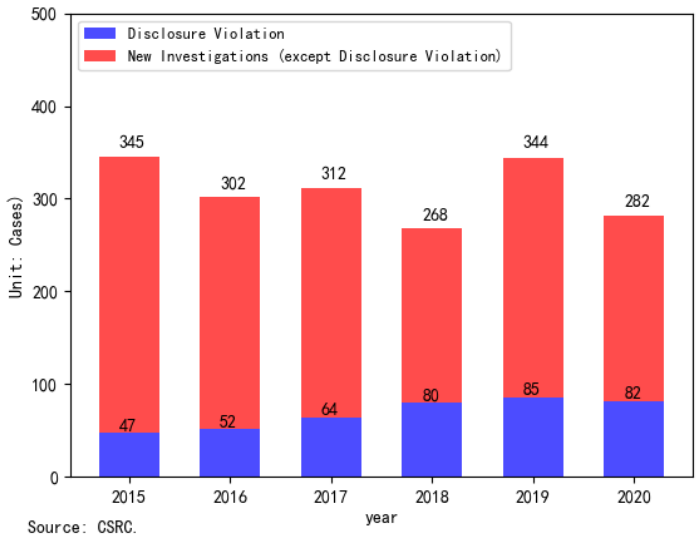

Figure 2. CSRC actions against securities violations (2015–2020).

The key to combat financial statement fraud is to predict it as early as possible, all the better to prevent it from ever happening. the on-site examinations are more costly USA status. A faster and efficient fraud detection strategy can substantially reduce the magnitude and loss of fraud. However, detecting financial statement fraud has long been a global challenge. Among existing data mining techniques of financial shenanigans, logistic regression is one of the most widely used methods to detect financial statement fraud [2], and somewhat surprisingly it also performs well relative to other more complex detection techniques [3]. Nevertheless, the logistic regression or other data mining models incorporate estimation errors which may affect the classification of the financial statement fraud. Alternatively, this paper aims to contribute on the topic of detecting financial statement fraud by applying an early warning model based on the mixture hazard model (MHM) of Farewell [4]. This early warning model approach is introduced by Almanidis and Sickles [5] which effectively combine a static model to identify companies with suspected fraud and a duration model to provide estimates of the probability of detecting such fraud by the regulators. The logistic regression is used as a benchmark to identify suspected financial shenanigans. The main assumption of this approach concerns the fact that companies with low performance as measured by the financial characteristics in their annual accounting reports will increase their probability of cooking the books.

The estimation results indicate that in detecting financial statement fraud, the financial characteristics may have different implications in different industries. For example, in the construction industry, manipulation of financial data is probably followed by a low level of the return on assets (ROA). In other words, a low level of the ROA implies a poor usage of its capital to generate profitability, hence provides a motivation for financial statement fraud. In

the capital-intensive construction industry in China, profitability instead of growth is the key to survive and keep a company off the financial statement fraud. Alternatively, in the real estate industry, financial statement fraud are more closely linked to a high level of inventory. In other words, a low inventory turnover ratio will increase the company's finance cost, worsen its liquidity, and induce the management to cook the books. The intense financial pressure in the real estate industry in China, mainly from the high leverage, high debt and high turnover business mode, may motivate desperate management of a company to manipulate its financial data. We also find evidence from the MHM model that better financial conditions, which are measured by the Altman's Z-score [6], will reduce the risk of financial statement frauds.

The rest of the paper is organized as follows. Section 2 provides a literature view on financial statement fraud detection. Section 3 introduces the MHM model and its estimation method. Section 4 describes the dataset and defines the variables for this research. Section 5 gives the estimation results with a comparison of detecting financial statement fraud in both the construction industry and the real estate industry in China. Section 5 provides a summary.

2. Literature review

Research into financial statement fraud has traditionally focused on understanding its causes, consequences, and detection methods. Reurink [7] distinguishes financial statement fraud from financial scams and fraudulent financial mis-selling and finds that financial fraud is a complex phenomenon that can take very different forms, depending on the market segments in which it occurs, the financial instruments it pertains to, and the actors involved. Amiram et al. [8] pointed out that there is conflicting evidence in the literature concerning whether internal controls are effective in reducing financial misconduct within organizations. In contrast, Rashid et al. [9] investigate the literature concerning corporate fraud as well as financial crime from 2003 to 2018 and found that the internal control system, as a component of good governance, is the best approach to prevent and detect fraud. Ashtiani and Raahemi [10] systematically review and synthesize the existing literature on intelligent fraud detection in corporate financial statements, suggesting that in addition to structured data such as financial ratios, unstructured data in the financial fraud detection domain, such as textual content, deserves more attention to achieve remarkable results.

Effective detection of financial statement fraud is critical in mitigating its impacts. Traditional methods such as logistic regression have been widely utilized to identify potential fraud [11]. One notable advancement in fraud detection is the use of early warning systems as outlined by Almanidis and Sickles [5]. This approach integrates static models with duration models, offering a more nuanced and comprehensive method for identifying fraudulent activities. Hajek and Henriques [12] argue that a low relative frequency of negative words in annual reports may indicate non-fraudulent firms and it is necessary to use information extracted from both publicly available financial statements and analysts' forecasts of revenues and earnings. Kassem [13] finds that effective corporate governance can help reduce fraud risk, prevent fraud and detect fraud, particularly corporate fraud, insider fraud and asset diversion. Mandal [14] examines how auditors perceive the influence of crucial fraud prevention factors in deterring financial statement fraud within the corporate sector. Chen and Han [15] model the corporate financial data into a 3-Dimension data cube that contains both temporal and financial feature domain information, and find that the detection performance is dramatically improved when the accumulated number of quarters increased.

Recent developments in fraud detection focus on big data techniques, especially data mining techniques [16]. Hooi et al. [17] propose a fraud detection algorithm named FRAUDAR, which provably bounds the amount of fraud adversaries can have, even in face of camouflage. Shin et al. [18] propose DenseStream, an incremental algorithm that maintains and updates a

dense subtensor in a tensor stream, and DenseAlert, an incremental algorithm spotting the sudden appearances of dense subtensors, which successfully detects anomalies, including small-scale attacks, in real-world tensors. Craja et al. [19] employ a hierarchical attention network model, by extracting textual features from the annual reports and providing red-flag sentences, significantly enhances fraud detection capabilities by combining both content and context of managerial comments with financial ratios. Jiang et al. [20] propose a real-time fraud detection framework called SPADE, which enables developers to design their fraud semantics to detect fraudulent communities by providing the suspiciousness functions of edges and vertices. Jiang et al. [21] further refine the Spade fraud detection system to Spade+, which manages both edge additions and removals on dynamic graphs and efficiently handles batch updates and employs edge packing to diminish latency. Chen et al. [22] present RUSH, a novel system for efficiently detecting burst subgraphs in dynamic graphs, and offerr user-friendly APIs for customizable fraud detection across different scenarios.

3. The model

This paper follows the MHM approach of Almanidis and Sickles [5] to identify companies who cook the books. First, we define H_{it} as the financial health indicator of corporate i at time t. If the financial health H_{it} of the company i falls bellow a certain level, which can be represented by a threshold H_{it}^*, then the company is considered at risk of cooking the books. The difference between the threshold level H_{it}^* and H_{it} is denoted as $h_{it}* = H_{it}^* - H_{it}$, and is assumed to be dependent on company-specific financial metrics as

$$h_{it}^* = x_{it}'\beta + e_{it}, \tag{1}$$

where e_{it} represents the identically and independently distributed (iid) error term. Empirically, the financial threshold level $H_{it}*$ and the h_{it}^* are not observable. Instead, whether a company manipulates its financial record can be defined by a binary variable h_{it} as

$$h_{it} = \begin{cases} 1 & \text{if } h_{it}^* > 0 \\ 0 & \text{if } h_{it}^* \leq 0. \end{cases} \tag{2}$$

Hence, the probability that a company will become a $problem$ one is given by

$$P(h_{it} = 1) = P(h_{it}^* > 0) = P(e_{it} > -x_{it}\beta) = F_e(-x_{it}\beta), \tag{3}$$

where F_e is the cumulative distribution function of the random error e, which can be defined as normally distributed in the probit model or logistically distributed in the logit model. The main assumption of this approach concerns the fact that companies with low performance as shown in the accounting report will increase the probability to intentionally misstate their financial statement.

In practice, the rate at which regulatory authorities tend to misclassify healthy companies as fraudulent ones is close to zero. Hence the likelihood function for a company i can be expressed as

$$L_i(x, w) = [F_e(x\beta)\lambda_i^p(t; w_i)S^p(t; w_i)]^{d_i}[F_e(x_i\beta)S^p(t; w_i) + (1 - F_e(x_i\beta))]^{1-d_i}, \tag{4}$$

where λ^p represents the hazard rate or probability that such company will cheat during the next instant and S^p is a survivor function, which represents the probability that a problem company will not be detected for a period longer than t. A binary variable d_i takes on a value of 1 for

observations of the fraud by regulators with a warning letter at time t and 0 otherwise. The variables of x and w are covariates associated with the probability of financial statement manipulation and the probability of been detected, respectively. For convenience of interpretation, we refer to the portion of the model that assesses the financial health of a company as the incidence component, and the portion of the model that assesses survivial times of financial statement frauds before been detected as the latency component. After some simplification of Equation (4), the sample likelihood for all the companies can be written as

$$L(x,w,d)=\prod_{i=1}^{n}L_i(x,w,d)=\prod_{i=1}^{n}F_e(x\beta)^{h_{it}}(1-F_e(x_i\beta))^{1-h_{it}}(\lambda_i(t;w_i))^{d_ih_{it}}(S_i(t;w_i))^{h_{it}}. \tag{5}$$

Following the approach of Kalbfleisch and Prentice [23], the discrete-time hazard function $S_i(t;w_i)$ in Equation (5) is given by

$$S_{ij}(t;w)=\prod_{j=1}^{t_i}\frac{1}{1+e^{w_{ij}\alpha}}, \tag{6}$$

and the discrete-time survivor function $\lambda_i(t;w_i)$ can be derived as

$$\lambda_{ij}(t;w)=1-\frac{S(t_{ij})}{S(t_{i,j-1})}=\frac{\exp(w_{it}\alpha)}{1+\exp(w_{it}\alpha)}, \tag{7}$$

where both the survivor function in Equation (6) and the hazard function in Equation (7) are assumed to be in discrete times of $j=1,2,...,t_i$.

In the real life, h_{it} is not observable. We follow the approach of the expectation–maximization (EM) algorithm by Dempster et al. [24] to deal with the unobservable latent variablesapply. The EM algorithm consists of two iterative steps: the expectation (E) step and the maximization (M) step. The E step creates a function for the expectation of the log-likelihood evaluated using the current or initial estimate for the parameters, and the M step computes parameters maximizing the expected log-likelihood found on the E step while treating the incomplete data as known. Iterating between these two steps yields estimates that under suitable regulatory conditions converge to the maximum likelihood estimates. In detail, in the E step, we compute h_{it} as

$$\begin{aligned}h_{it}&=\Pr(h_{it}=1|t_i>T_i)\\&=\begin{cases}\frac{F(x_i\beta)S_i(w_i)}{F(x_i\beta)S_i(w_i)+(1-F(x_i\beta))} & \text{if } d_i=0\\ 1 & \text{otherwise.}\end{cases}\end{aligned} \tag{8}$$

In the M step, we optimize the log-likelihood function of Equation (5) as

$$E(L)=h_{it}\ln(F(x_i\beta))+(1-h_i)\ln(1-F(x_i\beta))+h_id_i\ln(\lambda_i)+h_i\ln(S_i). \tag{9}$$

In practice, the initial estimate for the parameter β is calculated by the logistic regression. Then we iterate between Equations (8) and (9) until convergence is reached.

4. The data

Our data for the listed companies in the Chinese stock market are from the iFinD database. As it is well known that the real estate sector is among the most crucial sectors of the Chinese economy, we choose companies in the construction industry and the real estate industry during 2015–2020 to study the features of the financial statement fraud in the real estate market. Hence

the sample includes 504 and 626 observations from the construction industry and the real estate industry, respectively. Based on the annual revenue in 2015–2020, the market size of the sample in these two industries is around 20% of all the listed companies in China's stock market.

The dependent variable is a binary variable, labeling if the company received a warning letter of misstatement from the CSRC. Following Summers and Sweeney [25], we select four financial statement characteristics, including financial condition, financial performance, growth, and changes in inventory, as explanatory variables to model the propensity to commit fraud. The advantages of choosing these four financial statement characteristics as explanatory variables are twofold. First, these characteristics are public data available in the annual report of the listed companies, avoiding the missing data or biased data issues if the data are collected from unofficial channels. Second, it provides a criteria in detecting unethical misstatement based on key information from the financial statement.

The measurement of financial condition is proxied by Altman's Z-score, which takes into account profitability, leverage, liquidity, solvency, and activity ratios to predict whether a company has a high probability of becoming insolvent [6]. In general, a Z-score closer to or higher than 3 implies a solid financial situation, while a Z-score below 1.8 implies a poor financial condition which might motivate unethical financial reporting. The financial performance is measured by the ROA, which is a bang-for-the-buck financial ratio calculated by dividing a company's net income over its total assets. A low level of ROA indicates that the management could not maintain or improve the profitability of the company, which might trigger financial statement fraud. The GROWTH is computed as the simple average of the percentage growth in sales over a three year window ending in the current year (t). Rapid growth is expected to be associated with the incidence of fraud, because unethical managers may be induced to misstate financial statements when growth slows or reverses in order to maintain the appearance of consistent growth. Therefore, the usage of a three year average growth rate provides a measure of sustained growth of a company, avoiding the short-run fluctuations by the measurement of one year growth rate. The changes in inventory, ΔI, is defined as the changes in the ratio of inventory (I) to sales (S) between the current year (t) and the previous year $(t-1)$ that $\Delta I = \frac{I_t}{S_t} - \frac{I_{t-1}}{S_{t-1}}$. Since overstating ending inventory has the effect of reporting higher profit, management may be motivated to inflate income through the misstatement of inventory records.

Table 1 shows the descriptive statistics of the variables. Among the 504 observations from the construction industry in 2015–2020, there are 11 detected fraudulent financial statement cases, while among the 626 observations from the real estate industry in 2015–2020, there are 6 financial statement fraud cases been detected. The distribution of the explanatary variables, such as the Z-score, the GROWTH, and the ΔI are heavily right-skewed, implying that a few leading companies outperform the others in the market, especially in the real estate industry. On the other hand, the similar distribution of the ROA in the construction industry and the real estate industry is consistent with the fact that both industries are highly capital intensive. The next section will further discuss how the changes in these financial characteristics may give clues in identifying the financial statement fraud in both industries.

Table 1. Descriptive statistics.

	Min	Q1	Median	Mean	Q3	Max	N
Construction Industry							
FRAUD	0.000	0.000	0.000	0.022	0.000	1.000	504
Z-score	−5.639	1.238	1.678	2.247	2.530	27.536	504
ROA	−2.509	0.017	0.031	0.030	0.053	0.252	504
GROWTH	−35.343	4.820	11.590	15.314	21.961	235.742	504
ΔI	−2.766	−0.083	−0.003	−0.029	0.034	5.733	504
Reak Estate Industry							
FRAUD	0.000	0.000	0.000	0.010	0.000	1.000	626
Z-score	−9.776	0.972	1.333	3.892	2.329	248.760	626
ROA	−0.833	0.013	0.027	0.027	0.047	0.345	626
GROWTH	−64.161	1.119	16.714	32.684	32.286	600.800	626
ΔI	−78.115	−0.646	−0.008	0.019	0.566	99.235	626

5. Estimation and inference

Since financial statement fraud is a rare but deliberate action, although there are many attempts to study the detecting methods of the financial statement fraud, it can be very hard to predict. This study chooses three econometric approaches, including the ordinary least squares (OLS) regression, the logistic regression, and the MHM model, to compare the key affecting financial factors of fraudulent misstatement cases in the construction industry and the real estate industry in China. The OLS is the most widely used linear regression method. However, in this study the dependent variable is a binary outcome. Although there are cases to model binary outcomes using the OLS regresion, in general it is not recommended because of the interpretation difficulties and the issue of inconstant conditional variances. The logistic regression is an althernative approach for binary outcomes, but it still depends on distributional assumptions of the unknown error term. As discussed in Section 2, the MHM early warning model is a preferred approach in this study, since it combines a static model to identify suspected fraud companies, and a duration model to estimate the probability of detecting such frauds by the regulators.

Table 2 provides the estimation results of all the three models for the listed companies in the construction industry in China. Among the four key financial characteristics of the Z-score, the ROA, the GROWTH, and the ΔI, the ROA is significantly negatively correlated to detected misstatement in all the three models. As the return on capital slows down in China in the past decades, the capital-intensive construction industry is struggling in a world of painfully low margins. A high level of ROA could give the company in this industry a wide economic moat against the risk of financial statement fraud. At the same time, though the relationship between the detected misstatement and the variables of the Z-score, the GROWTH, and the ΔI are vague in the OLS and the logit models, the unambiguous negative impacts of the Z-score and the ΔI to the financial statement fraud are shown in the incidence portion of the MHM model. A higher Z-score indicates a solid financial situation, while a higher inventory level implies potential business expansion in the near future, both will reduce the threat of financial statement fraud. On the other hand, it is worth paying attention to the positive effect of the GROWTH to the fraudulent misstatement, which might suggest that the increasement of revenue, if not accompanies by the increasement of profit, would not be sound or robust for a company but to trigger fraudulent dealings.

Table 2. Estimates for the construction industry.

Variables	OLS	Logit	MHM Model	
			Latency	Incidence
Intercept	0.027**	−3.294***		−1.736 ***
	(0.010)	(0.765)		(0.064)
Z-score	−0.001	−0.416	0.018	−0.172 ***
	(0.003)	(0.447)	(0.082)	(0.023)
ROA	−0.417***	−13.655 **	−0.297	−6.635 ***
	(0.066)	(5.502)	(1.478)	(0.252)
GROWTH	0.053	1.638	−0.121	0.569 *
	(0.032)	(1.424)	(0.392)	(0.241)
ΔI	−0.024	−0.633	−0.062	−0.268 ***
	(0.016)	(0.573)	(0.166)	(0.058)
N	504	504	504	504

NOTE: $^{*}\ p < 0.05$, $^{**}\ p < 0.01$, $^{***}\ p < 0.001$.

Table 3 demonstrates the estimates for the listed companies in the real estate industry in China. Among the four key financial characteristics of the Z-score, the ROA, the GROWTH, and the ΔI, only the ΔI demonstrate s significant and positive effects to detected misstatement in all the three models. As is well known, the real estate industry is highly capital intensive in China. With the raipd urbanization in the last decades, property enterprises in China expand quickly via the high leverage, high debt and high turnover business mode. Hence to control the level of inventory becomes critical for companies in the real estate industry to reduce finance cost and improve liquidity. Since a increase of ΔI will cause increased financial burden of a company, the management might have the motivation to cook the books in urgent cases of financial difficulties. Concurrently, the impacts of the Z-score and the GROWTH to the detected misstatement are positive and visual, similar as the results shown in **Table 2** for the construction industry.

Table 3. Estimates for the real estate industry.

Variables	OLS	Logit	MHM Model	
			Latency	Incidence
Intercept	0.009* (0.004)	−4.831*** (0.53)		−2.402 *** (0.012)
Z-score	−0.000 (0.000)	−0.023 (0.092)	0.003 (0.002)	−0.009 *** (0.001)
ROA	−0.079 (0.058)	−3.407 (3.269)	−0.015 (0.042)	−1.643 *** (0.017)
GROWTH	0.010 * (0.005)	0.239 (0.363)	0.026 (0.016)	0.098 (0.016)
ΔI	0.003 *** (0.000)	0.050 *** (0.017)	−0.001*** (0.000)	0.025 *** (0.000)
N	626	626	626	626

NOTE: $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

Furthermore, the estimation results in **Tables 2** and **3** provide evidence that the MHM model delivers more information than the OLS regression or the logistic regression in detecting the financial statement fraud for the listed companies. Specifically, the incidence portion of the MHM model, which assesses the financial health of a company, is analogous to the OLS regression or the logistic regression, while the latency portion of the MHM model provides additional information of the survivial times of financial statement frauds before been detected. However, the estimation results of the latency portion of the MHM model are statistically not significant for either the construction industry or the real estate industry, which also support the facts that the fraudulent misstatements are hard to be detected.

6. Summary and conclusions

Financial statement frauds or accounting scandals arising from intentional manipulation of financial statements are ubiquitous among listed companies in China. Since the disclosure of financial misdeeds are from trusted executives of the public corporations, the fraudulent financial statements are difficult to be detected. Based on the fact that a common incentive for companies to manipulate financial statement is a decline in the company's financial prospects, this study apply the MHM early warning model to identify the key impacting financial characteristics in detecting the financial statement fraud. The estimation results indicate that in the construction industry the warning sign of suspecious business practices is a falling ROA, while in the real estate industry the financial red flag is an increase in the inventory level.

The policy implications of this study are twofold. First, the financial characteristics may have different implications in different industries in detecting financial statement fraud. The financial pressures for the management to commit fraud, which are constrained by the industry heterogeneity such as capital intensity, resource intensity, and technology intensity, will be manifested in different financial characteristics in the company's accounting report. Hence, setting specific financial characteristics by peculiarities of the industry, such as the ROA for the construction industry, and the inventory ratio for the real estate industry, would be recommended

for fraud monitoring and detecting by the regulators. In the aftermath of the Evergrande crisis, China's Real Estate Market has emerged as a prominent source of economic and financial risk, prompting the government to prioritize comprehensive measures aimed at addressing the underlying issues in the sector to effectively prevent and mitigate systemic financial risks. In response to the rising inventory ratio in the real estate market in the post-COVID period, Chinese government encourages real estate enterprises to transform from traditional development and sales models towards diversified and integrated business models. This includes developing long-term rental apartments, senior living communities, tourism real estate, and strengthening property management and community services to enhance profitability and market competitiveness.

Second, it is vital to a company, instead of the market regulators, to have a fraud prevention plan in place, as preventing fraud is much easier than recovering the losses after a fraud has been committed. In practice, internal accounting controls, including segregation of duties, the usage of an external auditor, and performing accounting reconciliations on a regular basis, can help to reduce the risk of fraud from occurring. In the Chinese real estate market, while not all companies may publicly disclose their detailed fraud prevention plans, many have implemented a range of measures to safeguard against fraud and ensure market fairness and transparency. By strengthening internal controls, enhancing transparency, refining contract and after-sales services, overseeing advertising, and rigorously managing partners, real estate companies can effectively mitigate fraud risks, uphold market order, and protect consumer interests. Moreover, with advancements in technology and regulatory oversight, real estate firms are increasingly leveraging digital tools like big data and AI to monitor sales data, promptly detect and address anomalies, further enhancing market fairness and transparency.

At the same time, the principle of the regulators should be grounded in strengthening legal foundation, non-intervention in the market, and zero tolerance against violations. As China's domestic economy experiences a slowdown compared with the frantic pace of growth of the past decades, an efficient, stable, and well-designed capital markets become more critical than ever to China's sustainable growth. On the one hand, China is deepening the reform of the capital markets constantly. The Financial Stability and Development Committee was established in June 2017 to further collaboration and alignment among the various regulatory bodies in China. The new securities law came into effect on March 1^{st} 2020 to allow for registration-based systems for IPOs. Additionally, disclosure requirements and fines for violations have been increased to improve investor protection. On the other hand, China is taking steps to further opening-up the Chinese financial markets to foreign institutional investors. The increased connectivity between domestic and foreign capital markets will bring new opportunities and challenges for both the companies, the investors, and the regulators. Detecting financial statement fraud will remain a long-term task with the further reform and opening-up of the Chinese stock market.

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Conflict of interest: The authors declare no conflict of interest.

Notes

[1] ftc.gov/business-guidance/blog/2022/02/ftc-2021-data-just-facts

[2] Enron Corporation (NYSE: ENE), an American energy company based in Houston, Texas, was discovered in 2001 that the company had been using accounting loopholes to hide billions of dollars of bad debt.

[3] Tyco International Ltd. (NYSE: TYC) was discovered in 2002 that its CEO, Dennis Kozlowski, and CFO, Mark Swartz, had stolen over US$150 million from the company and had inflated the company's earnings by over US$500 million in their reports.

[4] The Federal National Mortgage Association, commonly known as Fannie Mae, and the Federal Home Loan Mortgage Corporation, better known as Freddie Mac, are federally backed home mortgage companies created by the U.S. Congress. They purchase, package, and sell home loans in the form of mortgage-backed securites (MBS) to provide liquidity to the U.S. mortgage finance system.

[5] Lehman Brothers (NYSE: LEH) was the fourth-largest investment banks in the U.S. with 25,000 employees worldwide before filling for bankruptcy in the climax of the subprime mortgage crisis on 15 September 2008.

[6] sec.gov/news/press/2011/2011-267.htm

[7] Repo 105 is Lehman Brothers' name for an accounting maneuver that it used where a short-term repurchase agreement is classified as a sale.

[8] Wirecard was a German fintech company providing payment processing and financial services. The firm was a constituent of the DAX index between 2018 and 2020 before its collapse.

[9] The domestic Chinese stock market discussed in this paper mainly comprises three independently operated stock exchanges: the Shanghai Stock Exchange, the Shenzhen Stock Exchange, and the newly founded Beijing Stock Exchange. The Hongkong Stock Exchange and the Taiwan Stock Exchange are not included.

[10] Shenzhen Yuanye Textile Co., Ltd., established in 1987, was China's first listed Sino-foreign joint venture in 1990. The company is ordered by the SZSE to suspend trading on 7 July 1992, which is the first listed company fraud case in China's stock market history. Its stock resumed trading on 3 January 1994, after reorganization and changing the company's name to "Shenzhen Century Xingyuan Group Co., Ltd.", also the first listed company to be restructured.

[11] In 2001, China Securities Regulatory Commission unearthed non-existent profits at Guangxia (Yinchuan) Industry Co., Ltd. of 178 million yuan in 1999 and 567 million yuan in 2000.

[12] LeEco, formerly known as Letv, the first Chinese video website listed company, was delisted from the SZSE on July 20, 2020. The CSRC announced the details of the LeEco financial fraud on 13 April 2021, that LeEco has inflated revenue by 1.87 billion yuan, and inflated profit by 1.73 billion yuan in 10 consecutive years from 2007–2016. The CSRC fined LeEco a total of 241 million yuan and its founder Jia Yueting a total fine of 241 million yuan.

[13] Worldcom was the second largest U.S. telecommunication company, after the AT&T in the 1990s. The senior executives at Worldcom inflated revenue by over US$3.8 billion from 1999 to 2001 to maintain its stock price. After the scandal broke, the company filed for bankruptcy protection on 21 July 2002 and was eventually acquired by Verizon in January 2006

[14] csrc.gov.cn/csrc_en/c102063/c1606114/content.shtml

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Article

Conceptualizing a nexus between agility, unobserved differences of dynamic capability, and sustainable performance of microfirms

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Abstract: Recent studies have highlighted commonalities in the relationship between dynamic capabilities and firms' sustainable performance. However, the impact of unobserved differences within the dimensions of dynamic capabilities on firm-level sustainable performance remains unclear. Specifically, in this study, we investigate how unobserved variations in dynamic capabilities influence the sustainable performance of dairy microfirms. Additionally, the study examines the unobserved mediating effects of agility in the relationships between knowledge-sharing sensing capability, managerial cognitive capability, and sustainable performance. Grounded in the Knowledge-Based View (KBV) theory, our study rigorously tests these hypotheses using a unique quantile composite-based path modeling approach. The findings reveal both significant strong and weak unobserved differences in the relationships between knowledge sharing, sensing capability, managerial cognitive capabilities, agility, and the sustainable performance of microfirms. Notably, the results demonstrate that agility significantly mediates the unobserved dimensions of dynamic capabilities in supporting sustainable performance, with the study confirming both full and complementary partial mediation effects. Our findings offer a valuable framework for managers and employees to strategically invest in dynamic capabilities while also discussing the heterogeneous distribution of these capabilities among managers and employees across dairy microfirms.

Keywords: agility; dairy microfirm; knowledge sharing; sensing capability; sustainable performance

1. Introduction

Sustainable performance has increasingly become a concern for stakeholders of microfirms due to unpredictable disruptions that exacerbate limited resource availability and production costs, thereby jeopardizing firm-level competence [1–6]. To address these challenges, previous research has suggested solutions such as developing a sustainability scorecard [7]. This tool is designed to enhance sustainable performance by enabling individual managers and employees to better control both tangible and intangible resources, thereby maintaining positive dynamism within the firm [8–10]. Consequently, managers and employees play a crucial role in overcoming sustainability challenges by optimizing the use of tangible and intangible inputs to maximize production efficiency. Thus, promoting sustainable performance is essential for improving the overall effectiveness of the firm [9–11].

To address the rapidly growing challenges and enhance firms' sustainable performance, other scholars emphasize the crucial role of individual managers and employees in formulating strategies and leveraging both internal and external

resources to adapt to environmental changes [7,11]. Evaluating sustainable performance at the individual level, particularly among managers and employees who develop skills to become either innovators or architects and establish capabilities currency, has some limitations [9]. For example, the microfirm sector has been significantly impacted by disruptions such as rising energy costs and resource constraints [1–3]. Understanding environmental dynamism is essential for firm growth and can be categorized into two facets: 'internal growth' and 'acquisition' [10,11]. Integrating these factors illuminates the foundational aspects of dynamic capabilities, which involve managerial processes that develop the market and manage external factors to significantly enhance sustainable performance [12]. Thus, dynamic capability is defined as a firm's ability to intentionally create, extend, and modify its resource base [13]. Similarly, Jantunen et al. [14] and Fainshmidt et al. [15] describe dynamic capability as a firm's capacity to integrate, build, and reconfigure internal and external resources to tackle environmental challenges.

The definition of dynamic capability enhances the understanding of key components: creating, extending, and modifying resource-based optimization to fundamentally improve sustainable performance [16]. These core elements collectively enhance the efficacy of microfirms in managing their resources, aligning with the Knowledge-Based View (KBV), which extends the Resource-Based View (RBV) [3,17]. According to the KBV, dynamic capability is conceptualized as a composite set of attributes—such as sensing capability, knowledge sharing, managerial cognitive capabilities, and agility—that are essential for modifying and extending resources to support sustainable performance [18,19]. The existing literature highlights ongoing efforts to address these challenges by integrating dynamic capabilities and KBV theories. This combination serves as a tuning mechanism to enhance sustainable performance at the firm level and build the internal resilience and endurance of microfirms [5,8,16].

Nonetheless, studies have illustrated that a firm's degree of heterogeneity is crucial for explaining dynamic capabilities from the perspective of the KBV framework. This perspective acknowledges that dynamic capabilities are unique and specific factors that exhibit direct commonalities influencing sustainable performance through idiosyncratic elements [19–21]. Arguably, there are recognizable patterns of dynamic capabilities across firms that positively impact sustainable performance. At the same time, the KBV framework also highlights that nuanced and hidden interdependencies among dynamic capabilities play a critical role in shaping an organization's strategic capabilities and knowledge-based advantages [22]. Understanding these commonalities and patterns at the firm level is essential for helping informal networks involved in sensing, knowledge sharing, managerial cognitive capabilities, and agility. This gives a sense that networks create a dynamic environment conducive to learning and innovation among managers and employees of microfirms. Furthermore, these hidden dimensions of dynamic capabilities, which cut across individual managers and employees, represent interconnected aspects rather than isolated activities [11]. Leveraging these differences in dynamic capabilities can significantly enhance a firm's knowledge-based advantage by fostering adaptability, innovation, and strategic competitiveness.

Building upon the preceding arguments, addressing the challenges faced by dairy microfirms requires a deeper examination and not only the direct relationship between dynamic capabilities and sustainable performance [1]. For instance, numerous studies have highlighted the direct commonalities between dynamic capability dimensions and sustainable performance [23,24]. However, testing these dimensions for direct similar pattern effects on sustainable performance can be tautological, as it often neglects contingency hypotheses and unobserved differences [25]. Following the seminal works of Fainshmidt et al. [22] and Kurtmollaiev [26], which emphasize that understanding the common patterns and unobserved dynamic capabilities is essential for improving internal structures, processes, and pathways that influence a firm's dynamic capabilities and ultimately its sustainable performance, it becomes evident that a re-evaluation is necessary. To effectively address these issues, it is crucial to reconsider how unobserved differences in dynamic capabilities dimensions and contingency hypotheses impact the nature and growth paths of dairy microfirms [11]. Thus, uncovering hidden differences in these dimensions can help managers and employees identify performance gaps and address resource shortages, which are exacerbated by rapid innovations in the dairy industry [6]. Therefore, revealing variations in the interplay between sensing capability, knowledge sharing, managerial cognitive capabilities, agility, and sustainable performance can offer valuable insights for dairy microfirms to achieve a balance between growth, efficiency, and internal development.

The primary objective of this study is to investigate how unobserved variations in dynamic capabilities influence the sustainable performance of dairy microfirms. Additionally, the study examines the unobserved mediating effects of agility in the relationships of knowledge sharing, sensing capability, and managerial cognitive capability on sustainable performance. To test the hypotheses outlined in the conceptual framework (**Figure 1**), we first employed Partial Least Squares Path Modeling (PLS-PM), which is widely recognized and adheres to global analytical standards [27]. Following this, we applied a sophisticated technique—Quantile Composite-Based Path Modeling (QC-PM)—developed by Davino and Vinzi [28] and refined by Dolce et al. [29]. This advanced methodology enables a detailed analysis by incorporating variations across different quantiles, thereby offering a deeper and more comprehensive understanding of the dynamic capabilities and their impact on sustainable performance.

Our study advances the dynamic capabilities theory and sheds further light on sustainable performance in three significant ways. First, it enhances the empirical literature by conceptualizing the direct relationship between dynamic capability dimensions and sustainable performance specifically within the context of dairy microfirms in Tanzania, highlighting the existence of commonalities [2,30,31]. Second, it extends the theory by examining how individual differences among managers and employees influence the relationship between dynamic capability dimensions and sustainable performance [22]. Third, in this study, we explored the role of agility in mediating the unobserved effects of dynamic capability dimensions on sustainable performance, an area that remains empirically unexamined [32]. Notably, it is the first study to develop a mediation model that utilizes agility to

mediate the unobserved effects of dynamic capability dimensions on sustainable performance.

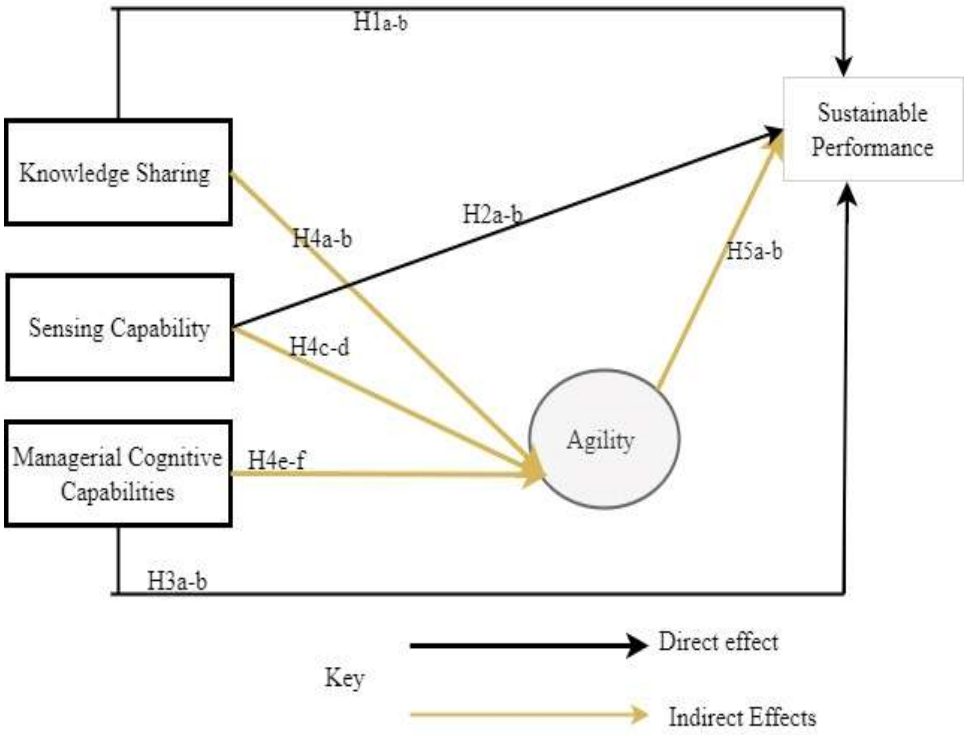

Figure 1. Theoretical and conceptual framework

The remainder of the article is structured to critically address the study's objectives. We utilize the KBV as the theoretical framework to formulate hypotheses and develop the proposed conceptual model. The article used theoretical and empirical review to detail the study's materials and methods. Following the empirical testing of the conceptual framework, we present the findings. Then, we established a discussion section that deeply elaborates on the results, including its theoretical and managerial implications, policy recommendations, future research directions, limitations, and concluding remarks.

2. Literature review and hypotheses development

2.1. Knowledge sharing and sustainable performance

Knowledge sharing involves the process of transmitting or disseminating information, skills, or expertise from one individual or group to another within an organization or community [33]. Likewise, the definition is in line with KBV theory, which asserts that knowledge sharing is crucial to highlighting how managers and employees organize resources to create and replicate new technologies, thereby opening strategic windows for understanding firm capabilities [23,34]. Prior research has suggested that effective knowledge sharing enables managers and employees to foster creativity and protect knowledge, leading to enhanced transformation and sustainability within firms [1,3,35]. Therefore, knowledge sharing encompasses both know-how and know-what [21], which are critical for influencing sustainable

performance for microfirms. For example, the dairy industry, recognizing the importance of this process, has called for the development of strategic knowledge-sharing systems between managers and employees. In so doing, it can protect tacit knowledge among employees and managers as the important ingredient for sustainable performance [36]. Thus, knowledge sharing should be emphasized as a critical process for transferring know-how within the firm, particularly between managers and employees.

Furthermore, knowledge sharing between microfirms plays a crucial role in resource integration, utilization, and configuration, all of which are essential for achieving sustainable performance [37]. In that case, it is indispensable for enhancing managers' and employees' learning routines, thereby improving their ordinary capabilities. Importantly, knowledge sharing is not merely about information exchange; it encompasses the sharing of thoughts, experiences, and ideas, which are vital for organizational learning. This learning, in turn, is a significant driver of sustainable performance [38]. While some authors in the dairy industry argue that knowledge sharing can be understood in terms of intensity and knowledge base [37,39,40], the combination of these elements has a substantial impact on dairy microfirms, fostering growth, capabilities, and sustainability. Despite this, few studies have positively correlated knowledge sharing with sustainable performance, particularly when considering variations in dynamic capabilities [1]. The literature review overlooked the effect of knowledge sharing variation among the managers and employees on microfirms sustainable performance. Therefore, we hypothesize that knowledge sharing significantly influences sustainable performance in dairy microfirms, especially when accounting for these quantile changes.

H1a: Knowledge-sharing positively affects sustainable performance.

H1b: Unobserved differences in knowledge sharing positively affect sustainable performance.

2.2. Sensing capability and sustainable performance

Sensing capability refers to the ability to identify, interpret, and capitalize on opportunities within the business environment [41]. In the same vein, empirical literature highlights the importance of sensing capabilities, which encompass generating market information, disseminating market intelligence, and responding effectively to market changes [42]. Thus, in the current digital age, the growing complexity of markets has compelled managers and employees to continuously identify new opportunities, adapt to market dynamics, and enhance their firms' flexibility [22]. In that process, it's bringing the fundamental dynamism for both managers and employees of microfirms to integrate sensing capabilities implicitly to knowledge sharing that has become crucial for detecting and leveraging new opportunities, thereby driving sustainable performance.

The KBV theory further emphasizes that a firm's adaptive capability is closely linked to its sensing capability. Thus, the previous studies proposed that flexibility serves as a fundamental mediator between sensing capability and the sustainable performance of dairy microfirms in Tanzania [1]. Therefore, debating a direct and unobserved influence of either sensing or knowledge sharing among managers and

employees are vital components of knowledge-based dynamic capabilities in the context of the dairy industry [43], which are critical for sustaining competitive advantage. While most research has focused on sensing capability as a potential mediator as well as the direct effect towards sustainable performance [44], Therefore, there is limited empirical exploration regarding the parallel analysis among the managers and employees of microfirms about the effectiveness of sensing capability on sustainable performance. Based on this reasoning, we posit the following hypothesis

H2a: Sensing capability positively affects sustainable performance.

H2b: Unobserved differences in sensing capability positively affect sustainable performance.

2.3. Managerial cognitive capabilities and sustainable performance

Management literature defines managerial cognitive capabilities as the capacity of managers and employees to handle multiple tasks while performing daily mental activities, which are closely tied to cognition [22]. These capabilities assume that managers and employees function as knowledge workers, spending significant time acquiring, organizing, absorbing, processing, and distributing information related to opportunities [45]. In a nutshell, previous research has highlighted the role of managerial cognitive capabilities in linking the mental cognition of managers and employees to actions that directly influence firm performance [14]. This suggests a direct relationship between the mental actions of organizing and acquiring information and a firm's sustainable performance. Consequently, the ability of managers and employees to absorb and process information is crucial for ensuring a firm's sustainability. The KBV theory further supports the importance of managerial cognitive capabilities in enhancing the mental cognitive functions of managers and employees. These cognitive activities encourage accurate information processing and organization, which are vital for improving firm performance [2]. Therefore, the mental cognitive capabilities of managers and employees play a pivotal role in driving the sustainable performance of firms.

Moreover, the mental activities of managers and employees that impact sustainable performance are of particular concern. Factors such as education levels, age, and marital status of managers and employees can significantly influence business performance. It's important to recognize that heterogeneity in how managers and employees mentally organize and process information can affect the dairy industry, leading to spillover effects that play a crucial role in differential sustainable firm performance. Understanding the managerial cognitive capabilities between managers and employees could serve as a pivotal factor in enhancing dynamic managerial capabilities [46,47]. Crucially, managerial cognitive capabilities are closely linked to knowledge sharing between managers and employees [48]. When managers and employees effectively share their experiences and knowledge, it can significantly enhance the sustainable performance of dairy microfirms [1]. This seamless exchange of knowledge and experience is vital for driving improvements in sustainability and overall firm performance.

Moreover, the literature demonstrates that managerial cognitive capabilities play a significant role in promoting sustainable performance, which can favor development within a firm. However, if the firm lacks the ability to modify, integrate, and extend resources effectively among managers and employees, the impact of these capabilities diminishes [49]. This limitation can lead to disorganized resources, making it increasingly difficult for the firm to absorb and process information essential for sustainable performance. Integrating knowledge sharing as an intangible resource can enhance the information-processing capabilities of managers and employees, thereby positively influencing sustainable performance [50]. Therefore, it is crucial to codify hidden managerial cognitive capabilities to facilitate knowledge sharing, which in turn supports sustainable performance [51]. Undoubtedly, previous research has primarily focused on the relationship between managerial cognitive capabilities and innovation, leaving a gap in understanding how these unobserved managerial capabilities influence the sustainable performance of dairy microfirms. Based on this reasoning, the study proposes the following hypothesis.

H3a: Managerial cognitive capabilities positively affect sustainable performance.

H3b: Unobserved differences in managerial cognitive capabilities positively affect sustainable performance.

2.4. Agility (mediator)

Agility is defined as a firm's ability to swiftly respond to market opportunities while effectively mitigating threats by leveraging resources such as available assets and human capital. This capability, characterized by the dynamism and mobility of managers and employees, plays a crucial role in enhancing the sustainable performance of microfirms. It is fair to argue that agility among managers and employees can support the sustainable management of customer delivery and the maintenance of strong supplier relationships, which are essential for long-term success in the dairy industry [1]. Certainly, the importance of agility lies in its ability to provide reliable products and services to customers, thereby ensuring sustainable performance. This has been underscored by other scholars who chronicled that "agility" and "flexibility" can be used interchangeably; of course, it underlines the close relationship between agility and sustainable performance toward reducing the business dark side [49,52,53]. However, agility, in particular, is emphasized for its role in creating delivery value and fostering strong supplier relationships by combining dynamic resource capabilities within the firm. As suggested by KBV literature, integrating the dynamic capabilities dimensions—such as sensing capability, managerial cognitive capabilities, and knowledge sharing—with firm agility can significantly enhance sustainable performance [9,50].

There is growing interest in understanding the role of agility in the dairy industry, particularly in light of reducing business disruptions significantly. Agility is seen as a critical factor in reducing production losses across economic, social, and environmental dimensions [5]. In this context, it is important to analyze whether agility can mediate the effects of sensing capability, knowledge sharing, and managerial cognitive capabilities to mitigate these production losses. To explore this, some researchers have measured a firm's agility using sustainability scorecards

specifically designed for the dairy industry [8,54]. By contrast, other scholars have argued that assessing an organization's agility, alongside its sensing capability, knowledge sharing, and managerial cognitive capabilities, plays a crucial role in enhancing growth and improving innovation capacity, ultimately supporting the sustainable performance of microfirms [55].

In light of this backdrop, the existing literature demonstrates that only a few researchers have examined the mediating role of agility in the relationships between sensing capability, knowledge sharing, and managerial cognitive capabilities and evaluated its impact on sustainable performance [56]. Consequently, there is growing concern about the sustainability of the dairy industry, which is closely linked to the unobserved role of agility. As noted earlier, microfirms human capital is considered to be an intangible asset that can enhance internal and external firm resource integration, reconfiguration, and extension to support sustainable performance. In this sense, a flexible and resilient system, built upon knowledge sharing, sensing capability, and managerial cognitive capabilities, can significantly influence the individual flexibility of the firm [5]. However, there is a notable shortage of empirical analyses that evaluate the mediation effects of agility following the unobserved effects analysis, particularly in the context of knowledge sharing, sensing capability, and managerial cognitive capabilities. This gap in the literature leads to the formulation of the following hypotheses.

H4a: Agility mediates the effects of knowledge sharing on sustainable performance.

H4b: Agility mediates the unobserved difference effects of knowledge sharing on sustainable performance.

H4c: Agility mediates the effects of sensing capability on sustainable performance.

H4d: Agility mediates the unobserved differences effects of sensing capability on sustainable performance.

H4e: Agility mediates the effects of managerial cognitive capabilities on sustainable performance.

H4f: Agility mediates the effects of unobserved differences in managerial cognitive capabilities on sustainable performance.

2.5. Sustainable performance

Sustainable performance in the dairy industry has been examined from various perspectives by different authors [1,57,58]. In this context, managers and employees play a crucial role in developing and improving microfirms dynamic capabilities [19]. However, there is growing concern about integrating dynamic capabilities with sustainable performance to keep pace with both local and global growth. Sustainable performance is defined as "the strategic, transparent integration and achievement of an organization's social, environmental, and economic goals through the systemic coordination of key inter-organizational business processes, aimed at improving the long-term economic performance of the company and its supply chains" [59–61]. In a similar context, KBV theorists postulated that achieving economic sustainability requires the effective deployment of resources to enhance sustainable performance

[62]. In this regard, the dairy microfirm's resources, including the knowledge of managers and employees, industry assets, and various capabilities such as agility and sensing capability, are vital to helping social, environmental, and economic goals.

For example, sustainable performance aligning with dairy microfirms has been presented by different authors from different perspectives [59]. The literature suggested that managers and employees in the dairy industry typically play a key role in developing dynamic capabilities [41]. Nonetheless, there is an emerging concern regarding integrating the industry's capabilities and sustainable performance to keep up with local and global growth. Thus, sustainable performance is defined as "the strategic, transparent integration and achievement of an organization's social, environmental, and economic goals in the systemic coordination of key inter-organizational business processes for improving the long-term economic performance of the individual company and its supply chains" [61,63]. Of course, KBV pieces of literature have suggested that to achieve economic sustainability among the microfirms, the deployment of resources should be adequate to enhance sustainable performance [64]. It is important to note that knowledge of managers and employees is among the important resources within the industry, and managerial learning is a crucial resource to affect sustainable performance.

Several researchers have a growing interest in navigating sustainable performance in the dairy industry [1]. For example, Bourlakis et al. [57] have pointed out the measurement of sustainable performance in the dairy food sectors through efficiency, responsiveness, flexibility, and product quality as potential indicators. However, most of the authors have been focused on measuring these sustainable performance indicators in the supply chain of the dairy industry. For instance, Beske et al. [38] examined the sustainable supply chain and dynamic capabilities in the food industry. The study concluded that dynamic capability in the supply chain is sustainably oriented through knowledge sharing [64]. On the other hand, the empirical literature has less explored relationships between agility and its embedded unobserved variation toward sustainable performance. Based on the above reasons, we hypothesize that.

H5a: Agility positively affects sustainable performance.

H5b: Unobserved differences in agility positively affect sustainable performance.

3. Materials and methods

3.1. Descriptive analysis

Table A1 (Appendix) presents the descriptive analysis of the observed indicators and social demographic variables, including occupational levels for managers and employees, sex, size, and educational level. The data reveals a high degree of agreement among managers and employees concerning knowledge sharing, sensing capability, managerial cognitive capability, agility, and sustainable performance. This agreeability is reflected in the mean values for each indicator, which range between 3.62 and 3.02 on a seven-point Likert scale. However, the study also highlights a significant degree of variability within the data sets, as evidenced by the high level of dispersion in the manifest variables associated with these indicators. Additionally, the kurtosis and skewness values indicate both negative (−) and positive (+) values,

suggesting that the study sample is normally distributed [65]. Although our study does not rely on the Gaussian principle, this distribution supports the data's validity. Consequently, the observed indicators and social demographic variables exhibit minimal noise.

3.2. Measures and data description

The structured questionnaire in this study was developed based on an extensive review of empirical literature related to sensing capability (four items), knowledge sharing (four items), managerial cognitive capabilities (four items), agility (four items), and sustainable performance (four items). We utilized Likert scales ranging from strongly disagree (1) to strongly agree (7) to measure each dimension within the latent constructs, enabling a multidimensional perspective on the dynamic capabilities and sustainable performance of Tanzanian dairy microfirms [65]. In summary, the study designed a survey questionnaire that included both structured and unstructured questions. The initial draft was pretested by collecting responses from one hundred (n = 100) managers and employees across dairy microfirms in three regions: Kilimanjaro, Tanga, and Arusha. The pilot survey helped identify any ambiguities, vagueness, or confusion in the wording of the questions. Feedback from respondents during the pilot phase was invaluable in refining the questionnaire to enhance clarity and ensure consistent interpretation of the questions.

The selection of managers and employees from Tanzanian dairy microfirms as the study population is justified by their significant economic role, particularly in rural development and poverty alleviation. The dairy sector contributes substantially to Tanzania's agricultural GDP and provides essential employment and income for smallholder farmers. Additionally, these dairy microfirms face unique challenges such as market access, financial constraints, and infrastructural deficiencies, making them an ideal focus for examining how dynamic capabilities like agility, knowledge sharing, and sensing capabilities contribute to sustainable performance. Furthermore, studying this sector aligns with broader national development goals related to rural development, food security, and economic empowerment. Addressing this specific context also fills a gap in the existing literature by providing empirical evidence on the application of dynamic capabilities in Tanzanian dairy microfirms, thereby enriching the theoretical understanding of these concepts in a developing country context.

In this study, the selection of three Tanzanian regions for obtaining the sample population is pivotal due to their distinctive characteristics, which collectively provide a comprehensive understanding of the dairy microfirm landscape in Tanzania. First, these regions exhibit varying levels of infrastructural development, market integration, and access to support services, such as veterinary care and financial institutions. By selecting regions with different levels of these critical factors, the study can explore how such variations influence the dynamic capabilities of dairy microenterprises, including their agility, knowledge sharing, and sensing capabilities. Moreover, these regions represent the broader dairy sector in Tanzania, encompassing both well-established and emerging dairy-producing areas. This selection ensures that the findings are generalizable across the country and can provide insights that are relevant

to policymakers and stakeholders aiming to support the growth and sustainability of dairy microenterprises in Tanzania.

We tested the conceptual framework (**Figure 1**) using a survey questionnaire on managers and employees of dairy microfirms. The final version of the structured questionnaire was distributed to 400 managers and employees to conduct the empirical analysis. Due to the pandemic, the study employed a drop-and-collect method. Data collection occurred between June 2021 and January 2022 in multiple waves. Notably, collecting data in multiple waves was crucial to mitigating the common method variance (CMV) effect, which is important for enhancing the reliability and validity of the indicators [34]. In the first wave, conducted between April and May 2021, we collected data on the antecedent variables—knowledge sharing and sensing capability. The second wave, between June and July 2021, focused on gathering data about agility from managers and employees. In the final wave, between January and February 2022, we completed data collection by focusing on sustainable performance as the consequent variable [66].

Following the data collection, the study tested the hypotheses (**Figure 1**) using the R programming language (version 4.2.2) [67]. The rationale for using R is that it is open-source software with strong reproducible features. The study tested the conceptual framework by deploying the global model using PLS-PM, and our study added QC-PM within the R environment after installing two packages. First, we unpacked the plspm package (version 0.5.0) [68] to assess the global model for direct and indirect effects. Second, we complemented this with the QC-PM package (version 0.2) [67] to carry out the QC-PM analysis. In line with the standard procedure for QC-PM, we set the manifest variables as reflective indicators, enabling the QC-PM algorithm to iterate stepwise and reach convergence. Consequently, the study constructed quantile composite blocks using 20 manifest variables.

Validation of the QC-PM and PLS-PM was conducted through the outer and inner models. Certainly, loadings and path coefficients were estimated using quantile regressions. The study then applied a bootstrapping procedure to both the outer and inner models. Additionally, the underlying global model's inner and outer structures were estimated with 5000 bootstraps to detail standard errors and the lower and upper percentiles at a 95% confidence interval (CI). Finally, we compared the path coefficients of the global model with those of the QC-PM to address the study's first and second objectives. Furthermore, the study conducted a model quality assessment for both the global model and the QC-PM, following the suggestions by Davino et al. [28]. The internal consistency of the two models was first examined using Cronbach's Alpha, Goldstein's Rho, and Dijkstra-Henseler's Rho. For the QC-PM specifically, the study assessed its quality through pseudo-R^2 and redundancy measurements. Together, these standard metrics provided a comprehensive internal quality assessment of both the global model and the QC-PM [69].

Table A2 (Appendix) above presents the block unidimensionality and composite reliability for both the global model and QC-PM. For the global model, we used three indexes: Cronbach's Alpha, Dillon-Goldstein's Rho (DG.rho), eigenvalue, and Average Variance Extracted (AVE). The findings indicate that both Cronbach's Alpha and Dillon-Goldstein's rho are above 0.7, while AVE exceeds 0.5, meaning the indicator variance meets the necessary thresholds [70]. For the quantile model, four

index measurements were used, including Dijkstra-Henseler's Rho, to evaluate internal consistency in quantile-composite path modeling. The results show that Cronbach's Alpha, Dillon-Goldstein's Rho, and Dijkstra-Henseler's Rho are all above 0.7, confirming acceptable internal consistency and the reliability of the measurement model in both the global model and QC-PM. Additionally, the Dijkstra-Henseler Rho, with values above 0.7, further supports the reliability of the constructs [70–73]. The study concluded that the latent constructs demonstrate true reliability. Regarding the correlation matrix, the eigenvalue served as the measurement index, as presented in **Table A1** (Appendix), with the first and second eigenvalues falling within the acceptable threshold. It is fair to argue that our study's sampled data fits well with the two constructed models (PLS-PM and QC-PM), meeting the required thresholds of internal consistency.

3.3. Quantile composite-based path modelling (QC-PM)

The QC-PM is a composite analysis method that measures network relationships between observed and unobserved variables, initially proposed by Davino and Vinzi [73]. It integrates quantile regression [74] and quantile correlation within a single, unified framework [75]. As an extension of Ordinary Least Squares (OLS) regression [76], QC-PM focuses on the conditional quantiles of response variables. Meanwhile, PLS-PM converges by calculating the outer weight as a linear combination to reveal latent variables through OLS [77]. Notably, QC-PM complements the PLS-PM approach by exploring the entire dependence structure of an observed sample using quantile regression, thereby navigating variations across the full distribution of the response construct. This study employs both QC-PM and PLS-PM as dimension reduction approaches to test hypotheses (H1-H7) and uncover potential unobserved variations between dimensions of dynamic capabilities and sustainable performance. These dual dimension reduction methods are particularly robust when dealing with non-normal data [71]. QC-PM highlights how unobserved variables shift within the quantile of interest [18], while PLS-PM explores the homogeneous relationships within the study's conceptual framework (**Figure 1**). By integrating these two methods into a single, unified framework, this study provides a comprehensive explanation of the alternative relationships between dimensions of dynamic capabilities and sustainable performance.

The QC-PM method is the primary analytical approach used in this study. As outlined, QC-PM mirrors the PLS-PM algorithm (soft modeling) but replaces OLS regression with quantile regression. QC-PM follows a two-step procedure to achieve convergence. First, it computes the outer weights through iterative techniques, and then an algorithm uses these weights to develop the composites. Second, leveraging the composite estimates, the model parameters—such as loadings and path coefficients—are established [70]. The study then analyzed the model using quantile regression [77], while incorporating partial criteria at each step, similar to the PLS-PM method. QC-PM focuses on the model's conditional distribution for all involved response variables, allowing for the estimation of partial conditional quantiles. By following these QC-PM steps, our study combined the two models into a single conceptual framework (**Figure 1**) to unravel the differing relationships between the

dimensions of dynamic capabilities and the sustainable performance of dairy microfirms. This approach enabled us to precisely address the study's objectives.

4. Findings

4.1. Measurement model summary

Table A3 (Appendix) presents the initial evaluations of the quantile composite model using two indexes: loadings and communality at quantile levels of 0.25, 0.50, and 0.75. The model was constructed with reflective indicators, and the loadings were evaluated using quantile regressions. All loadings across the quantiles are above 0.7, indicating that the constructs explain at least 50% of the indicator's variance. Thus, the study demonstrates that each quantile's measurement model has acceptable reliability [72].

Figure 2 presents the measurement model summary for the global model, evaluated based on the correlations among latent variables and indicators. The figure shows that the loading scores are above 0.5, exceeding the required thresholds [16]. This indicates that the latent constructs capture at least 50% of the variation in the indicators.

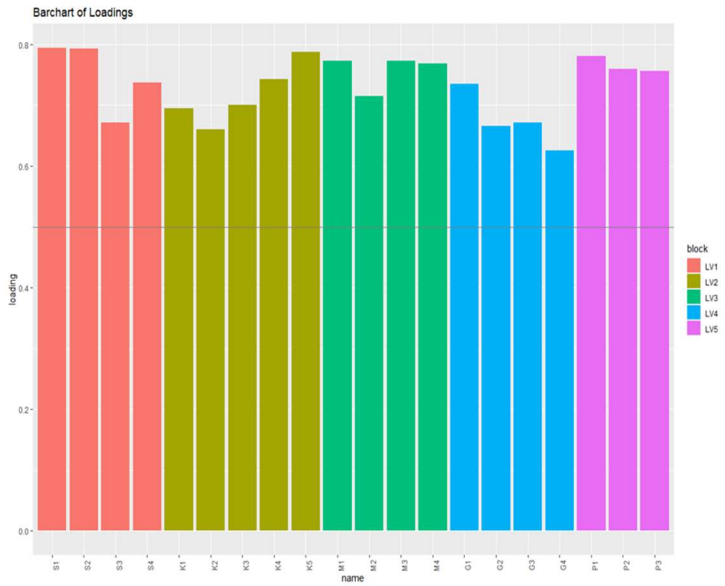

Figure 2. Measurement model summary.

4.2. Model assessment and validation

Table A4 (Appendix) presents the internal and external estimation scores assessed at quantile levels of 0.25, 0.50, and 0.75. The internal and external evaluations were conducted separately at each quantile level. To assess and validate the QC-PM model, we used three indexes: block communalities, block redundancy, and Pseudo-R^2. The findings indicate that block communalities are above 0.2, suggesting that the dimensions of dynamic capabilities have strong block communality values.

Regarding the measurement model, the study used Pseudo-R^2 to assess the variability explained by agility and sustainable performance concerning explanatory

variables such as sensing capability, knowledge sharing, and managerial cognitive capabilities. Agility showed Pseudo-R^2 values of 0.276 at the 0.25 quantile, 0.108 at the 0.50 quantile, and 0.38 at the 0.75 quantile, indicating satisfactory goodness of fit for each quantile. Similarly, sustainable performance demonstrated strong Pseudo-R^2 values of 0.125 at the 0.25 quantile, 0.161 at the 0.50 quantile, and 0.291 at the 0.75 quantile. Overall, the goodness of fit at the quantile level is significant [74]. **Table A5** (Appendix) displays the goodness of fit at the global level, with coefficient determination scores of 0.81 for agility and 0.82 for sustainable performance. Additionally, the calculated effect size (*f*) was 0.7, which is considered strong as it exceeds the threshold of 0.5 [70].

Additionally, we evaluated the endogenous blocks to illustrate the outer part of the model using redundancy measures. **Table A4** (Appendix) presents the redundancy values for agility as follows: 0.065 at the 0.25 quantile, 0.10 at the 0.50 quantile, and 0.128 at the 0.75 quantile. For sustainable performance, the redundancy values are 0.039 at the 0.25 quantile, 0.07 at the 0.50 quantile, and 0.932 at the 0.75 quantile [72]. Redundancy measures the variance explained by the observed variables corresponding to the endogenous blocks, such as agility and sustainable performance. Overall, the reliability assessment, constrained separately for each quantile, shows strong scores for both the inner and outer examinations. Consequently, the values for block communality, redundancy, Pseudo-R^2, and block redundancy are significant.

4.3. Comparison of internal structure between quantile and global levels

Table A5 (Appendix) presents the structural summary results of the tested theoretical and conceptual framework (see **Figure 1**) concerning the relationship between dimensions of dynamic capabilities and the sustainable performance of dairy microfirms. The table highlights the estimation, standard error, *p*-value (Pr), 95% lower confidence limit, and 95% upper confidence limit of the estimated path coefficients for the QC-PM model. It also includes the lower and upper boundaries obtained through bootstrap analysis at a 95% confidence interval for the classical PLS-PM model.

The summary directs effects; the findings show that knowledge sharing has a small positive coefficient effect on sustainable performance (H1a: β = 0.250: BCI 0.025 = 0.072; BCI 0.097 = 0.431). Thus, it supports H1a that knowledge sharing positively affects sustainable performance. Interestingly, the beta values at the quantile levels illustrated strong coefficient variations between lower and higher quantiles; certainly, at the quantile levels, the relationship is insignificant (H1b: θst0.25: β = 0.109; θnd0.5: β = 0.140; θrd0.75: β = 0.014). Thus, H1b has been rejected because unobserved differences in knowledge sharing positively impact sustainable performance. The link between sensing capability and sustainable performance has moderately significant positive beta values of (H2a: β = 0.376; BCI 0.025 = 0.257; BCI 0.097 = 0.594). Therefore, it supports H2a that sensing capability positively affects sustainable performance. At the same time, the findings show unobserved positive significant coefficient variations from lower to higher quantiles (H2b: θst0.25: β = 0.369***; θnd0.5: β = 0.435***; θrd0.75: β = 0.412*) between sensing capability and sustainable performance. Thus, it supports H2b that unobserved differences in

sensing capability positively impact sustainable performance. Furthermore, the path between managerial cognitive capabilities and sustainable performance has a lower significant coefficient value and is insignificant because it contained zero (H3a: β = 0.122: BCI 0.025 = −0.020; BCI 0.097 = 0.290). For that reason, it rejected H3a that managerial cognitive capability is positively associated with sustainable performance. Additionally, the same link has shown a strong, significant beta variation between lower and higher quantiles (H3b: θst0.25: β = −0.252; θnd0.5: β = 0.0.199; θrd0.75: β = −0.040). Thus, H3b has been rejected because unobserved differences in managerial cognitive capabilities positively impact sustainable performance. The link between agility and sustainable performance has significant positive beta values of (H5a: β = 0.217; BCI 0.025 = 0.074; BCI 0.097 = 0.370). Therefore, it confirmed H5a that agility is positively associated with sustainable performance. Furthermore, the same link demonstrated strong variations of coefficient score between lower and higher quantiles (H5a: θst0.25: β = 0.393***; θnd0.5: β = 0.350**; θrd0.75: β = 0.433***). Thus, it supports H5b. Unobserved differences in agility positively impact sustainable performance.

Regarding the mediation summary (Indirect effects), agility mediates the relationship between sensing capability, knowledge sharing, and managerial cognitive capabilities on sustainable performance. The findings highlight that agility has a significant mediation effect in the relationship between sensing capability and sustainable performance with beta values of (H4a: β = 0.425; BCI 0.025 = 0.257; BCI 0.097 = 0.594). It confirmed H4a that agility mediates the effects of knowledge sharing on sustainable performance. In the same breath, there are strong variations of coefficient values between lower to higher quantiles (H4b: θst0.25: β = 0.293**; θnd0.5: β = 0.407***; θrd0.75: β = 0.303***). Thus, it supported H4b that agility mediates the unobserved difference effects of knowledge sharing on sustainable performance. Moreover, findings showed that agility has significant positive mediation effects in the relationship between knowledge sharing and sustainable performance with a coefficient value of (H4c: β = 0.290: BCI 0.025 = 0.128; BCI 0.097 = 0.471) and confirmed H4c agility mediates the effects of sensing capability on sustainable performance. At the same time, the findings show coefficient values changed between lower and higher quantiles (H4d: θst0.25: β = 0.200*; θnd0.5: β = 0.214**; θrd0.75: β = 0.224*). Therefore, it supported H4d that agility mediates the unobserved differences effects of sensing capability on sustainable performance. Agility has also positively mediated the relationship between managerial cognitive capabilities and sustainable performance with small beta values of (H4e: β = 0.222: BCI 0.025 = 0.082; BCI 0.097 = 0.630). Therefore, it supported H4e that agility mediates the effects of managerial cognitive capabilities on sustainable performance. At the same time, at the quantile levels, the beta coefficients significantly changed from lower to higher quantiles (H4f: θst0.25: β = 0.232**; θnd0.5: β = 0.214***; θrd0.75: β = 0.180*). Thus, findings supported H4f that agility mediates the effects of unobserved differences in managerial cognitive capabilities on sustainable performance. In summary, the findings confirm a significant unobserved difference in the inner structure of relationships among knowledge sharing, sensing capability, managerial cognitive capabilities, agility, and sustainable performance.

4.4. Types and magnitude of unobserved mediation effects

Figures 3–5 present the mediation analysis and detail the type and magnitude of agility's mediating unobserved differences between knowledge sharing, sensing capability, and managerial cognitive capability on sustainable performance, based on the results from **Table A5** (Appendix). To determine if the mediation paths (a*b) are significant, we bootstrapped the sample. **Table A5** (Appendix) shows that both paths a** and b** are statistically significant across the three quantiles, but the type and magnitude of mediation remain unclear. Therefore, the study examined the mediation effects to clarify the role of agility as a mediator. The direct relationship between knowledge sharing and sustainable performance (C') was found to be non-significant (*t*-value = 1.05; Sobel test: *t* = 2.42**), indicating that the relationship is fully mediated by agility. Thus, agility demonstrates full mediation effects in this context. Conversely, agility exhibited complementary partial mediation effects in the relationship between sensing capability and sustainable performance, as the direct effect (C') is significant and both paths a and b are positively oriented (C': *t* = 7.87**; Sobel test: *t* = 3.05**). Additionally, agility displayed competitive partial mediation effects in the relationship between managerial cognitive capability and sustainable performance. Although paths a and b are significant, the direct effect (C') is not significant and shows a negative direction (C': *t* = −2.89; Sobel test: *t* = 3.29**).

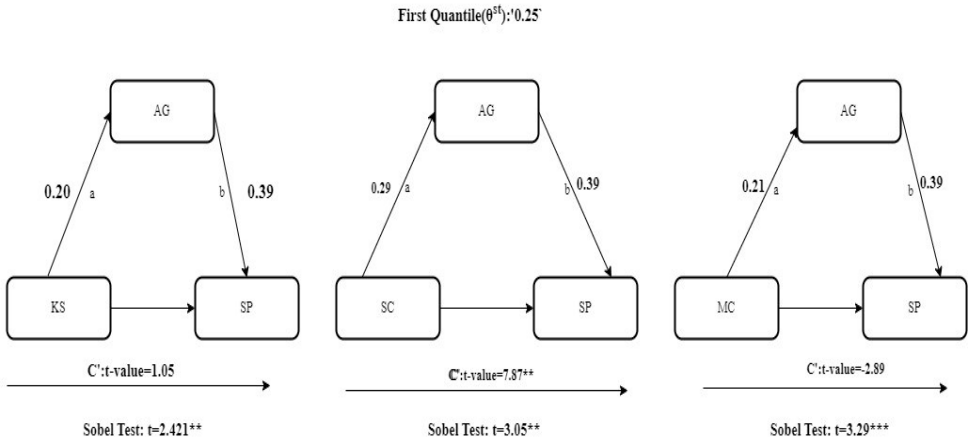

Figure 3. Mediation analysis at the first quantile (θ^{st}).

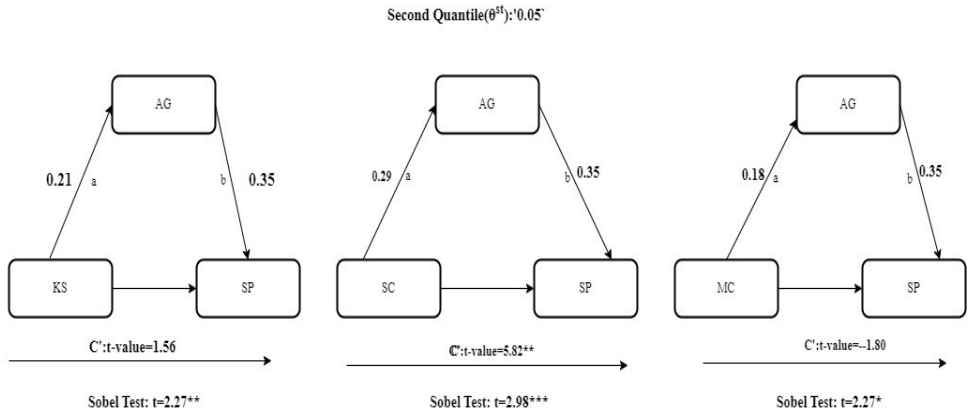

Figure 4. Mediation analysis at the second quantile (θ^{nd}).

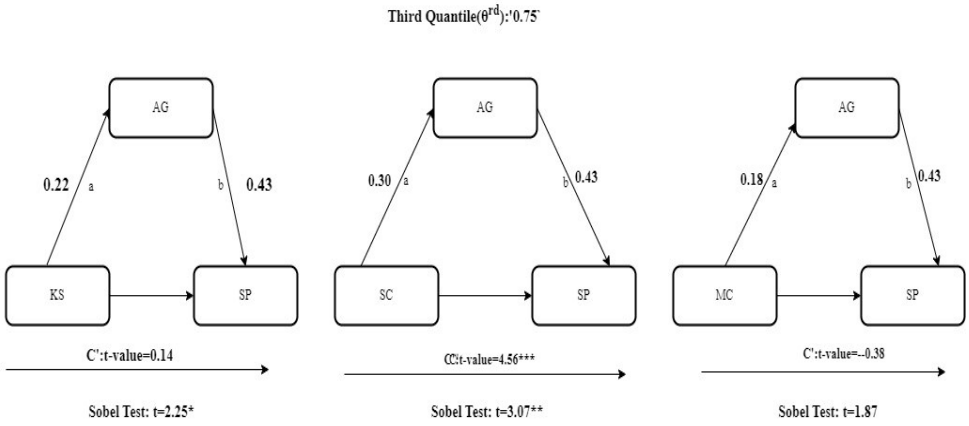

Figure 5. Mediation analysis at the third quantile (θ^{rd}).

Figure 4 illustrates the type and magnitude of mediation at the second quantile. The findings indicate that agility fully mediates the relationship between knowledge sharing and sustainable performance, as the indirect paths (a*b) are statistically significant, although the direct path (C') is not significant (*t*-value = 1.56; Sobel test: *t* = 2.27**). The second path, similar to the results in the first quantile, shows that agility serves as a complementary partial mediator in the relationship between sensing capability and sustainable performance (C': *t*-value = 5.82**; Sobel test: *t* = 2.98**). Additionally, at the second quantile, agility also fully mediates the relationship between managerial cognitive capability and sustainable performance (C': *t*-value = −1.80; Sobel test: *t* = 2.27**), which aligns with the results observed in the first quantile.

Figure 5 illustrates the mediation analysis at the third quantile, revealing that agility fully mediates the relationship between knowledge sharing and sustainable performance (C': *t*-value = 0.14; Sobel test: *t* = 2.25**, indicating statistical significance). Although the direct path (c') is not significant, the indirect effects (a*b) are statistically significant. Furthermore, the findings confirm that agility has a complementary partial mediation effect on the relationship between sensing capability and sustainable performance (C': *t*-value = 4.56; Sobel test: *t* = 3.07**, also indicating statistical significance). However, the study did not confirm mediation effects for the final link, as the direct effect (c') and Sobel test statistics were not supportive. For additional details, Appendix I (quantile correlations) presents the quantile correlation (QC) estimates, with *P*-values for all loadings being statistically significant according to the BCI at 95% confidence intervals (lower and upper).

5. Discussion

The main purpose of the study was to investigate the effects of unobserved variations in dynamic capabilities on the sustainable performance of Tanzanian dairy microfirms. Additionally, our study examined the unobserved mediating effects of agility in the relationship between knowledge sharing, sensing capability, and managerial cognitive capability on sustainable performance. The study draws on the KBV logic, suggesting that there are relationships between dimensions of dynamic capabilities that support the sustainable performance of dairy microfirms. Our study

also presents theoretical implications that stem from the tested conceptual framework (**Figure 1**) and thoroughly documents the study's findings.

Our approach is one of the first empirical studies to explicitly test a conceptual framework developed from KBV theory, applying it to the dimensions of dynamic capabilities and providing insights into dairy microfirms. The study not only demonstrates the direct effects of dynamic capabilities on sustainable performance but also highlights the significance of unobserved variations and the role of agility in mediating the relationships between knowledge sharing, sensing capability, and sustainable performance [56]. Specifically, the study found significant direct effects of sensing capability, knowledge sharing, and agility on the sustainable performance of dairy microfirms in Tanzania [1]. These findings suggest that dairy microfirms need to strategically enhance their ability to sense market trends, share knowledge, and remain agile in response to changing conditions [59]. This integrated approach can drive innovation, improve responsiveness to disruptions, and foster a culture of continuous learning, all essential for sustaining long-term performance in a competitive and volatile market [61]. Moreover, the insights provide valuable guidance for managers, employees, and owners in the dairy industry, emphasizing the importance of supporting microfirms through training, market intelligence, and incentives for sustainable practices to position sustainability as a competitive advantage.

Second, the study confirms that the unobserved effects of knowledge sharing, sensing capability, and managerial cognitive capabilities significantly influence the sustainable performance of Tanzanian dairy microfirms. These findings underscore the importance of intangible and often overlooked factors in driving long-term success for microfirms in developing economies like Tanzania. Managers and employees must recognize that both visible actions and underlying cognitive processes and knowledge dynamics are crucial for achieving sustainable performance [16]. This insight suggests that dairy microfirms should invest in developing and nurturing these capabilities within their management teams, fostering an environment that encourages knowledge sharing and enhances the ability to sense and respond to market changes [25]. Additionally, these findings may prompt further research into how these unobserved effects can be better measured and leveraged, opening new avenues for improving the sustainability and performance of microfirms.

Finally, we found that agility among managers and employees fully and partially mediates the unobserved differences between knowledge sharing, sensing capability, and managerial cognitive capability in supporting the sustainable performance of dairy microfirms in Tanzania. This underscores the critical role of agility in effectively translating these capabilities into tangible, sustainable outcomes [22]. Our findings suggest that even if a dairy microfirm has strong knowledge-sharing practices, sensing capabilities, and managerial cognitive skills, these alone may not directly lead to sustainable performance without agility [23]. Therefore, dairy microfirms should prioritize cultivating agility within their employees and management teams, integrating it into their organizational culture and processes to enhance responsiveness and adaptability.

In summary, our study opens the "black box" of dynamic capabilities and highlights the idiosyncratic nature of these capabilities. The results reveal varying

degrees of impact from sensing capability, knowledge sharing, managerial cognitive capabilities, and agility on the sustainable performance of dairy microfirms. This suggests that dairy microfirms possess strong, difficult-to-imitate competencies [78]. Systematic changes in resources are crucial, as they enable dairy microfirms to accumulate experience and knowledge in managing heterogeneity, which in turn helps in developing common resources that enhance dynamic capabilities and competitive advantages. Our study posits that the idiosyncratic nature of dynamic capabilities in Tanzanian dairy microfirms stems from multiple sources among managers and employees [26]. We argue that combining differentiation strategies to address heterogeneity is essential for developing evolutionary dynamic capabilities and enhancing managerial competencies. By doing so, dairy microfirms can achieve stability and resilience in the face of environmental changes while potentially reducing costs.

6. Conclusion and implication

6.1. Conclusion

The study provides significant insights into the dynamics of capabilities within Tanzanian dairy microfirms, particularly focusing on the roles of sensing capability, knowledge sharing, managerial cognitive capabilities, and agility in achieving sustainable performance. By uncovering the unobserved effects and demonstrating how agility mediates the relationships between these capabilities and sustainable performance, the research highlights the complexity and importance of dynamic capabilities in this context.

Key Findings:

1) Unobserved Effects: The study confirms that the unobserved effects of knowledge sharing, sensing capability, and managerial cognitive capabilities significantly influence sustainable performance. These factors, though often intangible and overlooked, are crucial for the long-term success of dairy microfirms.
2) Role of Agility: Agility among managers and employees is found to be a critical mediator. It not only fully but also partially mediates the relationship between knowledge sharing, sensing capability, and managerial cognitive capability with sustainable performance. This emphasizes that agility is essential in translating these capabilities into practical, sustainable outcomes.
3) Strategic Implications: Dairy microfirms must strategically enhance their agility, alongside developing their knowledge-sharing practices, sensing capabilities, and managerial cognitive skills. This integrated approach can drive innovation, improve responsiveness to disruptions, and foster a culture of continuous learning.
4) Competitive Advantage: The study suggests that dairy microfirms possess unique competencies that are difficult to imitate, giving them a competitive edge. Systematic resource changes are vital for accumulating experience and knowledge, which helps in managing heterogeneity and developing common resources that contribute to dynamic capabilities and competitive advantages.

5) Practical Recommendations: Managers and employees should focus on cultivating agility within their teams and integrating it into the organizational culture and processes. This will enhance their ability to respond to environmental changes effectively and improve overall performance.

Conclusively, our study underscores the importance of both visible and intangible factors in driving sustainable performance. It suggests that a holistic approach, combining strong dynamic capabilities with high agility, is essential for dairy microfirms to thrive in a competitive and volatile market.

6.2. Study implication, limitation, and future research directions

Besides the theoretical contributions mentioned above, the study also highlights managerial, practical, and policy implications. From a managerial perspective, our study provides valuable insights for managers, employees, and owners of dairy microfirms in Tanzania on how to effectively manage differences in dynamic capabilities to enhance sustainable performance. For instance, to improve dynamic capabilities, dairy microfirms should leverage unique resources accumulated through knowledge sharing, sensing capabilities, managerial cognitive skills, and agility to address underlying differences that impact sustainable performance. In terms of practical contributions, the findings indicate that differences in dynamic capabilities can enhance sustainable performance, with agility partially mediating these differences. Therefore, owners of dairy microfirms should streamline resources while considering individual capabilities to effectively implement sensing capabilities, knowledge sharing, and managerial cognitive skills. This approach can help balance growth and maintain a sustainable competitive advantage. Furthermore, the study's empirical results reveal both strong and weak direct and indirect effects. Managers and owners of dairy microfirms can use these insights to enhance agility and strengthen their organizational structure, thereby better supporting dynamic capabilities and improving sustainable performance.

Our study findings offer two key policy insights regarding the dimensions of dynamic capabilities and their impact on the sustainable performance of Tanzanian dairy microfirms. First, resource allocation should be tailored to manage each aspect of sensing capability, knowledge sharing, managerial cognitive capabilities, and agility to enhance sustainable performance. Policymakers can assist owners in optimizing the extension and reconfiguration of physical, natural, human, financial, and intellectual assets to minimize the differential effects of dynamic capability dimensions on sustainable performance. Second, the allocation of resources between managers and employees should align with quantile structural variations to improve sustainable performance. Both internal and external resources can create significant spillover effects, fostering better communication and collaboration. Establishing a robust communication infrastructure is crucial for effectively developing dynamic capabilities and enhancing sustainable performance.

This study has several limitations. While the findings confirm that differences in dimensions of dynamic capabilities significantly influence the sustainable performance of Tanzanian dairy microfirms, the study's conceptual framework utilized a single mediator and tested hypotheses at the individual level. This approach

makes it challenging to establish causality with cross-sectional data analysis. To enhance the understanding of dynamic capabilities in dairy microfirms, future research should explore causality between dynamic capability dimensions and sustainable performance at the business unit level and consider antecedents such as alliance transformation. Additionally, the study's conceptual framework is limited to the firm level; future research could extend this framework beyond firm boundaries to verify the validity and reliability of the hypotheses. Furthermore, this study faces a major drawback due to the ripple effects of the COVID-19 pandemic. Data collection occurred at a peak of the pandemic, during which local governments imposed strict restrictions to curb the virus's spread. Consequently, this led to significant delays in both data collection and analysis. Additionally, the pandemic impacted the manuscript development, as the writing and revisions were conducted remotely among the authors.

Future research areas have been built following the findings of this study. First, conducting longitudinal studies would help establish causality between dynamic capabilities and sustainable performance by tracking changes over time. Therefore, expanding the research to the business unit level could provide more detailed insights into how these dimensions of dynamic capabilities impact sustainable performance across different operational contexts. Additionally, investigating antecedents such as alliance transformation could offer a broader perspective on the factors influencing dynamic capabilities and sustainability. Likewise, extending the conceptual framework to include cross-border and multi-firm studies would validate the findings in diverse contexts and assess their generalizability. Last, addressing the specific impacts of the COVID-19 pandemic on dynamic capabilities and performance is also crucial, as it would shed light on how firms adapted and the long-term effects of these adaptations. In summary, combining quantitative methods with qualitative approaches could provide deeper insights into the nuances of dynamic capabilities for sustainable performance.

Author contributions: Conceptualization, MB and ZM; methodology, MB; software, ML; validation, MB, ZM and ML; formal analysis, MB; investigation, ZM; resources, MB; data curation, ML; writing—original draft preparation, MB; writing—review and editing, ML; visualization, ZM; supervision, ML; project administration, ZM; funding acquisition, MB, ZM and ML. All authors have read and agreed to the published version of the manuscript.

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Appendix

Table A1. Descriptive analysis.

Indicators	Mean	Sd	Median	Trimmed	Skew	Kurtosis	Se
S1	3.11	1.79	3	2.95	0.61	−0.67	0.08
S2	3.39	1.72	3	3.31	0.30	−0.91	0.08
S3	3.24	1.78	3	3.10	0.50	−0.69	0.08
S4	3.19	1.62	3	3.06	0.47	−0.42	0.07
K1	3.24	1.76	3	3.12	0.47	−0.78	0.08
K2	3.42	1.74	3	3.33	0.35	−0.82	0.08
K3	3.28	1.68	3	3.17	0.37	−0.69	0.08
K4	3.75	1.93	4	3.69	0.12	−1.16	0.09
K5	3.42	1.72	3	3.32	0.41	−0.67	0.08
M1	3.41	1.76	3	3.29	0.46	−0.71	0.08
M2	3.19	1.72	3	3.06	0.44	−0.74	0.08
M3	3.48	1.84	3	3.38	0.36	−0.90	0.08
M4	3.62	1.85	4	3.53	0.27	−0.87	0.08
G1	3.51	1.92	3	3.39	0.36	−1.02	0.09
G2	3.28	1.85	3	3.14	0.38	−0.91	0.08
G3	3.04	1.75	3	2.86	0.66	−0.52	0.08
P1	3.13	1.72	3	2.98	0.53	−0.63	0.08
P2	3.18	1.76	3	3.03	0.46	−0.72	0.08
P3	3.14	1.77	3	2.99	0.45	−0.86	0.08

Note: Ind = indicators, sd = standard deviation, trimm = trimmed mean, se = standard error of mean, skew = skewness.

Table A2. Internal consistency of the global model and QC-PM.

Global model						Quantile composite-based path modeling				
Constructs	C.alpha	DG.rho	Eig.1st	Eig.2nd	AVE	C. alpha	DG. rho	Rho. A	Eig. 1st	Eig. 2nd
Sensing	0.846	0.897	2.74	0.617	0.564	0.745	0.790	0.746	2.121	0.021
Knowledge	0.785	0.812	2.17	0.943	0.517	0.846	0.896	0.844	2.740	0.616
Managerial	0.867	0.802	2.13	0.965	0.574	0.902	0.931	0.945	3.096	0.437
Agility	0.794	0.816	2.18	0.927	0.500	0.880	0.716	0.791	1.570	0.388
Sustainable	0.720	0.832	2.34	0.969	0.587	0.798	0.822	0.804	2.321	0.989

Note: C. alpha=Cronbach's alpha, DG. rho=Dillon-Goldstein's rho, rho. A=Dijkstra-Henseler rho, E. 1st = first eigenvalue value, E. 2nd = second eigenvalue value, AVE = Average Variance Extracted.

Table A3. Estimation of outer loadings at quantile levels 0.25, 0.50 and 0.75.

Indicators	0.25	0.5	0.75
Knowledge K1	0.7362	0.7651	0.7666
Knowledge K2	0.7414	0.7382	0.6746
Knowledge-K3	0.7509	0.8067	0.8073
Knowledge-K4	0.8843	0.7952	0.8415
Sensing-S1	0.7651	0.7884	0.8478

Table A3. (*Continued*).

Indicators	0.25	0.5	0.75
Sensing-S2	0.8324	0.8136	0.8174
Sensing-S3	0.5560	0.7351	0.7732
Sensing-S4	0.7500	0.7708	0.7257
Manager-M1	0.8151	0.7913	0.7737
Manager-M2	0.7916	0.7245	0.7863
Manager-M3	0.8238	0.8290	0.8104
Manager-M4	0.7617	0.7858	0.7456
Agility-G1	0.7713	0.8323	0.9321
Agility-G2	0.6280	0.7287	0.8179
Agility-G3	0.5190	0.6881	0.7480
Sustain-P1	0.7805	0.7819	0.9127
Sustain-P2	0.7371	0.7628	0.7620
Sustain-P3	0.7284	0.7612	0.8434

Notes: SC = sensing capability, KS = knowledge sharing, MC = managerial cognitive capabilities, AG = agility, SP = sustainable performance.

Table A4. Assessing inner and outer model summary.

Communality				**$pseudo. R2**		
	0.25	**0.5**	**0.75**	**Agility**		
Knowledge-K1	0.2836	0.3512	0.3861	**0.25**	**0.5**	**0.75**
Knowledge-K2	0.2597	0.3147	0.2870	0.276	0.108	0.340
Knowledge-K3	0.2523	0.3786	0.4152	Sustainable		
Knowledge-K4	0.3916	0.4168	0.4571	**0.25**	**0.5**	**0.75**
Sensing-S1	0.3101	0.4548	0.4779	0.125	0.161	0.291
Sensing-S2	0.4234	0.4380	0.4282			
Sensing-S3	0.0625	0.2839	0.3767			
Sensing-S4	0.3371	0.3429	0.2930			
Managerial-M1	0.3209	0.4066	0.3989			
Managerial-M2	0.2143	0.3381	0.4121			
Managerial-M3	0.3650	0.4326	0.4130			
Managerial-M4	0.3585	0.3863	0.4130			
Agility-G1	0.4278	0.4052	0.4271			
Agility-G2	0.1999	0.3388	0.3592			
Agility-G3	0.0529	0.2549	0.3411			
Sustainable-P1	0.3392	0.4075	0.4867			
Sustainable-P2	0.3155	0.4524	0.3564			
Sustainable-P3	0.3001	0.4602	0.4291			

Table A4. (*Continued*).

$Block Communality					
	Knowledge	Sensing	Managerial	Agility	Sustainable
0.25	0.2968	0.2833	0.3147	0.2269	0.3182
0.5	0.3653	0.3799	0.3909	0.3329	0.4401
0.75	0.3864	0.3940	0.4093	0.3758	0.4241

$Redundancy				**$Block Redundancy**		
	0.25	**0.5**	**0.75**	Agility		
Agility-G1	0.1181	0.1319	0.1455	**0.25**	**0.5**	**0.75**
Agility-G2	0.0552	0.1103	0.1224	0.062	0.108	0.128
Agility-G3	0.0146	0.0830	0.1162			
Sustainable-P1	0.0426	0.0657	0.1070	Sustainable		
Sustainable-P2	0.0396	0.0729	0.0783	**0.25**	**0.5**	**0.75**
Sustainable-P3	0.0377	0.0741	0.0943	0.0399	0.070	0.932

Table A5. Estimated path coefficients at the quantile levels and global model.

$boot. path $`0.25` (*θ* st)						
Indirect	***β***	**Std**	***t*-value**	**Pr(>|t|) |**	**Low 0.95%**	**Upper 0.95%**
Know → Ag	0.2000	0.0870	2.2971	0.0220*	0.0289	0.3710
Sens → Ag	0.2938	0.0933	3.1473	0.0018**	0.1104	0.4772
Mana → Ag	0.2327	0.0731	3.1836	0.0015**	0.0891	0.3763
Direct						
Know → Su	0.1097	0.1081	1.0155	0.3104	−0.1026	0.3221
Sens → Su	0.3694	0.0733	5.0433	0.0000***	0.2255	0.5134
Mana → Su	−0.2523	0.0896	−2.8156	0.0051**	−0.4283	−0.0762
Agil → Su	0.3935	0.0499	7.8798	0.0000***	0.2953	0.4916
Indirect	$boot. path $`0.5` (*θ* nd)					
Know → Ag	0.2145	0.0729	2.9441	0.0034**	0.0713	0.3576
Sens → Ag	0.4073	0.1016	4.0074	0.0001***	0.2076	0.6070
Mana → Ag	0.2142	0.0600	3.5673	0.0004***	0.0962	0.3322
Direct						
Know → Su	0.1402	0.0898	1.5607	0.1193	−0.0363	0.3166
Sens → Su	0.4359	0.0749	5.8232	0.0000***	0.2888	0.5830
Mana → Su	−0.1994	0.1106	−1.8039	0.0719	−0.4167	0.0178
Agil → Su	0.3503	0.1059	3.3089	0.0010**	0.1423	0.5583
Indirect	$boot. path $`0.75` (*θ* nd)					
Know → Ag	0.2241	0.0981	2.2839	0.0228*	0.0313	0.4169
Sens → Ag	0.3033	0.0875	3.4649	0.0006***	0.1313	0.4752
Mana → Ag	0.1803	0.0913	1.9752	0.0488*	0.0009	0.3597

Table A5. (*Continued*).

$boot. path $`0.25` (*θ* st)						
Direct						
Know → Su	0.0140	0.0997	0.1403	0.8885	−0.1819	0.2099
Sens → Su	0.4128	0.0905	4.5606	0.0000***	0.2349	0.5906
Mana → Su	−0.0409	0.1060	−0.3860	0.6997	−0.2491	0.1673
Agil → Su	0.4333	0.0851	5.0906	0.0000***	0.2661	0.6006
Internal structural summary at the global level (95CI)						
Indirect	**Estimates**	**Std.**	**0.025**	**0.097**	**Predictive scores**	
SC → AG	0.425	0.426	0.257	0.594	R^2 Agile = 0.28	
KS → AG	0.290	0.291	0.128	0.471	R^2 SP = 0.58	f = 0.7
MC → AG	0.222	0.222	0.082	0.360	GoF = 0.46	
Direct						
SC → SP	0.376	0.373	0.157	0.573		
KS → SP	0.250	0.247	0.072	0.431		
MC → SP	0.122	0.128	-0.020	0.290		
AG → SP	0.217	0.217	0.074	0.370		

Note: std. = standard errors, Pr = *P*-values, LCL = lower confidence limit at 95%, β = Coefficient, UCL = 95% upper confidence limit, R2 = coefficients determination, GoF = Goodness of the fit improvement index, *, **, &***, implies significance at $p < 0.05$, $p < 0.01$, $p < 0.001$, BCI = bootrap confidence intervals.

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Article

Brown vs green energy sources and resource productivity: The role of human capital and technology transfer in developing economies

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Abstract: This study determined the impacts of non-renewable and renewable energy consumption on natural resource productivity alongside human capital and technology transfer roles for 40 selected developing economies. The study relied on a dataset sourced between 1991 and 2021. The study applied the method of moments quantile regression (MMQREG) procedure for the analyses while ensuring inferential robustness through the fully modified ordinary least squares (FMOLS), dynamic OLS (DOLS), and Driscoll-Kraay (D-K) methods. Empirically, the study revealed that an increase in brown energy consumption exhausted resource productivity from the lower to the upper quantiles. In contrast, green energy utilisation enhanced resource productivity from the lower to the higher quantiles. Also, while human capital adversely affected resource productivity for both energy means, technology transfer positively impacted it from the lower to the upper quantiles. Likewise, inferences from the DOLS, FMOLS, and D-K techniques revealed similar findings. However, despite non-renewable energy being the dominant means of energy in these developing economies, the size of its adverse impact on resource productivity falls short of the increasing effect of renewable energy across all quantiles. Also, the magnitude of the negative impact of human capital on resource productivity is marginally more substantial with non-renewable energy. In contrast, the robustness of the enhancing impact of technology transfer is slightly more with renewable energy.

Keywords: non-renewable energy; renewable energy; economic growth; human capital; technology; developing economies
JEL Classification: O47; Q2; Q32

1. Introduction

At no particular point has climate change been a critical threat to life's existence as now. Globally, its impact is significantly revealed in changing atmospheric conditions, rising sea levels and distortion of landscapes. Climate change is associated with the enormous utilisation of fossil/brown energy sources such as oil, natural gas, and coal. These energy sources are pivotal in nations' economic prosperity, as energy consumption is critical for economic growth. Consequently, economies desiring to expand their productivity and output require more energy consumption. However, the quest for more energy to accelerate economic output continues to grow the quantum of world greenhouse gas (GHG) emissions [1–7]. Carbon dioxide (CO_2) emissions constitute the lead contributor to GHG emissions and aid the rise in global warming [8–11].

Energy utilisation is a foremost requirement for advancing economic development since it contributes significantly to producing jobs, transportation, commerce, and agriculture [12]. Thus, energy is needed for poverty eradication and,

by extension, sustainable human development [13,14]. For a lengthy time, brown energy sources served as triggers of economic prosperity. Hence, their demand remains swift even in the last decades for guaranteeing economic and social developments. For instance, the world's energy demand rose from 107 to 595 exajoules between 1991 and 2021 [15]. Although the proportion of conventional energy sources in total energy demand declined marginally from 86.5% to 82.3% between 1991 and 2021, renewable sources grew from 7.3% in 1991 to 13.5% in 2021 [16]. Nevertheless, brown energy sources still account for over 80% of global energy requirements in 2021.

Furthermore, the world's reliance on traditional energy sources has produced various worldwide challenges, the most prominent being the environmental harm of oil, coal, and natural gas, energy price shocks, energy depletion rate, supply security and independence [12]. These issues force economies to transit their reliance from non-renewable sources to renewable/green energy sources [17]. Thus, in the growing energy demand in economies, developed and developing countries are gravitating towards exploring green energy sources [18,19]. These green energy sources responsible for nominal ecological degeneration include solar, wind, hydrothermal, waves, geothermal heat, bio-fuel, hydrogen, etc.

Aside from the consequential impact of energy consumption on economic productivity, human capital and technological development are needed. Hence, developing nations have been trying to advance on these front to boost their industrialisation process for better production of goods and services [20–22]. However, many developing economies still struggle with the needed human capital and technology for efficient resource utilisation [23]. Thus, the crucial challenges of high unemployment, poverty, inflation, weak per capita, and sluggish industrialisation persist. Surviving with these challenges means the more the efforts to promote production and income growth, the more the intensity of natural resource use, which can accelerate resource depletion than their natural regeneration rate. Also, the phenomenon aggravates environmental debasement, which triggers global warming.

Several extant literatures provide evidence of the significance of energy, technology, and human capital for economic growth [23,24]. However, few studies have considered these factors on resource productivity, particularly for developing economies. Thus, this study expands the literature on this front. Higher production in developing countries demands more natural resource intensity, and the nature of energy adopted, combined with the available human and technological resources, can either exacerbate or mitigate the depletion rate of natural resources for output growth.

Hence, the primary objective of this study is to compare the effects of non-renewable and renewable energy consumption on natural resource productivity, alongside the roles of human capital and technology transfer for 40 selected developing economies. Aside from the fact that this study chose these countries due to data availability and completeness, they comprise over two-thirds of the world's population and economy. For instance, the world's gross domestic product (GDP) in 2022 is $101.6 trillion, and 67.5% ($68.6 trillion) of this sum belongs to developing economies [25]. This category's five largest developing economy include China, India, Russia, Iran, and Brazil, with $18.3 trillion, $3.5 trillion, $2.1 trillion, $2 trillion, and $1.9 trillion, respectively [25]. Furthermore, developing nations consume over

half of the world's energy but have significantly weak per capita incomes [22,26]. Energy demand in developing countries has doubled in almost two decades and is estimated to rise by another 30% in the next two decades [27]. Their energy utilisation increasingly influences the global energy landscape, including trade and investment flows and climate change dynamics. Consequently, the intense resource utilisation for economic growth in developing economies, the applied energy source, the level of technological advancement, and human capital development are crucial for the sustainable use of natural resources for development.

This research relied on a dataset sourced between 1991 and 2021. For inferential robustness, this study applied the fully modified ordinary least squares (FMOLS), dynamic OLS (DOLS), Driscoll-Kraay (D-K), and the method of moments quantile regression (MMQREG) techniques for the analyses. Since the economic development of the selected countries is not the same despite their classification as developing economies, the MMQREG approach is appropriate because it captures the distributional heterogeneity of the subject matter by integrating fixed effects (FE). Thus, the method allows for heterogeneous nexus between the dependent and regressor variables at distinct conditional quantile distributions, which conventional mean regressions might ignore. Empirically, the study demonstrated that increasing brown energy utilisation diminishes resource productivity from the lower to the upper quantiles. In contrast, by accelerating green energy utilisation, resource productivity is improved and is evident from the lower to the higher quantiles. Also, while human capital adversely affected resource productivity for both energy sources, technology transfer positively impacted it from the lower to the upper quantiles. Likewise, estimates from the DOLS, FMOLS, and D-K methods echoed these findings.

The rest of the research reveals Section 2 as the literature section; Section 3 as the research's data and method; Section 4 as the study outcomes and discussion; Section 5 as the concluding remarks.

2. Literature review

2.1. Theoretical review

This study's brief theoretical exposition is grounded in the endogenous growth theory, which infers that human capital, innovations, and knowledge are the fundamental propellers of economic growth as against physical investments [28,29]. The endogenous growth premise encourages the convergence of economies through the spread of technology [30,31]. It is a phenomenon where developing nations gradually catch up to developed economies regarding technology. One endogenous component that connects to technology is energy. Today's equipment mostly thrives on the availability of usable energy to function. Hence, the more energy employed alongside well-equipped human capital, the better the economy's productivity. This assertion of the endogenous model validates the law of energy conversion that "no production process can be driven without energy conversion". However, energy is not the only form of technology application used in the production process. There are other forms in hard and software which are also vital components to ensure the application of technology at whatever level of the production process. The energy transformation from an unusable state into a usable one is enormously technology-driven. Also, the

more efficient the energy source, the greater the capital required for production. Thus, significant expenditures in the energy sector are needed for any economy to achieve efficiency in energy production.

2.2. Empirical review

The scarcity of studies on the role of energy sources, human capital, and technological advancement on resource productivity led this study to review other related literature.

2.2.1. Economic output-energy sources relationship

By applying the DOLS and FMOLS techniques, Rahman and Velayutham [32] found that using renewable and non-renewable energy positively impacted the economic growth of South Asian nations. In contrast, Maji and Suleiman [33] used panel DOLS for 15 West African countries and revealed a deflating effect of renewable energy on economic growth. Similarly, in a selected African study for oil-producing economies, Awodumi and Adewuyi [34] demonstrated with the use of a panel non-linear autoregressive distributed lag (NARDL) model and submitted that after exceeding a particular threshold, developing nations experience a positive impact of renewable energy consumption on economic growth; but before then, it is adverse. Taskim et al. [35] employed the FMOLS and DOLS approaches and found that renewable energy positively affected green economic growth for OECD countries. Likewise, Shabbaz et al. [36] used the FMOLS and DOLS methods. They reported that although renewable and non-renewable fuels affected economic prosperity, renewable energy had the most influence across the 38 energy-consuming economies considered by the study. Similarly, Saidi and Omri [37] used FMOLS and VECM and reported that renewable energy promoted economic output in the 15 world's largest consumers of renewable energy. Chen et al. [38] used a threshold model for 103 countries and found an increasing effect of renewable energy on economic output in OECD economies but an insignificant impact in developed countries.

Also, Anser et al. [39] demonstrated by using a vector error correction method (VECM) that renewable energy has a blessing effect on the economic expansion of South Asian countries. Similarly, Baz et al. [40] applied NARDL and asymmetric causality techniques and confirmed asymmetric positive feedback from renewable energy to economic growth. However, an adverse positive and negative shock existed from fossil fuels to economic growth. Likewise, Mohsin et al. [41] reported a reducing effect of non-renewable energy on economic growth in 25 developing Asian countries. In a related study, Yikun et al. [42] used the fixed effect (FE) and PVECM tests to conclude that renewable energy enhanced the economy of South Asian Association for Regional Cooperation (SAARC) countries. Also, Abid et al. [23] used the cross-sectional ARDL technique to confirm that renewable energy decelerates material footprint for G-10 economies. Similarly, Li et al. [43] expressed that renewable energy lowers the ecological footprint of South Asian nations.

Summarily, the above studies demonstrated the interaction between economic growth, renewable and non-renewable energy sources. While most of the studies reported an overwhelming benefit of renewable energy for growth, the effect in

African countries were either adverse or insignificant, hence, leaving room for ambiguity in its effect for developing nations.

2.2.2. Association between human capital and economic productivity

Usman and Adeyinka [44] used the FMOLS and showed a positive impact of public spending on education, health, and school enrolment on economic expansion in the ECOWAS nations. Gwale and Wagner [45] used a system-generalised method of moments (SGMM) and submitted that human capital promotes economic progress in China. Later, Ding et al. [46] revealed for 143 countries that human capital has higher production elasticity than physical capital. Furthermore, the study found green GDP is more responsive to human capital than traditional GDP. Rahim et al. [47] also showed for the Next-11 nations that human capital mitigates the impact of a resource curse. Sonmez and Cemaloglu [48] demonstrated that technology and innovations are crucial for 31 emerging and developed nations in promoting economic output. Likewise, Shidong et al. [49] employed continuously updated fully modified (CUP-FM) and continuously updated bias-corrected (CUP-BC) techniques for G-10 economies. The study reported a blessing effect of human capital on economic productivity. Furthermore, using the heterogeneous mean group (MG), augmented MG, and common correlated effects MG procedures, Aladejare [50] revealed that human capital development has an insignificant impact on economic prosperity in 45 resource-reliant countries.

The above reviews have attempted linking human capital development to economic prosperity in different developing countries. Overwhelmingly, the studies showed that human capital has an enhancing effect on the economic growth of most developing nations reviewed, hence, making it a critical ingredient for economic advancement. Nevertheless, there is a vacuum in research on the impact of human capital on resource productivity, extending beyond economic growth in these countries.

2.2.3. Economic growth–technological progress nexus

The study by Gyedu et al. [51] used the panel GMM and VAR estimator and submitted that R&D, trademarks, and patents positively impact the economic growth of the G7 and BRICS countries. Furthermore, Ahmad et al. [52] used a long-run model to determine the link between eco-innovation and economic output in G7 economies. However, Belazreg and Mtar [53] revealed a neutral effect of innovation on economic output for OECD nations. Khan et al. [54] applied the dynamic GMM technique to report a bi-directional relationship between technical innovation and renewable energy and a positive relationship between FDI and GDP growth. A study by Skare and Malgorzata [55] demonstrated that technological advancements at the micro level (business) are more significant for green growth than non-technological advancements. Fang et al. [56] applied a two-step OLS method and expressed that improving R&D helps to promote green economic output in South Asian nations. The study by Kurniawati [57] submitted that information and communications technology (ICT) and internet use enhanced the economic productivity of 25 Asian countries. Likewise, Anakpo and Ayenubi [58] used DOLS regression and showed a significant long-term effect of technological innovation on per capita economic growth in Southern African economies. Similarly, Iqbal et al. [59] proved that technological

improvements support economic output in Belt and Road Initiative countries (BRI). Abid et al. [23] further submitted that ICTs diminished the material footprint of G-10 economies.

Although, the above reviews significantly aligned with the beneficial effect of technology for economic growth in developed and developing countries, little is known about this impact on resource productivity, particularly as it pertains to sustainable growth.

2.3. Literature gap

Generally, evidence of scant studies on resource productivity exists from the reviewed literature, particularly for developing economies. Most studies focused on the effect of renewable and non-renewable energies, human capital, and technological advancement on economic growth. However, the pursuit of economic prosperity entails the use of natural resources which may have dire consequences on sustainable growth, depending on the management technique adopted. Hence, this study extends the literature on these fronts. As prior noted, developing nations' energy consumption is accelerating due to the need for output growth; and it is increasingly affecting the global energy landscape, trade and investment flows, and exacerbating climate change challenges. Hence, the intense resource use for output growth, the adopted energy source, technological advancement, and human capital development are critical for the sustainable use of natural resources in every economy.

3. Data and methodology

3.1. Data

This study employed a dataset between 1991 and 2021 for 40 developing economies. Presented in **Table A1** are the selected nations whose choice is by data availability and completeness.

This study expands the purpose of the real GDP (RGDP) and ecological footprint (EF) to derive a reliable measure of resource productivity by deflating the former by the latter to have RGDP per EF indicator. The measure suits well as it demonstrates output efficiency from productive behaviours and natural wealth since it is the ratio between GDP (the output index) and EF (the natural resource utilisation). Apart from the EF serving as an appropriate measure of natural resource consumption, it further defines man's impact on (built-up, arable, grazing, energy, and forest) land and fishing grounds [60]. Also, Rees [61] posited that EF is significantly equivalent to Ehrlich and Holdren's [62] typical submission of man's environmental effect represented as I = PAT; where I denotes impact, P shows population, A is affluence, and T expresses technology. Hence, the EF accommodates the impacts of population and technology on natural resources. Further justification for this indicator is that since the production function seldom captures the ecological resource, their overexploitation without replenishment is mostly inevitable. In other words, as economies expand in GDP size, the availability of resources to aid such growth becomes overly limited (i.e., in EF).

Furthermore, fossil energy per total energy consumed indicates brown energy. Fossil energy includes energy from oil, natural gas, and coal. Similarly, the proxy for

green energy is renewable energy per total energy consumed. It is the share of renewable energies, including wind, solar, hydro, geothermal, biomass, etc., in total energy utilisation. Also, human capital development is essential for economic growth and resource productivity. When a country has sufficient quality human capital engaged in its production process, it can serve as a balancing factor between output growth and resource utilisation. Likewise, technology is critical for output growth and resource consumption. While countries can use technology to increase output, it can harm or enhance sustainable resource usage equally. Therefore, this study applied the KOF's information globalisation index to proxy technology transfer. The research variables, their measurement, and sources are in **Table 1**.

Table 1. Variable description.

Variable	Measurement	Source	Symbol
Resource productivity	$\frac{RGDP}{Ecological\ Footprint}$	WDI [63] and GFN [64]	rep
Non-renewable energy	Fossil energy % of total energy consumption	OWD [16]	$nrew$
Renewable energy	Renewable energy % of total energy consumption	WDI [63]	rew
Human capital	Human capital index	Feenstra et al. [65]	hc
Technology transfer	Weight index	Gygli et al. [66]	tgb

Source: Authors' compilation.

3.2. Methodology

Two relationships are estimated based on this research's objective: to compare the impacts of non-renewable and renewable energy consumption on natural resource productivity alongside the roles of human capital and technology for developing economies. The first determines the effect of non-renewable energy, human capital, and technology transfer on resource productivity.

$$lnrep_{it} = \alpha_0 + \alpha_1 nrew_{it} + \alpha_2 lnhc_{it} + \alpha_3 lntgb_{it} + \mu_{it} \quad (1)$$

The second equation ascertains the impact of renewable energy, human capital, and technology transfer on resource productivity.

$$lnrep_{it} = \beta_0 + \beta_1 rew_{it} + \beta_2 lnhc_{it} + \beta_3 lntgb_{it} + \varepsilon_{it} \quad (2)$$

For inferential robustness, this study employed DOLS, FMOLS and D-K techniques. Pedroni [67] noted that when estimating dynamic cointegrated panels, heterogeneity issues, mean variation between cross-sections and divergence in cross-sectional alignment to the long-run equilibrium are critical. Hence, Pedroni's FMOLS model incorporates individual-specific constants and accommodates heterogeneous serial correlation properties of the stochastic processes across each panel cross-sectional unit, thereby treating these issues accordingly [68]. Later, Kao and Chiang [69] extended the DOLS estimator to panel data analyses based on the outcomes of Monte Carlo simulations. In contrast to the OLS and FMOLS, the DOLS estimator produced unbiased coefficients in finite samples [70]. Also, the DOLS estimator corrects for endogeneity by augmenting lags and leads variations to inhibit the endogenous feedback. Furthermore, Driscoll and Kraay [71] proposed a method that

can yield robust results regardless of cross-sectional dependency (CSD), serial and spatial dependence, and heteroscedasticity in panel datasets. Also, the D-K technique is efficient for small and large panels and unbalanced and balanced panels [72].

The constraints of previous estimation approaches motivated the development of a panel quantile regression method for investigating the heterogeneous and distributional impact across quantiles. Essentially, quantile regression determines the dependent variance and conditional mean concerning the values of the regressors' coefficients. Quantile regression outcomes are more robust even when incidences of data outliers are evident. In addition, it suits adequately when the association between the conditional means of two series is weak or non-existent [68].

Consequently, this study applied the Machado and Silva [73] MMQREG with FE. Despite quantile regressions being robust to outliers, it fails to control for potential unobserved heterogeneity across panel cross-sectional units. In contrast, the MMQREG approach enables the identification of the conditional heterogeneous covariance impacts of the independent variables on resource productivity by permitting the specific effects to predict the entire distribution instead of just altering averages. Furthermore, the MMQREG estimation method applies to events where individual effects and endogenous regressor variables constitute the panel data model. Thus, the MMQREG conditional quantiles $Q_Y(\sigma|X)$ estimation for a model of the location-scale variant is:

$$Y_{it} = a_i + X'_{it}\beta + (\pi_i + G'_{it}\aleph)U_{it} \quad (3)$$

given the probability, $P\{\pi_i + G'_{it}\aleph > 0\} = 1(a, \beta', \pi, \aleph')'$ are coefficients to be determined. $(a_i, \pi_i), i = 1, \dots, n,$ represents the individual i FE, and G denotes a k-vector of identified elements of X which are differentiable transformations with component l described as:

$$G_l = G_l(X), l = 1, \dots, k \quad (4)$$

X_{it} is uniquely and identically distributed for any fixed i and is unique throughout the period (t). Likewise, U_{it} is uniquely and identically distributed across cross-sections (i) and through the period (t) and is orthogonal to X_{it} and normalised to fulfil the moment conditions in Machado and Silva [73], which do not suggest strict exogeneity; thus, Equation (5):

$$Q_Y(\sigma|X_{it}) = \left(a_i + \pi_i p(\sigma)\right) + X'_{it}\beta + G'_{it}\aleph p(\sigma) \quad (5)$$

From Equation (3), X'_{it} represents a vector of regressors in this research: non-renewable energy, renewable energy, and the natural logarithm of human capital and tech-globalisation. $Q_Y(\sigma|X_{it})$ signifies the quantile distribution of the response variable Y_{it} (natural logarithm of resource productivity) which is a function of the location of explanatory variables X_{it} - $a_i(\sigma) \equiv a_i + \pi_i p(\sigma)$ expresses the scalar parameter related to the quantile $-\sigma$ FE for each i. The individual impact does not represent a constant change, unlike the traditional least-squares FEs. They represent time-invariant coefficients whose independent effects are free to vary through the quantiles of the conditional distribution of the dependent variable. $p(\sigma)$ signifies the σ-th sample quantile, determined by treating the given optimisation challenge;

$$min_p \sum_i \sum_t \varphi_\sigma \left(W_{it} - (\pi_i + (\pi_i + G'_{it}\aleph)p \right. \quad (6)$$

where $\varphi_\sigma(J) = (\sigma - 1)JI\{A \leq 0\} + TAI\{A > 0\}$ represents the check function.

4. Results

4.1. Descriptive statistic test outcome

Table 2 reveals the defining feature of the panel data. It shows that resource productivity (RGDP per EF) has a mean value of $2.08 billion. This value shows the average efficiency of natural wealth in developing countries which is substantial. Also, while the mean non-renewable energy consumption is 83%, the average renewable energy utilisation is 14.3%; thus, non-renewable energy is the dominant energy source in developing countries. Furthermore, the mean human capital index is 144,610.8, while the average technology index is 72,421.5.

Table 2. Aggregate descriptive statistic.

Variable		Mean	Std. Dev.	Min	Max	Observations
	Overall		1.330	41.132	1.14×10^{11}	N = 1240
rep	Between	2.08×10^9	1.310	250.651	8.30×10^{10}	N = 40
	Within		3.010	-2.46×10^{10}	3.34×10^{10}	T = 31
	Overall		20.034	11.2	100	N = 1240
$nrew$	Between	82.992	19.970	15.008	99.995	N = 40
	Within		3.494	60.357	101.806	T = 31
	Overall		20.091	0	88.8	N = 1240
rew	Between	14.290	20.083	0.015	84.992	N = 40
	Within		3.174	−4.524	36.925	T = 31
	Overall		3,599,265	1.244	8.97×10^7	N = 1240
hc	Between	144,610.8	914,583.5	1.634	5784336	N = 40
	Within		3,484,035	−5,639,723	8.40×10^7	T = 31
	Overall		2,547,118	12	8.97×10^7	N = 1240
tgb	Between	72,421.53	457,291.9	37.258	2,892,227	N = 40
	Within		2,506,711	−2,819,772	8.68×10^7	T = 31

Source: Authors' estimated output.

4.2. Correlation, slope heterogeneity, and CSD test results

Table 3 contains two test outputs; the upper section is the correlation outcome, and the lower area is the slope heterogeneity test. Deducible evidence from the table shows low multi-collinearity between the covariates, except between renewable and non-renewable energies. However, both energy types do not belong in the same estimated equation, nullifying their high collinearity nexus. Remarkably, the lower section of **Table 3** demonstrates the validity of slope heterogeneity for the study variables.

Captured in **Table 4** are the four CSD tests applied in this research, and the output reveals the none significance of the null hypothesis of cross-sectional freedom. Hence, the acceptance of the alternative hypothesis of significant CSD in the study's panel dataset.

Table 3. Correlation matrix and heterogeneity tests.

	$lnrep$	$nrew$	rew	$lnhc$	$lntgb$
$lnrep$	1				
$nrew$	−0.097	1			
rew	0.122	−0.958	1		
$lnhc$	−0.055	0.017	−0.076	1	
$lntgb$	0.040	0.089	−0.152	0.642	1
Slope heterogeneity test					
		Equation 1		Equation 2	
Test-Statistics		Value	*P*-value	Value	*P*-value
$\bar{\Delta}$		41.741	0.000***	41.313	0.000***
$\bar{\Delta}_{adjusted}$		45.446	0.000***	44.979	0.000***
H_0	Slope coefficients are homogenous.				

Source: Authors' estimated output.

Table 4. CSD test output.

Variable	Breusch-Pagan LM	Pesaran scaled LM	Bias-corrected scaled LM	Pesaran CSD
$lnrep$	12,369.06***	293.418***	292.751***	82.594***
$nrew$	5564.997***	121.149***	120.482***	15.750***
rew	5367.725***	116.154***	115.488***	14.951***
$lnhc$	21,175.82***	516.391***	515.725***	143.704***
$lntgb$	21,103.64***	514.564***	513.897***	143.529***

Note: *** indicates statistical significance at 1%. H_0: No cross-section dependence.
Source: Authors' estimated output.

4.3. Unit root and cointegration results

Table 5 presents the output for three different unit root tests capable of incorporating heterogeneity and CSD issues in panel analysis. The results show that all the variables are stationary at the first difference level.

Table 5. Unit root test output.

	First-generation unit root		Second-generation unit root				
Variable	Maddala and Wu (1999)		Pesaran's CADF (2003)		Pesaran's CIPS (2007)		
	Without trend	With trend	Without trend	With trend	Without trend	With trend	Decision
$lnrep$	67.388	103.392	−2.269***[a]	−3.183***[b]	−3.372***	−1.088	I (1)
$nrew$	86.207	39.769	−2.610***[b]	−2.936***[b]	2.465	5.435	I (1)
rew	91.790	42.217	−2.782***[b]	−3.004***[b]	3.072	3.959	I (1)
$lnhc$	130.687	49.242	−2.039**[a]	−2.591**[a]	0.500	−0.220	I (1)
$lntgb$	197.342	36.670	−7.311***[b]	−5.035***[b]	−3.820	−0.566	I (1)
H_0	Series is I (1)		Series is non-stationary		Series is I (1)		

Note: a and b represent stationarity at the level and first difference, respectively, while ** and *** indicate statistical significance at 5% and 1%, respectively.
Source: Authors' computation.

Furthermore, the Westerlund cointegration method is applied to ascertain the long-term association between the study covariates. This approach efficiently handles heterogeneity and CSD issues in panel data analysis. Consequently, in **Table 6** are the test results for the two equations, demonstrating the rejection of the null hypothesis of no cointegration association. Instead, the alternative view of the long-term covariate nexus is validated.

Table 6. Westerlund panel CSD cointegration test.

Equation 1		**Equation 2**	
Statistic	**Value**	**Statistic**	**Value**
G_t	−2.272***	G_t	−2.227***
G_a	−8.982***	G_a	−8.484***
P_t	−9.251	P_t	−9.254***
P_a	−6.631***	P_a	−5.835***
H_0:	No cointegration		

Note: *** indicates statistical significance at 1%.
Source: Authors' computation.

4.4. Panel estimated outcomes

The research presents Equations (1) and (2) outputs from the DOLS, FMOLS, and D-K estimates in **Table 7**. **Table 7** shows that the three assessments' non-renewable energy (Equation (1) result) significantly negatively affects resource productivity. In contrast, the impact of renewable energy (Equation (2) result) on resource productivity is substantial and positive in the three estimates. Human capital in both equations revealed a significant adverse effect on resource productivity, except in the D-K output, where the impact is insignificant. In contrast, technology transfer in both equations demonstrates a substantial benefit for resource productivity in the three estimates.

Table 7. DOLS, FMOLS, and D-K outputs.

	Equation 1			**Equation 2**		
Variable	PDOLS	FMOLS	D-K	PDOLS	FMOLS	D-K
$nrew$	−0.007**	−0.020*	−0.016**			
rew				0.019***	0.021*	0.020***
$lnhc$	−0.122***	−0.105***	−0.599	−1.377***	−0.101***	−0.590
$lntgb$	0.411***	0.386***	0.752***	2.147***	0.380***	0.802**

Note: *, **, and *** indicate statistical significance at 10%, 5% and 1%, respectively.
Source: Authors' Computation.

Presented in **Table 8** are the MMQREG results for Equation 1 estimates. The effect of non-renewable energy is statistically significant and adverse for resource productivity from the lower quantiles through to the 80th quantile. The magnitude impact of non-renewable energy decelerated from the lower to the middle and upper quantiles. However, in the 90th quantile, the effect turned insignificant. Likewise, the impact of human capital is statistically significant and negative from the 10th to the 80th quantiles, declining from the lower to the middle and upper quantiles, and

insignificant in the 90th quantile. In contrast, technology transfer positively affects resource productivity from the lower to the 80th quantiles. However, the magnitude of its positive impact waned from the lower to the middle and upper quantiles and turned insignificant in the 90th quantile.

Table 8. Equation 1 MMQREG with FE output.

Dependent variable: *lrep*											
			Lower quantile			**Middle quantile**			**Upper quantile**		
Variable	Location	Scale	10th	20th	30th	40th	50th	60th	70th	80th	90th
nrew	−0.016[c]	0.010[b]	−0.026[c]	−0.024[c]	−0.023[c]	−0.022[c]	−0.021[c]	−0.020[c]	−0.019[c]	−0.016[c]	0.002
lnhc	−0.599[b]	0.088	−0.683[c]	−0.669[c]	−0.660[c]	−0.650[c]	−0.644[c]	−0.634[c]	−0.621[c]	−0.597[c]	−0.437
lntgb	0.752[c]	−0.089	0.837[c]	0.823[c]	0.813[c]	0.803[c]	0.797[c]	0.787[c]	0.774[c]	0.749[c]	0.586
cons	7.523[c]	1.072	6.497[c]	6.669[c]	6.789[c]	6.909[c]	6.977[c]	7.100[c]	7.257[c]	7.555[c]	9.512[c]

Note: b and c indicates statistical significance at 5% and 1%, respectively.
Source: Author's Estimated Output.

Table 9 presents the MMQREG for Equation (2) outputs. The impact of renewable energy on resource productivity is significant and positive from the lower quantiles through to the 80th higher quantile. However, its magnitude impact declined from the lower to the upper quantiles and is insignificant at the 90th quantile. In contrast, the effect of human capital is significant and negative from the 10th to the 80th quantile. Nevertheless, human capital's influence diminished from the lower quantiles to the middle and upper quantiles and was not substantial at the 90th quantile. Technology transfer significantly and positively impacts the lower to the 80th quantiles. Nevertheless, it followed a similar trend as other regressors by reducing in magnitude from the lower quantiles to the middle and upper quantiles before its insignificance at the 90th quantile.

Table 9. Equation (2) MMQREG with FE output.

Dependent variable: *lrep*											
			Lower quantile			**Middle quantile**			**Upper quantile**		
Variable	Location	Scale	10th	20th	30th	40th	50th	60th	70th	80th	90th
rew	0.020[c]	−0.011[c]	0.032[c]	0.029[c]	0.028[c]	0.027[c]	0.026[c]	0.023[c]	0.023[c]	0.020[c]	−0.0004
lnhc	−0.590[c]	0.066	−0.658[c]	−0.644[c]	−0.635[c]	−0.629[c]	−0.624[c]	−0.605[c]	−0.605[c]	−0.588[b]	−0.464
lntgb	0.802[c]	−0.056	0.859[c]	0.847[c]	0.840[c]	0.835[c]	0.830[c]	0.815[c]	0.815[c]	0.801[c]	0.696
cons	5.674[c]	1.895[a]	3.746[c]	4.146[c]	4.395[c]	4.556[c]	4.706[c]	5.232[c]	5.232[c]	5.718[c]	9.260[c]

Note: a, b and c indicates statistical significance at 10%, 5%, and 1%, respectively.
Source: Author's Estimated Output.

Also represented in **Figure 1** is the graphic pattern of the regressors' parameters at different quantile levels. The output mirrored the behaviour in the estimated MMQREG in **Tables 8** and **9** for all significant quantiles.

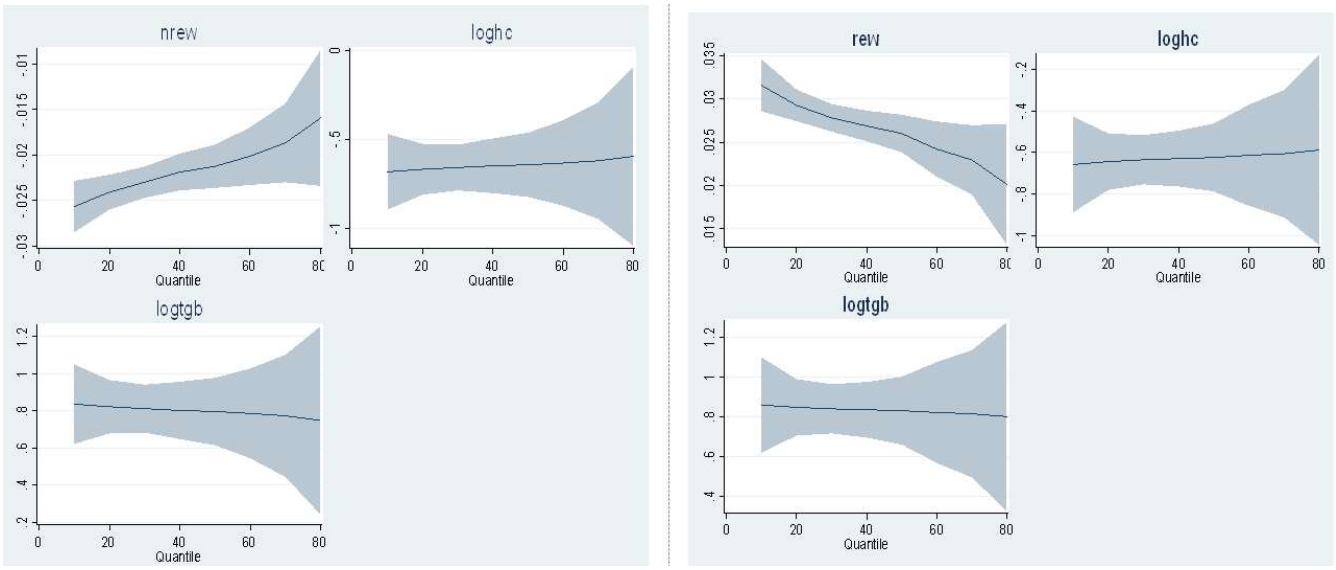

Figure 1. Graphical presentation of regressors' coefficient across quantiles for both equations.

4.5. Discussion of findings

The negative effect of non-renewable energy on resource productivity indicates the excessive depletion of natural resources for economic growth. It suggests that brown energy sources drain more natural resources to produce higher units of economic output. Furthermore, the MMQREG outcome suggest that the negative effect of non-renwable energy is more intense in developing economies with higher natural resources utilisation. For instance, China is the second largest and one of the fastest growing economies in the world. Furthermore, the country's speedy economic rise made it the largest energy consumer in the world and has enabled vast pressure on its natural wealth. A UNEP [74] report noted that China is out-running other countries in its natural resource utilisation. Also, Indonesia, Malaysia, Philippines, Thailand, and Vietnam are countries belonging to the Association of South East Asian Nations (ASEAN) that have an energy depletion rate of over 60% [75]. Their rapidly growing economies fuel the growth in brown energy demand in these ASEAN countries. In aggregate, ASEAN countries contributed about 9% of the global GDP increase between 2012 and 2022 [76]. Specifically, Indonesia, Malaysia, Philippines, Thailand, and Vietnam are at various economic transformation stages, launching them into the middle-income class. However, the reliance on fossil energy for GDP growth in these countries has continued to promote the overexploitation and degeneration of natural resources regarding land usage, water bodies, ecological and biodiversity conservation, and air quality. Ceterisparibus, the long-term effect of this poor resource management is weak resource efficiency which can stunt or retard growth in any economy.

In contrast, the MMQREG result demonstrated that the enhancing impact of renewable energy is more intense in developing economies with higher natural resources utilisation. The positive effect of renewable energy on resource productivity is plausible given that they are considered cleaner and eco-friendly ingredients of growth. Renewable energy reduces the prices of and demand for brown energy through the elevated competition since, unlike fossil energy sources that are dominantly capital and mechanised-intensive, renewable energy is highly labour-intensive. Consequently,

green energy sources exert less pressure on natural resources, enabling output expansion through higher resource efficiency. For instance, solar and wind energy are un-exhaustible and require less resource intensity to convert for electricity utilisation in the production process. In the last decade, this reason has encouraged the aggressive global campaign led by the United Nations for world economies to transit to green energy sources. For instance, in its drive to maintain its dominance as a world-leading economy, China embarked on a green economic efficiency transition drive and consolidated its position in 2012 as a critical player in the renewable energy market [74].

In addition, Brazil sources over 80% of its electricity from green energy, as against the world average of 15%–27% [77]. Brazil's significant use of renewable energy gives its economy a competitive edge in producing manufactured and green goods and services in the world market through the rational utilisation of nature's wealth to create jobs and economic prosperity [77]. Also, African economies are joining the trend of exploring the potential of green energy as a sustainable approach to natural wealth conservation. Countries including Ghana, Kenya, and South Africa are some of the African economies to have implemented green energy in rational natural resource consumption in different sectors of their economies. African countries, with international bodies' aid, have been developing a national sustainable energy production and consumption policy to promote green resource efficiency [78].

Interestingly, while human capital negatively impacted resource efficiency in both equations, the MMQREG outcome further expressed that the adverse effect of human capital is more intense in developing economies with higher natural resources utilisation. Hence, this result indicates that the investments in the health and education sectors are inadequate to promote resource productivity. For instance, individuals expended an estimated annual $500 billion (i.e., $80 per person) in developing countries to access health services which is not encouraging due to poor income levels in these economies [79]. Also, a learning crisis in developing economies varies from country to country. Thus, the knowledge, experience and skill sets of labour in these developing economies are inadequate for sustainable utilisation of natural resources and are inducing a weak resource productivity level. Practices including bush burning for farming and hunting, indiscriminate falling of trees for fire-woods and charcoal, use of hazardous chemicals for fishing, etc., are still applicable in many of these countries despite their adverse effect on human health [80]. Moreover, they accelerate the challenges of resource depletion through deforestation, soil and land degradation, and pollution of water bodies and air quality. Consequently, the inadequate investment in quality healthcare and productivity driven educational curricula cannot promote efficient resource utilisation—allow rapid economic growth in these developing economies. When there is an expansion in the access to quality human capital in the areas of education, science, health, and management, there is bound to be increases in innovation, productivity, and social well-being, necessary for enhancing economic growth.

However, technology transfer shows that these developing economies have been leveraging resource-friendly production techniques to enhance resource efficiency. In addition, the MMQREG outcome revealed that the beneficial impact of technology transfer is more intense in developing countries with higher natural resources

utilisation. Technology adaption by developing countries has a significant positive role in ensuring a rational consumption of natural wealth through production cost reduction, creating standards for quality, and enabling global interaction. Also, the swift pervasiveness of technology in developing countries induced by the internet increases positive cultural alterations that can promote resource efficiency for sustainable growth. Adapting resource or eco-friendly technology provides highly efficient means for saving resource utilisation by lowering reliance on fossil energy sources and enhancing sustainable business models [23].

5. Concluding remarks

This study determined the impacts of non-renewable and renewable energy consumption on natural resource productivity alongside human capital and technology transfer roles for 40 selected developing economies. This study relied on a dataset sourced between 1991 and 2021. For inferential robustness, the FMOLS, DOLS, D-K, and MMQREG are procedures applied in the analyses. Empirically, the study revealed that an increase in brown energy consumption exhausted resource productivity from the lower to the upper quantiles. In contrast, green energy utilisation enhanced resource productivity from the lower to the higher quantiles. Also, while human capital adversely affected resource productivity for both energy means, technology transfer positively impacted it from the lower to the upper quantiles. Likewise, inferences from the DOLS, FMOLS, and D-K techniques revealed similar findings.

From the empirical outcomes, it is evident that although brown and green energy, human capital, and technology transfer significantly impacted resource efficiency, the size of their effects are most potent in developing economies with more intense natural resource utilisation. Furthermore, despite non-renewable energy consumption being the dominant means of energy in these developing economies, interestingly, its significant adverse impact on resource productivity falls short of the significantly increasing effect of renewable energy utilisation across all quantiles. Also, the magnitude of the negative impact of human capital on resource productivity is marginally more substantial with non-renewable energy. In contrast, the robustness of the enhancing impact of technology transfer on resource efficiency is slightly more with renewable energy.

Hence, the study recommends that since green energy is an excellent alternative to slow the over-consumption of scarce natural wealth and improve resource productivity, developing economies must concentrate more on generating renewable energy. Also, it is pertinent for energy stakeholders to advocate an increase share of green energy in output enhancement to protect the long-term resource sustainability concerns and to ensure conformity with the sustainable development goals demand. The gains of renewable energy consumption for resource productivity should spur policymakers to implement clean energy portfolios that dissuade brown energy consumption by initiating a carbon tax or emission permits and rewarding businesses adopting green energy. Furthermore, stakeholders in different countries must develop a national energy policy outlining the transition path from brown to green energy and target a low-emission energy system for conservative use of natural resources.

Governments must consolidate the blessing effect of technology and reverse the adverse impact of human capital development. First, the overly rapid preference for quantity over quality in educated graduates must change to have efficient human capital capable of reversing the negative impact on and improving resource efficiency. Furthermore, educational infrastructure needs to be enhanced, and the appropriate authorities should augment the academic curricula in line with current realities that support the sustainable use of resources for economic output. Secondly, more involvement in technology can diminish the reliance on natural wealth and promote energy efficiency in production since it is evident it enhances resource efficiency regardless of the energy type. Thus, more investment in the technological drive is encouraged to innovate new ideas instead of just adapting existing ones. Although the cost may be huge in the short run, the long-term benefits will be more overwhelming. Also, countries should pursue measures that encourage the efficient utilisation of technology at different production stages.

A constraint of this study is the inability to access a complete dataset on technological innovation for all countries used in the study. The KOF's information globalisation index adopted by the study is limited since it measures foreign technology inflows, as well as conditions that aid such transfers to the country. However, data on domestic technological innovations and patents would have been more appropriate to assess how home-grown technologies are aiding resource productivity in these developing economies. The availability of these data would have further enriched testing the findings by using alternative indicators. Nevertheless, the absence of this information does not suggest a vacuum in technological innovation in the researched nations. Consequently, future studies can explore these options.

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Appendix

Table A1. List of 40 study countries.

Algeria	Ghana	Nigeria	Slovenia
Argentina	India	Pakistan	South Africa
Bangladesh	Indonesia	Peru	South Korea
Brazil	Iran	Philippines	Thailand
Bulgaria	Iraq	Poland	Trinidad and Tobago
Chile	Kazakhstan	Qatar	Turkey
China	Kenya	Romania	Ukraine
Colombia	Malaysia	Russia	United Arab Emirate
Ecuador	Mexico	Saudi Arabia	Venezuela
Egypt	Morocco	Slovakia	Vietnam

Source: Authors' computation.

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Article

Evaluating green supply chain management performance in the Indonesian mechanical assembly industry

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Abstract: This study aims to evaluate the efficiency and performance of implementing green supply chain management in a specialized mechanical assembly company. The research focuses on a company that produces plastic-molded components and mechanical assemblies for medical, industrial, automotive, and transport sector clients, representing a significant segment of the Indonesian mechanical assembly industry. Utilizing the Supply Chain Operations Reference (SCOR) model and the Analytical Hierarchy Process (AHP), the study assesses green supply chain performance across five domains: planning, sourcing, production, delivery, and returns. The results indicate a green supply chain performance score of 80.1, categorized as good, suggesting effective implementation of environmentally friendly practices. Based on these findings, it is recommended that the company continue to refine its green supply chain strategies, particularly in areas that scored lower, to further enhance overall performance. Future studies could expand this research by including a larger sample of companies within the Indonesian mechanical assembly industry, enabling broader generalizations and identification of industry-wide trends in green supply chain management implementation.

Keywords: green supply chain management; supply chain operations reference; analytical hierarchy process; key performance indicators

1. Introduction

Researchers have conducted comprehensive analyses of the environment in light of the recent publication of the report on global warming patterns. Both governmental and non-governmental organizations have implemented various efforts and programs to promote environmental awareness. As a result, both consumers and companies have shown an increasing interest in this matter. Corporations bear the responsibility for their supply chains, which compels them to conduct and evaluate research on environmental aspects of their supply chain activities [1]. Suppliers, manufacturers, and retailers are required to use sustainable practices throughout all aspects of their operations, with particular emphasis on actions within the supply chain that have a direct impact on the product, in order to acquire ecologically sustainable materials. Implementing Green Supply Chain Management (GSCM) can increase organizational productivity, both financially and efficiently; and improve environmental performance [2]. While the importance of GSCM is well-established, there is a notable gap in research specifically addressing its implementation and effectiveness in the Indonesian mechanical assembly industry. This study aims to address this gap by evaluating the eco-friendly supply chain in this sector, considering its unique challenges and opportunities.

The green supply chain management techniques of many businesses have garnered significant interest due to their potential environmental and economic benefits. The aim of these strategies is to mitigate the negative impacts of supply chain activities on the environment while simultaneously improving overall performance. Evaluating the effectiveness of the eco-friendly supply chain poses unique challenges in the mechanical assembly industry. The strategic implementation of green supply chain management will help manufacturing enterprises enjoy cost and efficiency benefits [3]. These challenges involve the complex features of mechanical assembly, which include multiple components and techniques. Moreover, it is crucial to integrate environmental sustainability into supply chain management strategies in this industry in order to achieve long-term performance and competitiveness [4]. In order to evaluate the effectiveness of the eco-friendly supply chain in the mechanical assembly industry, it is essential to consider specific attributes that are relevant to this field.

1.1. Background

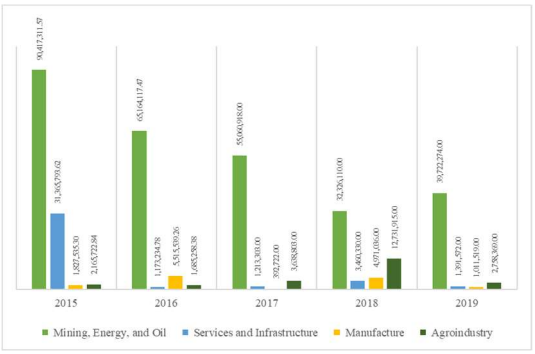

Figure 1. Amount of hazardous waste managed (Tons).

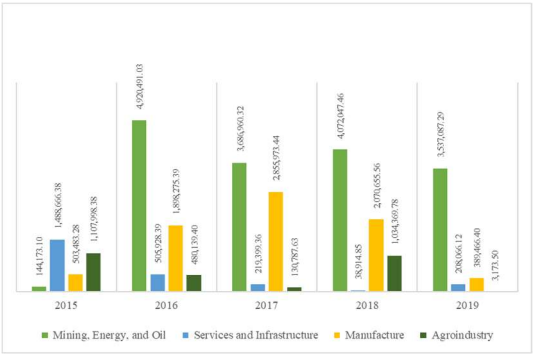

Figure 2. Amount of hazardous waste utilized (Tons).

Based on statistical data provided by the Ministry of Environment and Forestry of the Republic of Indonesia, the monitored industry generates a total of 60,309,198.23 tons of hazardous waste. This encompasses the waste produced by institutions tasked with the management of hazardous waste, which can be handled either by outsourcing it to third-party entities or by managing it internally. However, the supervision of hazardous industrial waste management and utilization in the manufacturing industry is insufficiently monitored in comparison to other industrial sectors, as evidenced by **Figures 1** and **2**. This is despite the Ministry of Environment and Forestry of the Republic of Indonesia overseeing multiple industrial units within the manufacturing

industry between 2015 and 2019. Moreover, the supply chain operations in certain industries significantly contribute to various types of pollution and waste caused by the movement of the industrial supply chain in Indonesia [5].

Implementing green supply chain efforts is an essential approach for firms seeking to improve sustainability and remain competitive in today's environmentally aware market. These initiatives involve various practices, such as green purchasing (obtaining materials from environmentally responsible suppliers), eco-design (developing products with minimal environmental impact throughout their lifespan), and reverse logistics (handling the return and recycling of products and materials) [6]. Multiple factors motivate the adoption of such practices, including the need to comply with increasingly stringent government regulations, the desire to improve customer relations and public perception, and the potential for financial benefits through cost reduction and improved effectiveness [7]. Strategic green supply chain management is of utmost importance in rising economies such as India, where the rapid growth of industry sometimes clashes with environmental considerations. Businesses can address growing environmental concerns and meet the changing expectations of environmentally conscious consumers. Nevertheless, the distinct factors and obstacles associated with implementing environmentally-friendly supply chain activities in these emerging nations may vary compared to those in more advanced countries. This emphasizes the need for additional investigation in order to comprehend the distinct aspects that influence the adoption of green supply chains in various economic settings. Such research could provide valuable insights for developing more efficient ways to apply sustainable practices in global supply chains [8].

PT CP, an upscale producer of accurate plastic-molded components and mechanical assemblies for medical, industrial, and automotive customers, runs a facility in Batam, Indonesia. This site offers assembly services, tool design and fabrication, plastic injection molding, vertically integrated secondary processes, and advanced spray paint process technologies in collaboration with the manufacturing industry in Singapore. The company primarily produces mechanical products, requiring an environmentally sensitive supply chain management system to align with its business operations. For three months, PT CP temporarily keeps its hazardous and toxic waste at a designated site. After this time, a third party is responsible for transporting and managing the garbage. The total amount of hazardous and toxic waste produced in the previous six months was 1.71 tons. PT CP generated more than 3 metric tons of hazardous and toxic waste within a span of one year. The Batam City Environmental Impact Handling Agency has issued the firm a permit to handle hazardous waste, specifically for temporary storage activities. Every quarter, the corporation consistently notifies the government of the periodic containment of dangerous waste. PT CP has obtained ISO 14001:2014 accreditation, which is a globally acknowledged standard for environmental management. The certification was revised in 2018. These activities exemplify the company's dedication to fostering a sustainable industry.

Therefore, the evaluation of performance will be carried out utilizing performance indicators specific to green supply chain management. These indicators will help the company improve its reputation, customer loyalty, sales, profits, and competitiveness [9]. The validation of these indicators will be conducted according to

the firm's business processes. Afterwards, work indicators that need improvement will be identified based on recommendations that are in line with the company's ability to make adjustments. This study employs an approach by combining the Green Supply Chain Operation Reference (Green SCOR) model with the Analytical Hierarchy Process (AHP). The results of this study will be classified using the Traffic Light System (TLS) in order to identify the Key Performance Indicators (KPIs) that require improvement. This company's process of designing performance metrics includes combining performance indicators with environmental issues. These features are directly associated with the steps of planning, sourcing, manufacturing, delivering, and returning.

1.2. Research objectives

The objective of this research is to evaluate the efficiency and performance of Green Supply Chain Management (GSCM) implementation in a company specializing in producing plastic-molded components and mechanical assemblies. By focusing on key areas such as planning, sourcing, production, delivery, and returns, the study aims to assess how well the company incorporates environmentally friendly practices throughout its supply chain operations. Using the Supply Chain Operations Reference (SCOR) model and the Analytical Hierarchy Process (AHP), the research seeks to measure the effectiveness of GSCM and identify areas that require improvement to enhance both environmental and operational performance. The study also explores which aspects of the supply chain need refinement to further boost the company's environmental sustainability.

2. Literature review

2.1. Green supply chain management

Studies have shown that the adoption of Green Supply Chain Management (GSCM) strategies can provide competitive advantages, reduce operational costs, and improve overall business efficiency [10]. Among these programs, eco-design is typically the most widely adopted, followed by green purchasing, while reverse logistics tends to have the lowest level of acceptability [11]. Participating in environmentally-focused organizations and having a larger number of suppliers (more than 10) are factors that positively influence the adoption of Green Supply Chain Management (GSCM) strategies [11].

Various factors, measured as a second-order construct, influence the implementation of a company's environmentally friendly supply chain initiatives in developing countries [8]. While implementing Green Supply Chain Management (GSCM) may have challenges, such as those related to waste management, it is critical to prioritize the pursuit of financial, social, and environmental benefits through these initiatives in order to achieve sustainability [8]. As environmental concerns become more important, companies are realizing the relevance of Green Supply Chain Management (GSCM) in creating their reputation as socially responsible and environmentally sustainable [10].

2.2. Measurement of Performance

A range of studies have delved into the complex task of evaluating the performance of Green Supply Chain Management (GSCM). There is a critical need for a comprehensive measurement system that takes into account the entire supply chain, including its green aspects [12]. This holistic approach is essential for accurately assessing the environmental impact and effectiveness of GSCM practices across all stages of the supply chain. Previous research [13,14] has proposed innovative methodologies for GSCM performance measurement. Both scholars advocate for the use of a modified balanced scorecard in combination with the analytic hierarchy process (AHP), specifically focusing on integrating AHP with the balanced scorecard to create a more robust evaluation framework.

2.3. Green supply chain operation reference

The Green Supply Chain Operation Reference (Green SCOR) model has emerged as a valuable tool for evaluating and improving the environmental performance of supply chains across various industries. This is evident from studies conducted in different sectors, including rubber processing, steel manufacturing, and green tea production. For instance, researchers applied the Green SCOR method to assess a rubber processing factory's green supply chain performance, yielding a score of 72.03%, which was considered good [15]. Similarly, other research evaluated a steel company's green supply chain performance using Green SCOR, resulting in an average score of 67.73 [16]. These studies demonstrate the versatility of the Green SCOR model in quantifying and benchmarking environmental performance across diverse industrial contexts.

The use of Green SCOR not only provides an overall performance score, but also identifies specific areas for improvement within supply chains. For example, Pulansari and Putri [16] found that water usage was a critical area needing improvement in the steel company they studied. In the case of green tea production, Suharno et al. [17] used Green SCOR to highlight both strengths (such as clean energy use and zero waste disposal) and areas for improvement (including water usage optimization and supplier screening). These findings underscore the importance of Green SCOR as a diagnostic tool that can guide targeted interventions to enhance the environmental sustainability of supply chains. Moreover, the evolution of Green SCOR from its inception, as described by Cash et al. [18], to its current applications demonstrates its growing relevance in integrating sustainability and environmental considerations into supply chain management practices.

2.4. The analytical hierarchy process (AHP)

Thomas Saaty developed the Analytic Hierarchy Process (AHP), a powerful decision-making methodology that combines mathematical rigor with psychological intuition. It is designed to handle complex multi-criteria decisions by breaking them down into hierarchical structures and using pairwise comparisons to derive priority scales [19]. At its core, AHP is based on the fundamental human capability to make pairwise comparisons, which allows decision-makers to cope with a constantly

changing world where fixed standards may not exist [19]. The process utilizes a psychophysical scale of 1-9 for making these comparisons.

AHP's strength lies in its ability to synthesize individual judgments into a cardinal group decision through a mathematically justifiable method [20]. Priority scales are determined by pairwise comparisons using expert judgments for both tangible and intangible factors [21]. These derived priority scales are then synthesized by multiplying them by the priority of their parent nodes and adding for all such nodes [21]. This approach allows AHP to address multiple objectives simultaneously, making it particularly useful for decisions involving benefits, costs, opportunities, and risks [19]. However, there are some potential flaws in AHP, suggesting that its rankings can be arbitrary due to the principle of hierarchic composition. It was proposed to synthesize AHP with concepts from multi-attribute utility theory to address this issue [22].

The process involves calculating the consistency ratio to ensure the reliability of expert opinions. This is done by comparing the Consistency Index (CI) with a predetermined Random Index (RI). The CI is calculated using the following formula:

$$CI = \frac{Lmax - n}{n - 1}$$

Description:

CI = Consistency Index;

Lmax = Eigen value max;

N = Number compared/matrix order

The Consistency Ratio (CR) is then determined by dividing (Consistency Index) CI by Random Index (RI). If the CR value is less than or equal to 0.10, the comparisons are considered consistent and acceptable. However, if the CR exceeds 0.10, decision-makers are required to review their assessments. This systematic approach allows for a structured evaluation of complex decisions, incorporating both objective data and subjective expert judgments [21,23].

Performance assessment can be conducted using many methods, and the achievement of performance is assessed by standardizing performance indicators. The process of normalization is referred to as Snorm De Boer normalization [24]. The Snorm De Boer normalization formula [25] facilitates the normalizing process in the following manner:

$$\text{Snorm (Score)} = \frac{(\text{Smax} - \text{Si})}{(\text{Smax} - \text{Smin})} \times 100\%$$

$$\text{Snorm (Score)} = \frac{(\text{Si} - \text{Smin})}{(\text{Smax} - \text{Smin})} \times 100\%$$

2.5. ISO 14000/14001

Organizations embark on the varied and challenging process of implementing ISO 14001, an Environmental Management System (EMS), to enhance their environmental performance. This system encounters multiple impediments and is influenced by different factors that can affect its successful implementation and efficacy. Typical obstacles include a lack of government encouragement to embrace

these systems, the significant financial commitment needed for implementation, and a dearth of support or interest from customers and stakeholders [26,27]. Notwithstanding these obstacles, firms that effectively apply ISO 14001 frequently enjoy substantial advantages. The benefits encompass increased environmental performance through the methodical handling of environmental factors, decreased operating expenses resulting from enhanced efficiency and resource management, and enhanced adherence to environmental laws and regulations [28]. Studies have demonstrated that ISO 14001 can be highly efficient in reducing environmental effects, particularly when it is coordinated with and enhances existing environmental standards [29]. The system offers a systematic framework for firms to establish environmental goals, track their progress, and consistently enhance their environmental management practices, ultimately leading to more sustainable company operations and potentially enhancing corporate reputation.

3. Research methods

This study is an evaluative research project that utilizes a qualitative approach, whose conceptual framework can be observed in **Figure 3**. Evaluative research is a methodical and systematic investigation to assess an object, program, practice, activity, or system. Its purpose is to provide decision-makers with valuable information for making informed decisions [30]. Primary data refers to data or information collected directly from the subject of study. The sample size in this study consisted of six experts directly involved in supply chain activities. The sample size in this study consisted of six experts directly involved in supply chain activities. While this sample size is limited, it represents key decision-makers across various functions within the company, providing a comprehensive view of the GSCM practices. These experts were carefully selected based on their extensive experience and their direct involvement in shaping the company's GSCM strategies. These experts include PPIC Managers, Purchasing Assistant Managers, Quality Managers, Engineering Managers, Operational Directors, and HSE personnel.

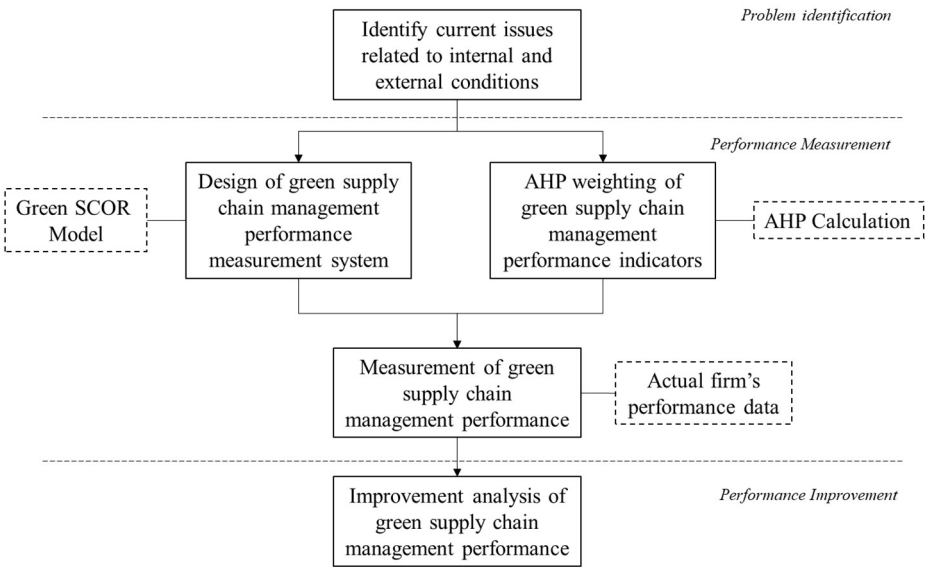

Figure 3. Conceptual framework.

The sampling strategy employed in this study is purposive sampling, conducting non-probability sampling. Purposive sampling is a method of selecting data sources based on specific considerations [31]. The criteria for expert selection were as follows: (1) a minimum of 5 years of experience in supply chain management, (2) direct involvement in the company's GSCM initiatives, (3) decision-making authority in their respective departments, and (4) a comprehensive understanding of the company's overall business strategy. This rigorous selection process ensures that despite the limited number of experts, the insights gathered are highly relevant and authoritative.

Table 1. Process, attributes, and indicators.

Process	Process definition	Attribute	Indicator	Indicator definition
Plan	Plan activities include all forms of production planning, through good planning it will be followed by a good production process. Production process is both effective and efficient.	Reliability	Forecast Accuracy	Accuracy of forecasting demand with actual demand
		Reliability	Raw Material Planning Accuracy	Total forecasting actual compared with actual needs
Source	Activities in the source process include the procurement of raw materials needed during the production process. The source process starts from purchasing raw materials to checking for defective raw materials.	Reliability	% Order Received Damaged Free	Percentage of rejected or defected raw materials
		Reliability	% Of Feasible Package	Percentage of damaged packaging
		Reliability	% Hazardous Material in Inventory	Percentage of hazardous materials
		Reliability	% Supplier with → an EMS → or ISO 14000 Certification	Percentage of suppliers that have an environmental management system or are ISO 14000 certified
		Responsiveness	Source Cycle Time	The total time required by the supplier from ordering until the goods are received in the warehouse, often referred to as lead time, with lead time.
Make	Make activities include production activities from raw materials to finished goods.	Reliability	Energy Used	Total electrical energy used for production.
		Reliability	Water used	Total water used for production.
		Reliability	Liquid Waste	Total liquid waste generated during the production process.
		Reliability	Solid Waste	Total solid waste generated during the production process.
		Responsiveness	Make Cycle Time	Total time required for manufacturing the finished product.
Deliver	Deliver activities include activities related to the delivery of products to customers.	Reliability	Shipping Document Accuracy	Total complete and correct shipping documents.
		Reliability	Delivery Quantity Accuracy	The total quantity of products delivered by the company in accordance with demand
		Responsiveness	Delivery Cycle Time	The total time taken is from when the product is packed until it is picked up by the delivery service.
Return	The activity of returning products for various reasons or not in accordance with the request	Reliability	% of Error Free Return Shipped	Percentage of products returned by customers.
		Reliability	Defective Product: Recyclable	Number of products returned as damaged or defective and recyclable

The study commences with the development of indicators for Green Supply Chain Management (GSCM). The Key Performance Indicators (KPIs) selected by researchers as variables and sub-variables are developed from a thorough assessment of literature studies, as can be seen in **Table 1**. These KPIs will then be validated by the company.

Subsequently, it is important to authenticate the GSCM performance indicators. The significance of this phase lies in its ability to identify the company's performance indicators for subsequent measurement. During this phase, a validation questionnaire was distributed to assess the existing state of the company's supply chain in relation to environmental factors. The stage involves evaluating the performance indicator information collected from the literature review and verifying it with company experts. The validation of KPI performance indicators will be distributed to PPIC Managers, Purchasing Assistant Managers, Quality Managers, Engineering Managers, Operational Directors, and HSE. These individuals have been selected due to their experience and knowledge of the company's supply chain process, which makes them well-suited to determine the company's GSCM performance measurement indicators. **Figure 4** below shows the indicators hierarchy based on the expert validation process.

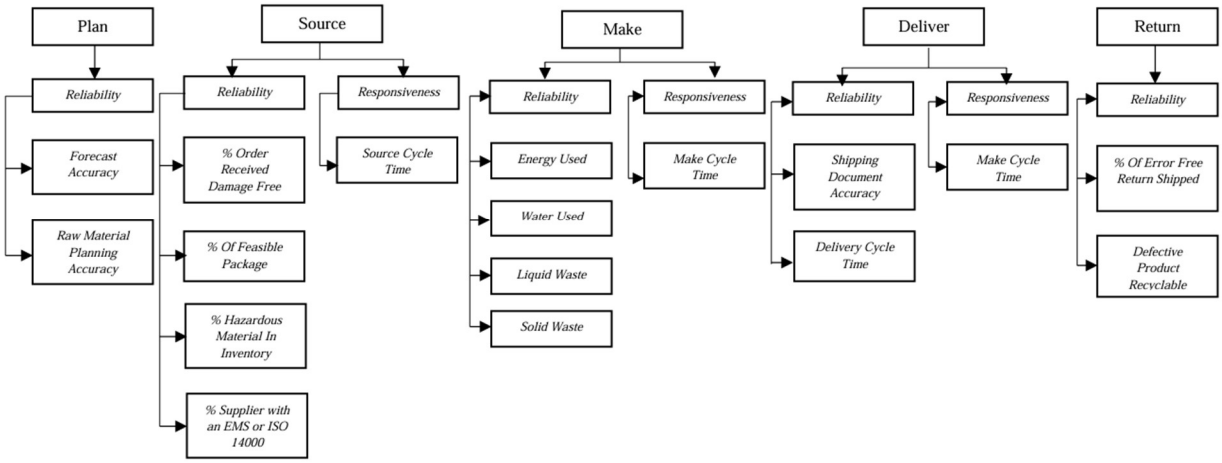

Figure 4. Indicators hierarchy.

Once the performance indicators have been validated, valid and feasible indicators will be acquired to measure the company's performance. Moreover, the significance of each job indicator is assessed using the Analytic Hierarchy Process (AHP) method. The AHP approach is employed as a weighting tool due of its ability to address both quantitative and judgmental difficulties. The limitation of the AHP weighting process in this research is that it only applies to the criteria and does not consider alternatives. The criteria are divided into three levels: at level one, the weighting is done between green SCOR processes; at level two, the weighting is done between attributes; and finally, at level three, the weighting is done between performance indicators.

Once the weight of the process, attributes, and performance indicators of GSCM has been determined using the AHP method, the next step will involve measuring GSCM performance. This will be done by collecting data on the company's green supply chain management performance from July to December 2021. The data will be

obtained through document studies focusing on each performance indicator process. Normalization is performed on each value of the performance indicators based on the data received from the corporate document research. Sumiati [24] defines the level of performance fulfillment as the normalization of these performance indicators. This is done due to the fact that each Key Performance Indicator (KPI) carries a distinct weight, which corresponds to a unique scale of measurement. To address this issue, it is necessary to implement a parameter equalization procedure, specifically through the process of normalization.

The Snorm De Boer normalization method considers zero (0) as the lowest value and one hundred (100) as the highest value for each performance indicator, representing the worst and best parameter, respectively. To clarify and facilitate understanding of performance measurement results, it is essential to use the Traffic Light System (TLS) method. This method categorizes performance values into three color categories: red, yellow, and green. The purpose of this categorization is to indicate whether the KPI score requires improvement or not. The red hue indicates that the indicator is below 60, signifying that the company's performance is unsatisfactory. Similarly, the yellow color indicates that the performance score is below 80, again indicating unsatisfactory performance. A performance score between 60 and 80 indicates that the company's performance is marginal. A performance score above 80, shown by the green hue, signifies good performance.

4. Result and discussion

4.1. AHP weighting performance indicators

The purpose of pairwise comparisons is to assess the significance of each indicator and assign weights to the three criteria levels. Performance indicators are assigned varied weights based on their respective levels of importance. The weighting mechanism assists in assigning priority to specific indications during the assessment of overall performance [32]. The first level consists of weighting criteria between processes, followed by weighting criteria between attributes at the second level, and finally weighting criteria between performance indicators at the third level.

Six corporate experts who comprehensively understood the organization's supply chain management completed the pairwise comparison questionnaire. For each expert, a separate pairwise comparison was conducted, where they scored the priority of each Key Performance Indicator (KPI) on a scale of 1 to 9. To consolidate these individual assessments into a single, representative pairwise comparison matrix, the geometric mean of the experts' scores for each comparison was calculated. This approach allows for the integration of diverse expert opinions while mitigating the impact of extreme values. The resulting consolidated pairwise comparison matrix was then input into the Expert Choice program as the result can be seen in **Table 2**.

Table 2. AHP weighting performance indicators.

Process	Level 1	Attribute	Level 2	KPI	Level 3
Plan	0.197	Reliability	1	Forecast Accuracy	0.24
				Raw Material Planning Accuracy	0.76
Source	0.344	Reliability	0.471	% Order Received Damage Free	0.24
				% Of Feasible Package	0.17
				% Hazardous Material in Inventory	0.23
				% Supplier with an EMS or ISO 14000	0.36
		Responsiveness	0.529	Source Cycle Time	1
Make	0.186	Reliability	0.774	Energy Used	0.65
				Waste	0.35
		Responsiveness	0.226	Make Cycle Time	1
Deliver	0.194	Reliability	0.317	Shipping Document Accuracy	0.601
				Delivery Quantity Accuracy	0.399
		Responsiveness	0.683	Delivery Cycle Time	1
Return	0.079	Reliability	1	% Of Error Free Return Shipped	1

4.2. Evaluating key performance indicator (KPI)

The subsequent task involves calculating the company's Key Performance Indicator (KPI) data, which includes all relevant information about the Key Performance Indicator (KPI) summarized for the period of July to December 2021. **Table 3** below is an illustration of the calculation process for forecast accuracy indicator:

Table 3. Forecast accuracy.

Month	Forecast Demand	Actual Demand	Forecast Accuracy
July	7,067,397	8,166,837	86.54
August	9,140,812	7,499,746	78.12
September	9,212,925	6,959,503	66.00
October	6,973,523	6,536,629	93.32
November	6,384,949	6,514,759	98.01
December	5,674,338	5,788,311	98.03

The data will undergo processing utilizing the Green SCOR methodology for each Key Performance Indicator (KPI). The data that has been handled before will be normalized by using the Snorm de Boer method. Here is an illustration of a calculation for the forecast accuracy indicator.

$$Forecast\ Accuracy = \left(\frac{87-66}{98-66}\right) \times 100 = 66$$

4.3. Performance score

After processing the data using the Green SCOR method for each KPI, the previously processed data will be normalized using the Snorm de Boer method. The

results in **Table 4** show that the final value of the company's performance is "80.1". This figure indicates that the company's current performance falls into the satisfactory category.

Table 1. Calculation of the final performance score.

KPI	Snorm	Final Weight	Norm × Weight	Final Score
Forecast Accuracy	66	0.05	3.1	
Raw Material Planning Accuracy	77	0.15	11.6	
% Order Received Damage Free	80	0.04	3.1	
% Of Feasible Package	100	0.03	2.8	
% Hazardous Material in Inventory	99	0.04	3.8	
% Supplier with an EMS or ISO 14000	47	0.06	2.7	
Source Cycle Time	89	0.18	16.3	80.1
Energy Used	36	0.09	3.4	
Waste	100	0.05	5	
Make Cycle Time	80	0.04	3.4	
Shipping Document Accuracy	100	0.04	3.7	
Delivery Quantity Accuracy	58	0.02	1.4	
Delivery Cycle Time	91	0.13	12.1	
% Of Error Free Return Shipped	100	0.08	7.9	

Table 5. Traffic light system.

KPI	Actual	Min	Max	Snorm
Forecast Accuracy	87	66	98	66
Raw Material Planning Accuracy	90	80	93	77
% Order Received Damage Free	98	94	99	80
% Of Feasible Package	100	98	100	100
% Hazardous Material in Inventory	0.0183	0.0004	0.0266	99
% Supplier with an EMS or ISO 14000	47	0	101	47
Source Cycle Time	352	350	369	89
Energy Used	691.355	571.751	760.069	36
Waste	1.2	1.0	1.5	100
Make Cycle Time	7.4	6.5	11.0	80
Shipping Document Accuracy	100	0	100	100
Delivery Quantity Accuracy	58	52	62	58
Delivery Cycle Time	62	61	73	91
% Of Error Free Return Shipped	100	99	100	100

The Traffic Light System is utilized to identify the specific areas of the company's GSCM performance that require improvement, depending on the essential criteria, as shown in **Table 5**. The Traffic Light System utilizes red, yellow, and green indicators. When the SNORM value falls below 60, it indicates subpar performance and activates the red indicator. If the SNORM score falls between 60 and 80, the yellow indicator indicates marginal performance. The green indicator is employed

when the SNORM number reaches 80, signifying commendable performance on the criterion.

4.4. Plan process

Two essential Key Performance Indicators (KPIs) are pivotal in the planning process: forecast accuracy and raw material planning accuracy. The color yellow represents the current forecast accuracy indicator, which has a score of 66. The previous research also experienced a similar scenario, with forecast accuracy hitting the yellow mark [33]. The score indicates the difficulties the business faces in effectively forecasting demand, primarily because there are several projects with uncertain requirements. The yellow level signifies that although the forecast accuracy is not dangerously poor, there is substantial potential for enhancement. Several factors influence forecast accuracy, including production-related factors, information-related factors, the human factor, and technology and tools [34]. To realize the benefits of improved forecast accuracy, companies must implement techniques to improve forecast accuracy and integrate the more accurate forecasts into their planning and management activities [35].

The second key performance indicator (KPI), which measures accuracy of raw material planning, is also indicated by a yellow color, but with a higher score of 77. The score can be deemed satisfactory, indicating that the firm is adequately addressing its raw material requirements in its planning process. The yellow status indicates that the current performance is satisfactory, but there are still possibilities for improving and optimizing the raw material planning process. Factors such as supplier reliability, inventory management techniques, and the precision of production plans are likely to impact this Key Performance Indicator (KPI). Active management of raw material sourcing can add value to supply chains through strategies like direct supply to suppliers or facilitating supplier cooperation, in contrast to a hands-off approach [36]. To mitigate risks in raw material planning such as supply continuity, delivery delays, knowledge gaps, and quality issues, it is recommended enhancing buyer-supplier coordination and information sharing, as well as implementing Supplier Relationship Management (SRM) systems [37].

4.5. Source process

The source process consists of five essential Key Performance Indicators (KPIs) that offer significant insights into the effectiveness and durability of the supply chain. The Key Performance Indicators (KPIs) consist of several metrics. These include “percentage of order received damage-free,” which measures the quality of received shipments; “percentage of feasible packages,” which assesses the practicality of packaging solutions; “percentage of hazardous material inventory,” which tracks the management of dangerous substances; “percentage of suppliers with an EMS or ISO 14000,” which evaluates the environmental management standards of suppliers; and “source cycle time,” which gauges the overall speed of the sourcing process. Out of these five Key Performance Indicators (KPIs), four show adequate performance, as shown by their green color markers. These KPIs are “percentage of order received damage-free,” “percentage of feasible package,” “percentage of hazardous material

inventory," and "source cycle time." This indicates that the organization is proficiently overseeing the majority of its sourcing process.

Nevertheless, the Key Performance Indicator (KPI) "percentage of suppliers with an Environmental Management System (EMS) or ISO 14000 certification" is particularly worrisome, as it is highlighted in red and has a score of only 46. These findings suggest that a considerable proportion of suppliers, specifically 101 vendors who provide raw materials directly, have not achieved ISO 14000 certification, which is an essential benchmark for environmental management systems. In order to resolve this matter and establish a consistent certification process throughout the supply chain, it is recommended that the organization enforce a policy mandating all 47 vendors who currently do not possess ISO 14000 certification to acquire it. Suppliers who adopted the EMS and ISO 14001 standards have a greater impact on performance and a positive influence on innovation and commitment to the environment related to company targets than those firms that did not apply them [38]. Moreover, companies implementing formal environmental management systems (EMS), especially certified ones like ISO 14001, experience benefits beyond pollution reduction, including improved overall operating performance and a tendency to make more environmentally friendly choices over time [39].

4.6. Make process

The Make process measures three distinct Key Performance Indicators (KPIs): Energy Utilization, Waste Generation, and Make Cycle Time. Out of these metrics, the Energy Used measure is particularly noteworthy due to its alarming red warning and a score of 36. The operational requirements of the company's production units primarily drive its high energy consumption, contributing to its low score. The increased energy consumption not only has an influence on the company's environmental impact, but also has a substantial effect on operational expenses and overall efficiency.

In order to tackle this crucial matter, the organization should adopt a complete approach focused on energy management and sustainability. Evaluating end-energy uses and implementing measures to reduce energy consumption can improve energy efficiency in the industrial sector [40]. An exhaustive examination of the overtime schedule is also essential, with the goal of reducing excessive energy usage during off-peak hours. Moreover, it is highly recommended to gradually shift from traditional energy sources to more environmentally friendly alternatives. An explicit suggestion is to substitute fossil fuel-powered machinery with environmentally friendly alternatives, such as hydrogen-powered fuel cell forklifts. Better monitoring and control of energy consumption and performance indicators are important for improved energy efficiency performance in manufacturing for current and future enterprises [41]. Performance-based indicators are one way to enable companies to set energy efficiency targets for manufacturing facilities [42].

4.7. Deliver process

The delivery process is an essential element of supply chain management, which includes three vital key performance indicators (KPIs): Shipping Document Accuracy,

Delivery Quantity Accuracy, and Delivery Cycle Time. Although two of these key performance indicators (KPIs) are showing positive results, as evidenced by their green status, the Delivery Quantity Accuracy metric is currently in a critical state with a score of 57, indicated by the red zone. The main reason for this underperformance is the disparity between the production volume and the quantity of products delivered to clients. This is a result of the company's strategic decision to keep a stock of products for consumers rather than send all manufactured items directly to customers.

Although this inventory management approach may lead to a disparity in the Delivery Quantity Accuracy Key Performance Indicator (KPI), it plays a crucial role in the company's broader supply chain strategy. Management initiatives to improve delivery performance are best focused on informational flows within the supply chain and leveraging new process technologies that offer flexibility to respond to uncertainty [43]. Through the use of buffer stock, the company guarantees its capacity to constantly fulfil consumer demand and reduce the likelihood of stock shortages. This proactive technique aims to improve customer satisfaction and provide a dependable supply chain, even if it leads to a temporary discrepancy between production and delivery numbers. Meanwhile, the positive status of the Shipping Document Accuracy and Delivery Cycle Time KPIs indicates that the organization is operating well in these areas, demonstrating effective documentation processes and punctual deliveries.

4.8. Return process

Returns management is the supply chain management process by which activities associated with returns, reverse logistics, gatekeeping, and avoidance are managed within the firm and across key members of the supply chain [44]. A single Key Performance Indicator (KPI) is used within the return process: the percentage of errors. Return at no cost. The product received a score of 100 and is indicated as "green," indicating satisfactory performance for the Key Performance Indicator (KPI). This is due to the minimal number of customer returns. Additionally, returned products are destroyed, and the final product is sold, generating economic value from the returned item. This process demonstrates a highly efficient return system that not only minimizes errors but also maximizes customer satisfaction through a no-cost return policy. The "green" score reflects the company's success in maintaining product quality and meeting customer expectations, resulting in few returns. Furthermore, the company has implemented a sustainable approach to handling returned items by destroying them and selling the final product, thereby recouping some of the costs associated with returns and reducing waste. This comprehensive strategy showcases the company's commitment to customer service, quality control, and environmental responsibility, all while maintaining a positive economic impact.

5. Conclusions

According to the Green SCOR approach, the company's measurement findings indicate a positive performance, with a score of 80.1 out of 100, placing it in the Good category. This score reflects the company's overall commitment to sustainable supply chain practices. However, the evaluation also highlighted areas for improvement, as

three out of the 14 Key Performance Indicators (KPIs) were classified as red, signaling the need for targeted enhancements.

To address these areas of concern, several improvements have been suggested for PT CP. First, the company should require all direct and indirect material suppliers to obtain ISO 14000 certification. This aligns with ISO 14001:2015 clause 8.1, which emphasizes the importance of communicating environmental standards to external providers, including contractors. By implementing this requirement, PT CP can ensure a standardized approach to environmental management across its supply chain.

Secondly, the company is advised to implement measures to regulate energy use and evaluate overtime patterns. This recommendation aims to reduce the company's reliance on electrical energy, potentially lowering costs and environmental impact. Additionally, there is a strong emphasis on exploring alternative energy sources, such as adopting fuel cell forklifts that use hydrogen instead of fossil fuels. This initiative demonstrates a commitment to innovation and sustainability in the company's operations.

Lastly, effective inventory management is highlighted as a crucial area for improvement. This recommendation is in line with clause 8.1 of ISO 14001:2015, which stresses the importance of monitoring and measuring operations to ensure desired outcomes. By implementing strategic inventory management practices for both consumer materials and products, PT CP can avoid excess stock, reduce waste, and optimize its supply chain efficiency. This approach not only supports environmental sustainability but also has the potential to improve the company's overall operational performance and cost-effectiveness.

5.1. Limitation

While this study provides valuable insights into PT CP's green supply chain management performance, it is important to acknowledge certain limitations. The small sample size of six experts, though representative of key decision-makers within the company, limits the generalizability of the findings to broader contexts or other organizations. The cross-sectional nature of this study provides only a snapshot of the company's GSCM performance at a single point in time, rather than capturing changes over an extended period. Additionally, data collection challenges, such as potential bias in expert opinions or limitations in accessing certain types of data, should be considered when interpreting the results.

5.2. Future Research

Future research should utilize the fuzzy AHP approach as a weighting criterion. This approach is expected to produce more complex and subtle outcomes, improving the thorough analysis in evaluating green supply chain management. Companies aiming to enhance their green supply chain performance and obtain more precise measures should consider exploring options that enable more nuanced assessments. Utilizing sophisticated approaches and measuring tools can help gain a thorough comprehension of the company's environmental sustainability practices, assisting in pinpointing areas that can be improved.

Author contributions: Conceptualization, AMD and SAW; methodology, SR;

software, SAW; validation, YT; formal analysis, AMD; investigation, SAW; resources, AMD; data curation, SAW; writing—original draft preparation, AMD; writing—review and editing, SR; visualization, AMD; supervision, YT; project administration, AMD; funding acquisition, SAW. All authors have read and agreed to the published version of the manuscript.

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Article

Fostering a greener workplace: Assessing the impact of green human resource and low carbon behavior

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Abstract: Businesses in China are embarking on a transformative agenda, as reflected in their environmental performance, which signals a strategic shift towards fostering sustainability initiatives in the workplace. Accordingly, the research explores how green human resource management, organizational commitment, and green innovation climate drive low-carbon behavior and environmental performance. The research gathered 580 responses from senior staff among Chinese small and medium-sized enterprises. The partial least square structural model was employed to assess the study hypothesis. Key study findings are enumerated: First, green human resource management boosts green organizational commitment, green innovation climate, and low-carbon behavior. Second, the data showed that a green innovation climate and organizational commitment enhance low-carbon behavior. Third, according to the study, low-carbon promotes environmental performance. Fourth, the paper analysis showed that low-carbon mediated the connection between green human resources and low-carbon behavior. Fifth, this research outcome highlighted that environmental knowledge moderates the linkage between low-carbon behavior and environmental performance. This finding enriches the debate on green human resource management and how to promote low-carbon behavior and environmental performance.

Keywords: green human resource management; green organizational commitment; green innovation climate; environmental performance; low carbon behavior

1. Introduction

One significant challenge affecting the sustainability of humanity and natural resources is global environmental degradation. Due to the high-rate trends of CO_2 emissions and greenhouse gas emissions, all countries must consider their economic and environmental challenges [1–3]. Moreover, as Wiredu et al. [4] indicated, humans must address the world's most critical concerns, such as environmental pollution, which has emerged due to the reckless pursuit of economic gains at the expense of social and ecological benefits. Although SMEs promote economic growth and create jobs, new business models and technological change have become increasingly necessary. Thus, it is worth solving these problems by investigating how SMEs can improve their environmental performance (EP). Since SMEs operate mostly in a community, they cause environmental pollution [5]. This research focused on China because the country stands among the globe's most populous nations and is a significant player in the world economy, especially in the SME sector. China has initiated numerous policies and plans to promote green practices as a country actively addressing ecological issues and challenges and is committed to

achieving sustainable development. Focusing on China, this paper seeks to contribute novel insight into the mechanisms that drive low-carbon behavior (LCB) from the perspective of SMEs operating in the evolving Chinese business sector.

Low-carbon behavior (LCB) has become a topic of discussion in improving environmental sustainability among businesses. LCB can be defined as the intentional awareness and practices people engage in to avoid potential adverse environmental effects [6]. LCB involves the implementation of eco-friendly and sustainable habits in industrial processes, business operations, and daily life to mitigate climate change. This concept encourages organizations, communities, and individuals to prioritize environmentally responsible actions, energy efficiency, and renewable resources. Therefore, it is essential to understand the drivers of SMEs' staff's LCB and how it affects their EP. Accordingly, GHRM, as demonstrated by prior studies, is an innovative approach to managing human capital within organizations that prioritizes sustainability and ecological responsibility [7,8]. Additionally, GHRM incorporates environmental factors into HR procedures, including hiring, training, performance reviews, and staff involvement [8]. The focal point of GHRM is to foster a culture of sustainability within the workforce, encouraging employees to adopt eco-conscious behaviors at work and in their personal lives. Moreover, to mitigate these toxic emissions, SMEs have begun creating a green innovation climate (GIC) to reduce the environmental repercussions of production processes. GIC is an innovation aspect that focuses on eliminating waste, controlling emissions, and integrating environmental practices [9,10]. Also, the GOC of employees has been established by existing literature to be a significant predictor of the LCB of individuals [11,12].

Additionally, environmental knowledge (ENK) is recognized as an essential internal resource that enables individuals to adapt and understand the dynamic ecological landscape. Thus, ENK empowers businesses to identify sustainable initiatives that comply with environmental regulations and reduce resource consumption, ultimately enhancing the company's resilience and reputation. Existing literature has also predicted the role of ENK in enhancing LCB and EP [13]. Hence, this research explores the moderation role of ENK in the research model. ENK is the classical sense of factual information, such as knowledge about ecosystem processes, functions, and structures [14]. Hence, this study argues that adding ENK as a moderator is essential to understanding how it can enhance LCB and EP. Subsequent literature has established the direct effect of ENK on LCB [15,16], but a theoretical gap exists on the moderation role of ENK in this relationship. Hence, this study fills this gap by providing empirical findings on the influence of ENK on the relationship between LCB and EP. The objectives of this research include:

(1) Exploring the influence of GHRM on GIC, GOC, and LCB.
(2) Investigate the impact of GIC and GOC on LCB.
(3) Analyze the impact of LCB on EP.
(4) Determine the mediation effect of LCB on the connection between GHRM and EP.
(5) Lastly, evaluate the moderation role of ENK on the link between LCB and EP.

Based on the research objectives, the formulated research questions are as follows:

RQ (1) How does GHRM influence green innovation climate, green organizational commitment, and low-carbon behavior? RQ (2) What is the impact of GIC and GOC on LCB? RQ (3) How does LCB affect environmental performance (EP)? RQ (4) Does LCB mediate the relationship between GHRM and EP? RQ (5) What is the moderating role of environmental knowledge (ENK) in the relationship between LCB and EP?

This article enriches the body of knowledge in environmental and GHRM literature by dissecting how green organizational commitment, green innovation climate, environmental knowledge, and low-carbon behavior stimulate environmental performance. This finding enriches the discussion on the importance of GHRM and the appropriate mechanisms needed to strengthen LCB and EP. The novelty of this paper involves the comprehensive assessment of the pathway toward fostering low-carbon behavior, incorporating a multi-dimensional framework. The paper uniquely integrates the domains of GHRM, GOC, and the GIC to elucidate their collective impact on promoting environmentally conscious behaviors. Furthermore, the research introduces the moderation effect of ENK, emphasizing the significance of individual awareness and understanding of environmental issues in influencing the interplay between organizational practices and LCB.

Theoretically, this study comprehensively analyses the pathway to fostering low-carbon behavior within organizations, drawing upon the ability, motivation, and opportunity (AMO) theory. The paper integrates key elements, including GHRM practices, GOC, and a supportive green innovation climate. In addition, the integration of GHRM, GOC, and GIC underscores the connection of these indicators in fostering LCB and EP. The study also recognizes the essential role individuals within the enterprise play in stimulating EP and emphasizes the importance of supportive organizational innovation and culture in improving LCB. The mediation analysis provides a holistic approach to understanding the mechanism through which LCB can improve the nexus between GHRM and EP. Hence, the current analysis provides enormous practical implications for scholars, stakeholders, and government, providing a roadmap for improving environmentally responsible practices among SMEs in China. Lastly, this paper employed the PLS-SEM, which provides a unique statistical tool to assess a research model's direct, indirect, and moderation effects.

This research is original in its integrated exploration of green human resource management, organizational commitment, and green innovation climate as key drivers of low-carbon behavior and environmental performance within Chinese SMEs. It uniquely identifies the mediating role of low-carbon behavior between green HR practices and environmental outcomes and the moderating effect of environmental knowledge on the relationship between low-carbon behavior and environmental performance. These novel insights contribute to the growing discourse on fostering sustainable workplace practices, offering practical implications for enhancing environmental performance through strategic human resource and innovation initiatives.

This study was divided into six central portions. The primary subjects of Section 1 are the study's history, objectives, and significance to ecological sustainability. Section 2 captures the theoretical background and statement of the

hypothesis. The procedures employed are described in Section 3. The conclusions from the PLS-SEM investigation are further provided in Section 4. Section 5 emphasizes this paper's interpretation, which has implications for theory and practice. Section 6 offers the conclusion and suggestions for additional research.

2. Literature review and hypothesis formulation

The literature review commenced by meticulously assessing relevant search engines, including Web of Science, Scopus, and PubMed platforms, to provide transparency and rigorous evaluation of prior literary works. Considering targeted search terms such as "GIC", "GOC", "LCB", "GHRM," and "EP", the study systematically went through the abundance of literature, making sure every piece was relevant to the main themes of the current. The literature process focused on peer-reviewed articles. Following stringent publication guidelines from 2002 to 2024, the study sorted through the papers we had retrieved and ensured they fit the objectives of the current study. Using a systematic approach made obtaining a large dataset of academic publications for analysis easier. It guaranteed that the publications were categorized according to their relevance to the research questions. The next section of the literature focused on the theory and hypothesis outlined in the study.

AMO theory proposed by Appelbaum et al. [17] has been generally applied in analyzing the performance of GHRM practices. As suggested by the AMO theory, GHRM practices affect staff's ability (for instance, training and development, recruitment process), motivation (for instance, compensation, reward system, and incentives), and opportunity (for instance, empowerment and teamwork) to promote overall SMEs performance [18]. The AMO theory provides a comprehensive theoretical model for understanding the nexus between the key variables influencing LCB and EP. GHRM is essential in improving employees' abilities by fostering knowledge and skills associated with environmental stability [19]. In addition, GOC contributes to the motivation aspect of the AMO by instilling a sense of shared direction and value to environmental goals. Furthermore, creating GIC provides the necessary opportunities for staff to participate actively in ecologically friendly actions. Additionally, ENK acts as a catalyst, facilitating the integration of green actions and practices within the firm. These concepts create a synergistic influence, aligning organizations and individuals' abilities, motivation, and opportunities towards engagement in LCB and enhancing firms' EP.

The RBV was proposed by Barney et al. [20], where the researcher argued that an enterprise's success or growth depends on internal resources, indicating that inadequate resources hinder a firm's growth and development. This theory focuses on a firm's internal resources to create a competitive advantage [21]. Internal resources combine all available facilities and strengths to help enhance the development of firm value co-creation activities [22]. Moreover, the RBV theory stresses that firm performance and competitive advantage depend on how it can utilize the available strategic internal resources that are valuable, rare, imitability, and organization (VRIO) to be copied by a rival enterprise in the market [23]. Hence,

in this study, the researcher applied the RBV to analyze the EP of firms; thus, these concepts were linked to this theory, which includes (GIP, GOC, and ENK).

2.1. Hypothesis on GHRM

GHRM refers to HR policies and practices that motivate, inspire, and empower employees in a firm to engage in GIC, GOC, and LCB, eventually improving enterprises' EP. This section of the paper provides empirical studies exploring the influence of GHRM on GIC, GOC, and LCB. For example, Elshaer et al. [24] reported that GHRM directly impacts two different types of LCB (proactive and task-oriented). Their research further revealed that employee LCB mediates the linkage between GHRM and EP. Moreover, in Malaysia, the analysis by Naz et al. [25] explored the role of GHRM practices toward the LCB. Their research outcome indicated that GHRM (green discipline and green training and development) are essential predictors of LCB among 374 green hotel workers. Also, their study showed that GHRM indirectly improves EP through the LCB of the workforce. In addition, Ansari et al. [26] assessed the influence of GHRM on GOC and LCB. The empirical outcomes showed that GHRM affects staff GOC and LCB. Moreover, their findings indicated that GOC mediates the connection between GHRM policies and LCB. Shah and Soomro [27] explored the connection between GHRM and GIC among automobile firms in Pakistan. The study found a direct nexus between GHRM practices such as performance, rewards, compensation, development, and GOC. Similarly, Meng et al. [28] assessed the influence of GHRM on LCB, and the research employed a green lifestyle as the intermediary indicator and green share values as the iterative factor. Their study received 347 responses from hotel staff in China. The empirical results from the PLS-SEM approach indicated that GHRM has a favorable linkage with staff LCB and green lifestyle. The conclusion from the research proved that GHRM stimulates employees' LCB. Therefore, based on empirical evidence and the AMO theory, this research suggests that:

H1: GHRM contributes positively and significantly to GIC among SMEs.

H2: GHRM contributes positively and significantly to GOC among SMEs.

H3: GHRM contributes positively and significantly to LCB among SMEs.

2.2. GIC and LCB

GIC relates to all aspects of innovation targeted at pollution control, energy preservation, waste reduction, waste reprocessing, and ecological management initiatives. GIC activities have been related to firms engaging in eco-friendly products, using advanced technology for production, green skills, clean technology, efficient use of resources, and creating a green workplace environment as outlined by the RBV model [29,30]. GIC is an intermediary mechanism enterprises use to control environmental pollution and improve the organization's EP. Moreover, GIC relates to enterprise environmental management strategies that stimulate LCB and environmental performance. The direct association between proactive actions such as GIC and EP through environmental practices has been established [31,32]. LCB denotes employees' attitudes and behavior towards GIC, climate change, and low-carbon society. These studies acknowledge that firms' GIC is an essential factor that

improves LCB [33–35]. Grounded on the above explanation and the AMO theory, this paper suggests that:

H4: GIC positively and significantly influences stimulating LCB among SMEs.

2.3. GOC and LCB

GOC is defined as the perceived feelings and obligation to protect environmental degradation, assuming employees more committed to the environment are more likely to participate in LCB. Organizational commitment toward a particular program ensures highly committed workers have a higher GIC and improve LCB, established in the RBV theory [36]. GOC optimizes the relative strengths of staff relationships and identification with green initiatives proposed by their firm. GOC develops employees' faith to help firms implement green projects and plans to enhance LCB [37]. The three most important GOC concepts are continuance, affective, and normative commitment [38]. Firms' recognition, affiliation, and participation in achieving set objectives, such as higher EP, can be classified as affective commitment. According to the RBV proposition, the awareness of the consequences of not engaging in the preservation of the environment leads to a continuance of commitment. Normative commitment relates to the alleged obligation to sustain a higher level of EP [39–41]. Likewise, Fatima et al. [42] indicated that these concepts of GOC have a significant association with other factors like employment sustainability and LCB. Accordingly, this study suggests that:

H5: GHRM contributes positively and significantly to building LCB among SMEs.

2.4. LCB and EP

LCB is defined as improving the concept of a low-carbon environment through behavior such as energy conservation, recycling, and promoting environmental sustainability. Achieving environmental sustainability is an urgent agenda item for firms that want to simultaneously achieve economic goals and more outstanding EP [25,43]. Furthermore, Darvishmotevali et al. [43] specified that worker LCB significantly impacts EP. Employees' active participation in environmental decisions and LCB that address environmental challenges are presumed to be effective mechanisms and strategies for firms to become environmentally responsible, thereby improving EP [44,45]. The AMO theory captures that people's actions, especially those of employees in a firm, can directly affect the achievement or the non-achievement of firms EP [46]. Hence, Sampene et al.'s [47] study revealed that various environmental efforts, including new sustainable product development, processes, models, and technological advancements, are strategies SMEs can utilize to mitigate environmental dilapidation and increase EP. In this study, the researcher contends that engaging in LCB at the workplace will enhance SMEs' EP. Thus, a higher level of LCB will lead to a higher level of EP. As a result, this study hypothesized that:

H6: LCB positively and significantly influences EP.

2.5. Mediation of LCB

LCB comprises employee behavior that contributes to the improvement of environmental sustainability. Such behavior is generally shown in the workplace (such as waste separation, energy preservation, and sharing information about ecological sustainability among employees) [48]. People's behavior significantly contributes to the destruction of the environment through water and land, loss of biodiversity, and pollution from chemicals. LCB is generally associated with environmental challenges [49]. Kim and Lee [50] suggest a tripod of antecedents that affect people's LCB, including their exceptional traits, their results and actions, and the environment in which people exist by mutually affecting each other. Prior literature has revealed different categories of a person's LCB depending on the level of effort and engagement (for instance, individual to collaborative engagement) [50,51]. From the perspective of the AMO theory, this will stimulate the employee's discretionary sense and responsibilities towards the GOC and increase their LCB. Thus, the staff becomes more responsible for tasks and activities that promote ecological sustainability and meet the GHRM targets, enhancing the firms' EP [52]. Accordingly, the current article proposes that LCB mediates the link between GHRM and EP.

H7: LCB mediates the link between GHRM and EP.

2.6. Moderation of environmental knowledge

ENK refers to an individual consciousness about the consequences of their actions and actions (use of harmful chemicals and products) on the natural ecosystem. Employees are known for applying their expertise, experience, and talents to meet the needs and objectives of the business. Nevertheless, one's ENK may or may not participate in LCB, and as a result, the effect of LCB on firms' EP may depend on employees' ENK level [53]. In support of the RBV theory, employees with ENK are essential resources for adopting, developing, and executing green marketing and innovation, which affect firms LCB and EP. Moreover, ENK of staff drives them to think outside the box, provide solutions to environmental problems, and further engage in LCB, improving firm EP [54]. ENK, according to the RBV model and Paço and Lavrador [55], is the pursuit of alertness and knowledge about environmental issues to solve this challenge. Environmentally conscious individuals are more likely to purchase organic, natural, and green items and participate in green initiatives [56,57]. Employees at ENK have the potency to motivate tasks and actions to promote environmental stewardship, which results in LCB and EP [58]. Naz et al. [25] found that ENK moderates the association between LCB and EP among Chinese firms. The influence of the moderation of ENK on the interplay among LCB-EP remains limited in environmental studies. Hence, this study argues from the RBV model context that the ENK level among employees can enhance the interplay between LCB and EP. Moreover, this paper proposes that staff with a greater level of ENK are expected to put this accumulation of knowledge into practice by demonstrating LCB compared to those with lower levels of ENK. Thus, this investigation hypothesizes that:

H8: ENK positively moderates the link between LCB and EP.

2.7. Knowledge gap

To further clarify the knowledge gaps and the theoretical foundation of this study, we elaborate on the gaps in the current literature and justify the importance of examining these relationships. Despite the extensive literature on GHRM, organizational commitment, and green innovation climate, there is limited research exploring the combined impact of these factors on fostering low-carbon behavior and enhancing environmental performance. Specifically, the mediating role of low-carbon behavior and the moderating influence of environmental knowledge have not been thoroughly addressed in prior studies. Utilizing the AMO theory, this study aims to fill these gaps by providing a clear framework on how GHRM practices enhance employee ability, motivation, and opportunity to engage in low-carbon initiatives, promoting an organizational climate conducive to green innovation and environmental performance. The assumptions underlying the proposed relationships are based on the premise that GHRM enables employees to adopt sustainable behaviors, subsequently leading to enhanced environmental outcomes. This approach, grounded in AMO theory, offers a comprehensive understanding of the mechanisms through which green HR practices can drive sustainability in the workplace, thereby contributing valuable insights to the ongoing discourse on environmental performance in organizational settings.

2.8. Conceptual model

The conceptual archetype for this paper is displayed in **Figure 1**.

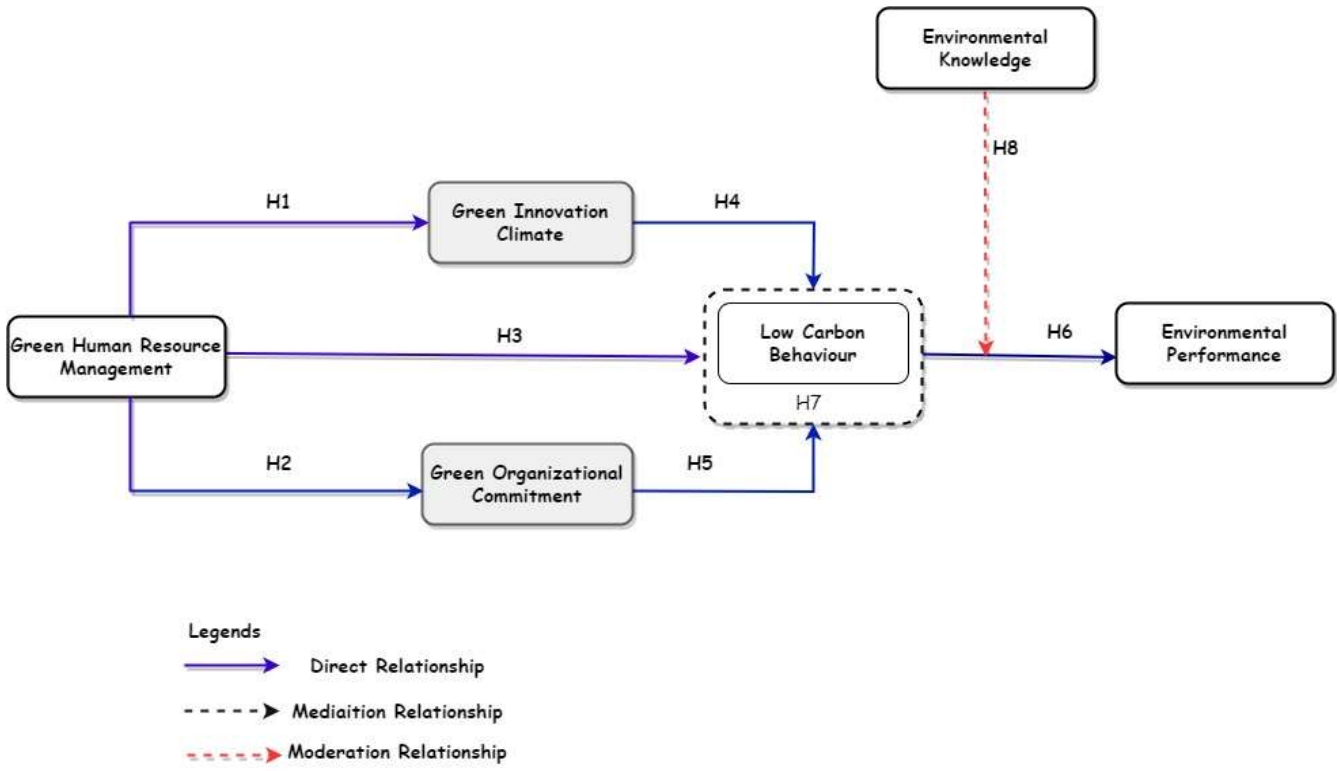

Figure 1. Conceptual model of the study.

3. Research methodology

3.1. Context selection

Ecological issues in China remain pressing, with industrial emissions exerting significant strain on water, air, and environmental quality. Despite efforts to curb pollution, challenges persist, affecting health and ecological balance nationwide. Hence, collaborative efforts and stringent regulations are imperative to alleviate the environmental pollution impacting China's landscape. Accordingly, this paper focused on top-level managers from SMEs in diverse cities in Jiangsu, including Nanjing, Zhenjiang, Suzhou, Wuxi, and Changzhou. The selection of Jiangsu province stems from its renowned economic and industrial prowess, making it an ideal setting to explore the dynamics of environmental initiatives within the workplace. In addition, Jiangsu's proactive approach to sustainable development and environmental conservation fits in nicely with the goals of our study, offering a favorable setting for analyzing how environmental knowledge influences workplace practices and performance results. The study targets small and medium-sized enterprises (SMEs) in Jiangsu, China, which represents a significant hub of industrial activities, with over 13,000 enterprises actively contributing to the province's economic output [59]. These SMEs are characterized by their adaptability, innovation potential, and substantial influence in local supply chains, which makes them critical drivers of regional sustainability efforts. The enterprises selected for this research vary in size, industry, and stages of digital transformation, providing a diverse representation of the SME sector. Focusing on Jiangsu is justified by the province's strategic role in China's economic development and its prominence in manufacturing and technological innovation. SMEs in this region are particularly under pressure to align with China's sustainability agenda, making them a relevant context for understanding how green human resource management practices and low-carbon behaviors can enhance environmental performance.

3.2. Operationalization of constructs

Employing a comprehensive strategy and improving the questionnaire's precision, the research employed the five-point Likert scale questionnaire designed for conducting surveys and gathering data. Considering the participants' diverse backgrounds and acknowledging English as a predominant communication channel, ensuring language accessibility was important in this study. Hence, the questionnaire was meticulously translated into Chinese to address this issue. Five bilingual experts with extensive international academic experience were recruited to evaluate the questionnaires' ease of understanding. These experts worked together to guarantee that the questionnaires were adapted as smoothly as possible. To improve the validity of the questionnaires, professionals from business and academia were consulted, and the survey questions were refined to adhere to established constructs. Additionally, pilot research was conducted, and the target audience was provided with updated survey questionnaires to fill out. This pilot study provided invaluable input for improving indicators and supporting the validation procedure, emphasizing the iterative process inherent in creating questionnaires.

The main questionnaire was categorized into two main sections. Thus, the first section included descriptive information about the participants. The second section outlined the measurement of the constructs. The construct of GHRM was retrieved from Ren et al. [60] and Bin Saeed et al. [45] and measured with six items. GIC was evaluated with five items taken from the research by Fatoki [61] and Makhloufi et al. [62]. GOC was evaluated with six items generated by Iqbal et al. [63]. Also, the studies retrieved LCB constructs, including seven items by Lange [64] and Bin Saeed et al. [45]. Five items were employed to assess ENK, and the measures were sourced from Karmoker et al. [18] and Usman et al. [65]. The study measured EP with five items adapted from Ubeda-Garcia et al. [66]. The appendix contains information about measuring items, including their respective codes and sources.

3.3. Sampling approach and data collection process

The research's philosophical background aligns with the positivist paradigm, which uses deductive mechanisms to understand an underlying phenomenon [67]. The study used purposive sampling to select the SMEs. The purposive sampling approach ensured the inclusion of SMEs with varying capacities and challenges in sustainability, allowing for an in-depth exploration of the factors driving green initiatives in this crucial economic sector. Therefore, the study applied Brewer and Miller [68] to calculate the sample size, which is outlined as follows:

$$n = \frac{N}{1 + N(\propto^2)}$$

here

N = represents the sample frame

n = depicts the size of the sample

$\propto$ = identifies the level of significance

The sample size calculation included a confidence level of 95% with a 5% margin of error. Hence, the level of significance is set at 0.05. Hence:

$$n = \frac{1300}{1 + 1300(0.05^2)}$$

$$n = \frac{1300}{4.25}$$

Hence, $n = 305.88$.

Based on the result from this calculation, the study's sample size is estimated to be 306. Accordingly, the study increased the sample size to 675 respondents from different SMEs across the Jiangsu province to gather accurate data and cover incomplete, unreturned, and unanswered questionnaires. The study employed online (use of emails) and physical data collection modules to gather the participants' responses. The authors employed diverse approaches through visitation, telephone calls, and emails to remind participants about the importance of engaging in this survey. After two to three rounds of reminders were sent to the participants, the study received 625, out of which 45 were deemed incomplete responses. The data collection process lasted almost six months (August 2023 to January 2024). The final analysis was evaluated with 580 responses, indicating a response rate of 92.28%.

This study engaged participants with direct experience with GHRM practices, individuals committed to the establishment's green agenda, and those working in an environment that fosters green innovation.

3.4. Analytical approach

This study applied the PLS-SEM because it is well-suited for predictive modeling. It can be used to develop and validate models explaining the link between latent and observed indicators, enabling the study to make predictions and test hypotheses [69]. The PLS-SEM provides insights into the quality of the measurement items and allows for identifying and removing items that do not contribute significantly to the model [70]. Moreover, PLS-SEM allows for integrating different data sources and measurement methods. It can handle both reflective (e.g., Likert scales) and formative (e.g., composite) measurement models, allowing researchers to combine diverse data types in their analysis [71]. In addition, this method is well-suited for exploratory analysis and theory development. It can identify underlying latent dimensions or constructs in a dataset and generate new insights or theories based on the relationships uncovered. It provides various methods for comparing alternative models and evaluating model fit [72].

3.5. Common method bias

Common method bias (CMB) can lead to increased standard errors of regression coefficients, making it difficult to distinguish the specific effects of each predictor variable on the dependent variable. By identifying and handling multicollinearity, the study can obtain more precise and informative interpretations of the interactions between variables. The likelihood of multicollinearity among the studies was therefore investigated using the variance inflation factor (VIF) assessment. The outcomes of this research demonstrate that all of the component's VIF scores of 50% (< 5.00) are below the suggested threshold by Harman [73], proving that the study was free of collinearity and CMB problems. Without accounting for the potential CMB issues with the study dataset, the VIF in this study was 29.37%. Furthermore, steps were taken to mitigate the possible effects of social desirability bias, including informing those participating on the goals of the investigation and guaranteeing their privacy.

4. Results

4.1. Demographic analysis

The sample comprised 58% male and 42% female respondents (see **Table 1**). Regarding firm age, 23% were 1–5 years old, 37% were 6–15 years old, 27% were 16–20, and 13% were more than 20 years old. Educational backgrounds varied, with 24% having a high school education, 50% holding a degree, 14% with a master's, and 12% with a PhD or higher. Job positions were distributed among senior managers (30%), supervisors (44%), and middle-level managers (26%). Respondents represented various industrial sectors: food and beverage (22%), basic iron and steel (16%), petroleum and chemical products (27%), textile and clothing (23%), and

furniture and others (12%). Firm sizes were divided into small (46%) and medium (54%) enterprises.

Table 1. Profile of respondents.

Demographic Indicator	Characteristics	Frequency	Percentage (%)
Gender			
	Male	325	58
	Female	255	42
Age of firm			
	1–5 years	133	23
	6–15 years	216	37
	16–20 years	155	27
	More than 20 years	76	13
Educational Background			
	High School	144	24
	Degree	288	50
	Master	80	14
	PhD and above	68	12
Job Position			
	Senior Manager	178	30
	Supervisor	254	44
	Middle-level Manager	148	26
Industrial Sector			
	Food and Beverage	127	22
	Basic Iron and Steel	95	16
	Petroleum and Chemical Products	160	27
	Textile and Clothing	128	23
	Furniture and Others	70	12
Firm Size			
	Small	268	46
	Medium	312	54

4.2. Convergent validity and reliability of constructs

The paper applied various tests, including Crochbach reliability, Cronbach's alpha, factor loadings, and average extracted variance (AVE). These tests are conducted to examine the internal reliability of the constructs. Manley et al. [74] proposed that the Crochbach reliability, Cronbach's alpha factor loadings, and statistical values should exceed 0.70. As indicated in **Table 2**, the data analysis for the indicators is reliable and valid. Hence, the statistical values of all the constructs were within the recommended threshold, inferring that the scales in this research have internal reliability among the constructs.

Table 2. Outcome of the measurement model.

Indicators	Items	Factor Loadings	Cronbach's alpha ($\alpha > 0.7$)	Composite reliability(ρc) (> 0.7)	AVE (> 0.5)	VIF
GHRM	GHRM1	0.737	0.851	0.869	0.602	1.695
	GHRM2	0.800				2.177
	GHRM3	0.862				2.879
	GHRM4	0.881				1.291
	GHRM5	0.875				1.458
	GHRM6	0.878				
GIC	GIC1	0.722	0.815	0.822	0.528	1.425
	GIC2	0.781				1.015
	GIC3	0.848				2.937
	GIC4	0.876				1.204
	GIC5	0.866				2.293
GOC	GOC1	0.803	0.837	0.944	0.673	2.424
	GOC2	0.848				2.441
	GOC3	0.830				2.260
	GOC4	0.835				2.725
	GOC5	0.873				2.508
LCB	LCB1	0.826	0.851	0.850	0.631	2.664
	LCB2	0.809				1.798
	LCB3	0.784				1.695
	LCB4	0.771				2.177
	LCB5	0.818				2.879
	LCB6	0.844				1.294
	LCB7	0.710				
ENK	ENK1	0.878	0.902	0.915	0.633	1.081
	ENK2	0.891				2.586
	ENK3	0.756				2.941
	ENK4	0.810				2.629
	ENK5	0.803				2.821
EP	EP1	0.813	0.833	0.927	0.589	1.813
	EP2	0.715				1.774
	EP3	0.708				2.837
	EP4	0.878				2.871
	EP5	0.790				1.844

4.3. Discriminant validity

Discriminant validity is a crucial aspect of construct validity, which refers to the extent to which a measurement precisely captures the intended theoretical construct. According to Henseler et al. [75], a study model is considered valid if the structural model constructions fall under the cutoff of 0.90. The study applied the Heterotrait-Monotrait (HTMT) and Fornell and Larcker criterion. The HTMT and Fornell and

Larcker [76] results, as indicated in **Table 3**, demonstrate that the proposed model of this study had good psychometric properties.

Table 3. Results of discriminant validity.

Fornell and Larcker, (1981) Criteria						
	GHRM	GIC	GOC	ENK	LCB	EP
GHRM	0.776					
GIC	0.322	0.632				
GOC	0.637	0.408	0.671			
ENK	0.997	0.329	0.694	0.766		
LCB	0.775	0.369	0.233	0.820	0.795	
EP	0.805	0.132	0.390	0.628	0.649	0.706
HTMT Criteria						
	GHRM	GIC	GOC	ENK	LCB	EP
GHRM						
GIC	0.274					
GOC	0.272	0.474				
ENK	0.176	0.328	0.772			
LCB	0.414	0.115	0.665	0.367		
EP	0.367	0.474	0.702	0.596	0.656	

Note: GHRM: Green HRM; LCB: Low carbon behaviour; GIC: Green innovation climate; GOC: Green organizational commitment.

4.4. Predictive relevance

Table 4. Goodness of fit indices.

Variables	R^2	F^2	Q^2
GHRM	0.502	0.396	0.141
Green innovation climate	0.931	0.472	0.172
Green Organizational Commitment	0.885	0.256	0.254
Environmental Knowledge	0.885	0.748	0.192
Low carbon behaviour	0.631	0.356	0.341
Environmental Performance		0.646	0.397
Model Fitness Indicators	**Saturated Model**	**Estimated Model**	
RMSE	0.030	0.031	
NFI	0.950	0.922	
(RMS_theta)	0.006	0.007	

Note: RMSE: Standardized Root Means Square; NFI: Normal Fit Index test.

Measuring the effective size is an essential complement to testing the significance level (*p*-value) of the relationship among the constructs. Thus, the effective size offers an evaluation technique to measure practical significance in testing the magnitude of the effect among research models. Therefore, this study examines the effect size with a series of tests, which include F^2, R^2, and Q^2. As indicated in **Table 4**, the results from this analysis revealed that all the statistical

coefficients of the F^2, R^2, and Q^2 for the construct range from small to large effect sizes. In addition to these tests, the research explored the goodness of fit through the RMSE, RMS_theta, and NFI. This result verified that the analysis's findings are solid and trustworthy and that policy-makers can base their choices on this study.

4.5. Assessment of structural model

4.5.1. Direct path analysis

The structural model PLS-SEM is a crucial component that allows researchers to examine the relationships between latent constructs and test hypotheses regarding these relationships [74]. This model goes beyond the measurement model and focuses on understanding how latent constructs are interrelated and how they influence each other. The path analysis for this research is structured as follows: Direct, indirect path analysis (mediation), and moderation (iteration) assessment. The analysis proposed six direct connections in the research model. The empirical outcome concluded that GHRM has a direct and substantial influence on GIC H1 (β = 0.695, p-value = 0.001), GOC H2 (β = 0.573, p-value = 0.000), and LCB H3 (β = 0.590, p-value = 0.000). The analysis further revealed that GIC H4 (β = 0.484, p-value = 0.001) has a positive influence on LCB. Likewise, the analysis confirmed that GOC H5 (β = 0.501, p-value = 0.001) has a direct association with LCB. In addition, the study revealed that LCB H6 (β = 0.208, p-value = 0.002) positively affects EP. The result of the structural archetype has been represented in **Figure 2** and **Table 5**.

Table 5. Outcome of path estimates.

Hypothesis	Effect of	Effect on	β	P-value
H1	GHRM	GIC	0.695***	0.000
H2	GHRM	GOC	0.573***	0.000
H3	GHRM	LCB	0.590***	0.000
H4	GIC	LCB	0.484***	0.000
H5	GOC	LCB	0.501***	0.000
H6	LCB	EP	0.208***	0.002

Note: ***significance level at 1%.

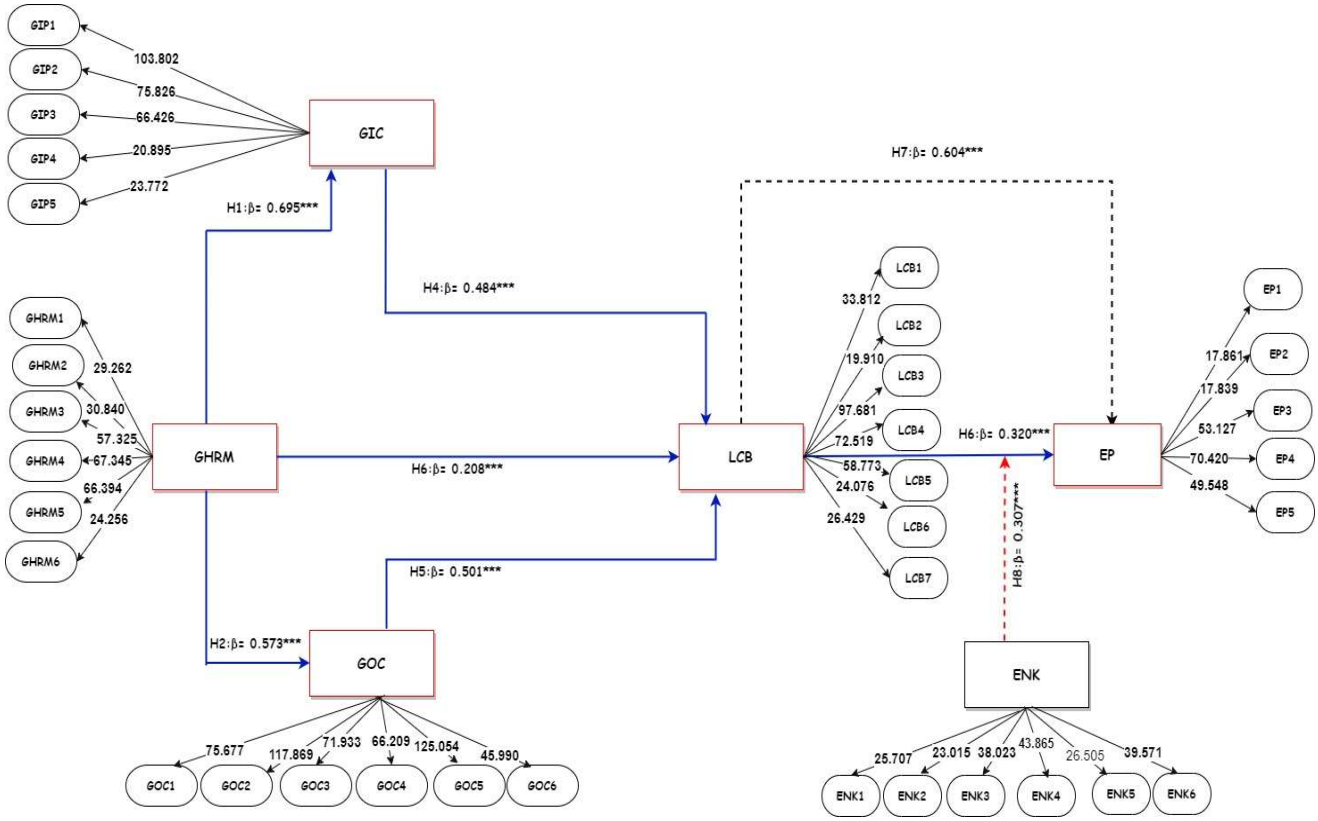

Figure 2. Outcome of the structural model.

4.5.2. Mediation and moderation analysis

The study research explored the mediation effect of LCB on the connection between GHRM and EP. The outcome has been captured in **Table 6**. The empirical findings from the study revealed that the indirect influence of LCB on the nexus between GHRM-LCB was statistically significant (H7) (β = 0.407; t-value = 40.283; p = 0.000). The extrapolation from this outcome indicates that LCB has a significant mediation impact on the GHRM-EP nexus.

Table 6. Estimates for mediation and moderation.

Hypothesis	Relationships	β	P-value
H7	LCB → GHRM → EP	0.604***	0.000
H8	ENK*LCB → EP	0.307***	0.000

Note: ***significance level at 1%.

Moreover, the results of the moderation assessment have been provided in **Table 5** and **Figure 3**. The empirical outcome indicated that ENK, H8 (β = 0.307, t = 40.283; p-value = 0.000) has a substantial and positive moderating influence on the association between LCB and EP. The graphical representation of the moderation impact of ENK has been demonstrated in **Figure 3**. The figure indicates that the simultaneous increase of ENK can reduce the strength between LCB and EP.

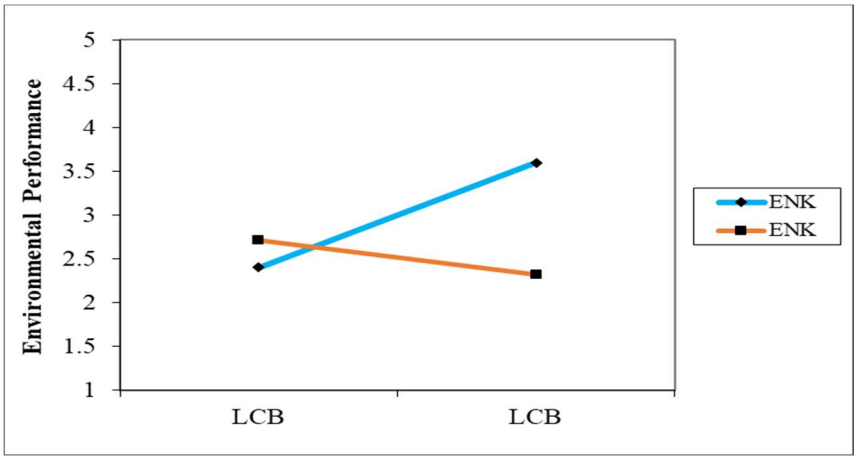

Figure 3. Moderation role of ENK between GHRM and LCB.

5. Discussion

The paper examined the influence of GHRM on GOC, GIC, and LCB on EP. Additionally, the research explored the indirect impact of LCB on the connection between GHRM and LCB. Moreover, the moderate impact of ENK was evaluated. The empirical evidence from the research revealed that GHRM has a favorable influence on GIC, GOC, and LCB, confirming the study's H1–H3 findings. This finding highlighted that GHRM promotes firms' GIC, GOC, and LCB among employees. The possible explanation for this outcome is that SMEs' adoption of GHRM strategies demonstrates the dedication to environmental sustainability, encouraging workers to engage in behaviors that promote ecological stability. The outcome of this study supports existing studies that proved that proper GHRM practices outlined by SMEs significantly impact their level of GOC [19,21,63,77]. As espoused by the AMO theory, the staff's comprehension of the necessity and urgency of adjusting the GHRM system would facilitate the accomplishment of higher-level LCB, GIC, and GOC among employees at the workplace [19]. The results from this investigation imply that GHRM practices improve workers' green motivation, capabilities, and desire to achieve SMEs' green goals. The findings of this study are comparable to erstwhile studies that highlighted that GHRM predicts GIC, GOC, and LCB [78–81].

In addition, the study outcome revealed that GIC substantially influences LCB, supporting the paper's H4. This outcome implies that SMEs can use GIC to proactively outline new standards to strengthen and enhance their LCB [47]. Promoting SMEs' GIC strategies and capacity can provide new approaches and strategic advantages for achieving environmental goals. Moreover, GIC includes the enterprise's ability to integrate green processes and products to produce eco-friendly products with lower energy consumption and a clean atmosphere at the workplace [62,82]. GIC supports responsiveness and efficiency capabilities to government regulations, customer preferences, and societal needs that emphasize the sustainability of the environment [83]. The findings of this investigation align with existing research that emphasizes that SMEs' investment in GIC can help them achieve higher LCB among employees [84–86].

Furthermore, the findings confirmed that GOC substantially influences LCB, implying the fifth hypothesis of this research was supported. The inference from this outcome is that the level of GOC verifies the mechanism and way the workforce is passionately and unequivocally attached to their enterprise. Such practice helps identify whether the staff is willing to engage in LCB. The study's findings reinforce the results by Kim et al. [87] that GOC influences the green behavior of employees in a business. Their study opined that staff with a strong and loyal commitment to their enterprise GOC results in proactive LCB and eco-friendly conduct, enhancing their firms' EP. The present paper confirms that GOC is an essential determinant of individual staff LCB behavior and is congruent with these existing studies [88–90].

This analysis revealed that the LCB of staff directly and substantially interacts with firms' EP, which was confirmed (H6). This outcome proves that if employees indulge themselves in LCB, it affects the environmental performance of SMEs. The interaction between individual action, behavior, and the preservation of the environment is intertwined. Thus, the engagement of workers towards green environmental interventions can be stimulated by the individual LCB, which influences the ecological performance of SMEs. As espoused by prior studies, LCB, such as waste reduction at the workplace, water conservation, reduction in the firm's overall cost, and usage of renewable resources, affects EP [91–93]. Another substantial inference from this study outcome is that the LCB of workers can better bolster environmental management goals.

The paper further assessed the mediation influence of LCB on the linkage between GHRM and EP. This finding supports (H7) of this paper. The implications of this research highlighted that the connection between GHRM and EP can be improved through employees' LCB. Thus, empirical evidence by Channa et al. [94] confirmed that the LCB of employees has an indirect and significant impact on the connection between GHRM and EP. In addition, Ojo et al. [80] proved that GHRM success generally depends on the LCB of employees in Malaysia. Erst while literary works have further pointed out that workers' LCB positively and substantially interacts among GHRM and EP [25,95–98].

Lastly, the findings from the analysis supported the positive moderating impact of ENK on the link between LCB and EP. A possible explanation for this finding implies that a deeper understanding of environmental issues empowers entities to optimize their eco-friendly initiatives, making them more effective in mitigating environmental impact. Essentially, environmental knowledge acts as a catalyst, amplifying the positive impact of LCB on overall EP and reinforcing the notion that informed actions contribute substantially to achieving sustainable outcomes. This nuanced relationship highlights the importance of educational initiatives and awareness campaigns in shaping environmentally conscious behaviors and ultimately driving positive environmental outcomes. The result of the present investigation is consistent with prior studies, which postulated that firms could improve ENK to help promote LCB and EP [9,56].

This study contributes to the overall body of knowledge by providing empirical evidence on the mechanisms through which green human resource management (GHRM), green innovation climate (GIC), and green organizational commitment (GOC) influence low-carbon behavior (LCB) and environmental performance (EP)

in SMEs. By highlighting the mediating role of LCB and the moderating impact of environmental knowledge, this research advances our understanding of how GHRM practices can foster a culture of sustainability and enhance environmental outcomes, particularly in the context of SMEs in emerging markets like China. Additionally, it enriches the application of AMO theory in green workplace practices, demonstrating the importance of employee motivation and organizational climate in achieving sustainability goals.

6. Conclusions and research implications

6.1. Conclusions

International organizations like the United Nations and the recent Glasgow Agreement are championing the need for carbon emissions and preserving the environment for future generations. This call has necessitated the importance of this study, which focuses on low-carbon behavior among employees of SMEs in China. The research hypothesis was evaluated using the SEM-PLS methodology. The research's empirical outcome delineated that GHRM positively influences GIC, GOC, and LCB. Second, the findings captured that GIC and GOC have a substantial and beneficial influence on LCB. Third, the research results discovered that EP can be promoted through LCB. Fourth, the outcomes approved the mediation influence of LCB on the linkage between GHRM and LCB. Fifth, the moderation effect of ENK on the linkage between LCB and EP was supported in this analysis.

6.2. Research implications

6.2.1. Theoretical implications

The theoretical implications of this study lie in its advancement of the AMO theory within the context of sustainability and environmental management in SMEs. This research expands the AMO framework by integrating GHRM as a core component that enhances employees' abilities, motivations, and opportunities to engage in low-carbon behavior. By demonstrating how GHRM practices positively influence GIC, GOC, and low-carbon behavior, this study adds depth to our understanding of how strategic HR practices can drive ecological outcomes. Specifically, it emphasizes that environmental sustainability can be approached through employee-oriented practices focusing on technical training and nurturing. Additionally, this research provides new insights into the mediating role of LCB in linking GHRM with environmental performance and the moderating effect of environmental knowledge, thereby enriching the literature on the complex interactions between organizational resources, employee behaviors, and sustainability outcomes.

Furthermore, the study contributes to the body of knowledge on green innovation by highlighting the role of GIC as a mechanism that empowers SMEs to align their strategic goals with environmental objectives. By illustrating how GIC and GOC can foster proactive low-carbon behavior, the findings provide a theoretical basis for understanding the role of internal organizational climate and commitment in promoting sustainable practices. This research also underscores the

importance of contextual factors, such as firm size and regional characteristics, in shaping the effectiveness of GHRM practices, thereby contributing to the contextualization of the AMO theory in different environmental and economic settings. The study's focus on SMEs in Jiangsu, China, adds to the limited empirical evidence on applying green HR practices in emerging economies, thus offering a valuable perspective that enriches the theoretical discourse on sustainability in diverse organizational contexts.

6.2.2. Practical implications

The practical contributions from the paper are presented as follows: Since the investigation findings demonstrated that GHRM is integral to improving employees' green behavior, the study suggests that organizations should incorporate sustainability principles into their HR policies and procedures. This includes integrating eco-friendly criteria into recruitment and selection processes, emphasizing sustainability-related competencies during employee training and development programs, and establishing performance metrics measuring employee contributions to environmental goals. Again, fostering a culture of sustainability is crucial. Organizations should encourage open communication about sustainability initiatives, promote employee engagement in green teams or environmental projects, and recognize and reward environmentally responsible behaviors.

Considering the relevance and centrality of these concepts (GOC, GIC on LCB), SMEs are expected to provide the needed support to their workforce to enable them to contribute to the business's ecological sustainability plan. In addition, by evaluating the mediation role of LCB between LCB-EP linkage, this study stressed the importance of LCB to SMEs. Hence, as a matter of practical significance, the study recommends that to improve LCB, managers should focus on the green involvement of employees in decisions regarding the environment. Employees' opinions, suggestions, viewpoints, creative ideas, and recommendations can be fostered into firms' environmental management plans. Employees generally show higher commitment and dedication once their firms recognize them and listen to their views regarding the firm's EP actions. Moreover, GHRM managers should outline measures that can empower and involve staff in green issues and help them have autonomy in addressing these challenges. These actions can be instituted under the firm's HRM auspices and captured under these themes (green empowerment and involvement strategies). Providing green feedback to workers on green performance can also be a strategic tool to enhance GOC and GIC.

Lastly, the study results supported the moderate influence of ENK on the interaction between LCB and EP. Hence, this study suggests that senior management and the GHRM section of SMEs should invest in employee training and development associated with ecological stability. In this regard, the GHRM department should educate staff about environmental protection issues, which will assist them in comprehending the firms' environmental policies and improve their understanding of the significance of engaging in LCB at the workplace. Moreover, the awareness and understanding gained through these environmental training activities can help the workforce become more considerate about ecological issues and devise prevention techniques. Thus, employees can be tasked to read about

current carbon emission trends and gather salient information about waste recycling. Once the individual has gained insight into some of these environmental degradation issues, they provide solutions and the necessary steps to mitigate such occurrences.

6.3. Limitations and future direction

While the research gives valuable insights, it is vital to acknowledge certain limitations. Firstly, the study might face challenges in generalizability due to its potential to concentrate on particular businesses or organizational contexts. Future studies could also explore how GHRM practices translate into tangible low-carbon outcomes, exploring employee perceptions and behaviors. Furthermore, investigating the potential moderating effects of external factors, such as regulatory environments or industry characteristics, would enhance understanding of the complexities of fostering sustainable organizational behavior. Another limitation of this study is the lack of a multi-group analysis to examine potential differences between small and medium-sized firms. Future research should consider conducting such an analysis to explore whether firm size influences the relationships within the investigated model. Lastly, exploring the role of technology and digital innovation in promoting green practices could be a promising avenue for future research, as technological advancements increasingly play a pivotal role in shaping organizational sustainability efforts.

Author contributions: Conceptualization, methodology, software, AKS; validation, formal analysis, and project administration, JW. All authors have read and agreed to the published version of the manuscript.

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Appendix

Construct	Item Code	Items	Source
GHRM	GHRM1	At our enterprise, environmental issues are a necessity for job descriptions.	Ren et al. [60]; Bin Saeed et al. [45]
	GHRM2	My firm chooses candidates sufficiently knowledgeable about greening to fill open positions.	
	GHRM3	Recruitment communications incorporate environmental commitment and conduct requirements.	
	GHRM4	This firm establishes an environment management system and environmental audit.	
	GHRM5	Our enterprise engages the employees in establishing environmental strategies.	
	GHRM6	Our firm recognizes employees as essential actors in environmental decisions and initiatives.	
GIC	GIC1	Our enterprise has enhanced environmentally friendly packaging for both used and new products.	Fatoki [61]; Makhloufi et al. [62]
	GIC2	Our enterprise produces goods and offers services while taking ecological considerations into mind.	
	GIC3	Our enterprise uses modern technology to neutralize pollution.	
	GIC4	Our enterprise uses repurposed and recycled materials when providing services to consumers.	
	GIC5	Our enterprise uses less material when providing services to clients.	
GOC	GOC1	I have an emotional attachment to the environmental goals of my enterprise.	Iqbal et al. [63]
	GOC2	I have a stronger sense of responsibility for the environmental goals of my enterprise.	
	GOC3	I feel ethically bound to support this enterprise's ecological goals, which is one of the reasons I will not leave this firm to work elsewhere.	
	GOC4	Despite a better employment opportunity from another firm, I wouldn't think it was appropriate to leave my current employer because of its commitment to the environment.	
	GOC5	Many of my career would be disrupted if I decided I wanted to quit my job immediately because I identify with its environmental obligations.	
LCB	LCB1	I take part in eco-initiatives at the workplace.	Lange [64]; Bin Saeed et al. [45]
	LCB2	I educate and share knowledge about environmental issues with my co-workers.	
	LCB3	I generate various proposals for procedures to help my company operate better regarding environmental sustainability.	
	LCB4	I enjoy being mindful of turning off technological devices to save energy.	
	LCB5	I use ecologically friendly methods to complete jobs that are required of me.	
	LCB6	I enjoy being mindful of turning off technological devices to save energy.	
	LCB7	I appreciate recycling and practicing energy efficiency.	
ENK	ENK1	I am aware of the issue of chemical-issued industrial contamination.	Karmoker et al. [18]; Usman et al. [65]
	ENK2	I have a thorough understanding of environmental issues.	
	ENK3	I am constantly mindful of how the environment is degrading.	
	ENK4	I know how to prevent pollution from putting the environment in danger.	
	ENK5	I am knowledgeable about environmental climate.	
EP	EP1	Our enterprise minimizes the influence of its products and procedures on the environment.	Ubeda-Garcia et al. [66]
	EP2	Our firm has switched to a renewable power source and reduced its fossil fuel use.	
	EP3	Our enterprise has drastically decreased the amount of solid waste it produces.	
	EP4	The current business operations of our firm are automated.	
	EP5	Our business uses ecologically friendly methods to dispose of waste.	

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Article

International rural new energy industry innovation development and benefit-linkage practices

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Abstract: The rural new energy industry is a crucial area for promoting green transformation and achieving sustainable development, significantly contributing to improvements in energy structure and environmental protection. While China's rural new energy industry has made substantial progress due to policy support and technological advancements, it still faces numerous challenges in practical development. This paper aims to compare and analyze the experiences and practices of various countries and regions—including the United States, the European Union, Brazil, and China—to identify their primary benefit-linkage mechanisms, policy support systems, and overall performance. Based on this analysis, the paper will provide policy recommendations and improvement measures for the innovative development of China's rural new energy industry. The research findings indicate that (1) different countries and regions employ various benefit-linkage mechanisms in the rural new energy sector, including cooperative models, public-private partnerships, and community participation models. Each mechanism has its unique advantages and disadvantages in facilitating project development and benefit linkage. (2) Although all countries have established comprehensive policy support systems, there are notable differences in the introduction and implementation of market mechanisms. The European Union and the United States possess relatively mature market mechanisms for carbon emission trading and green certificate trading, whereas the market mechanisms in China and Brazil are either new or not sufficiently developed. (3) The United States and the European Union demonstrate strong performance in technological advancement and market operations, yielding significant economic and environmental benefits. In contrast, China and Brazil have made progress in policy support and technology adoption but need to enhance their market mechanisms and international cooperation. (4) Social participation and community support yield important social benefits in new energy projects across various countries and regions, particularly the community participation model, which positively impacts community cohesion and project development.

Keywords: green and low-carbon; rural new energy industry; innovative development; benefit-linkage; policy analysis

1. Introduction

With the intensification of global environmental issues and the scarcity of energy resources, green and low-carbon development has become a global consensus and action goal. The increase in greenhouse gas emissions and the impact of climate change on the environment have prompted countries to accelerate their transition and seek sustainable energy solutions [1]. In this context, the development and utilization of new energy, especially the development of the rural new energy industry, have become important avenues for promoting green transformation and achieving sustainable development [2]. In China, the innovative development of the rural new

energy industry is considered an important component in achieving carbon neutrality goals and advancing rural revitalization strategies. With continuous technological advancements and policy support, the rural new energy industry plays a crucial role in promoting economic development, enhancing energy self-sufficiency, and improving environmental quality [3]. However, different countries and regions have varied experiences and challenges in the development of the rural new energy industry, providing us with valuable lessons and insights.

With the strengthening of global climate policies and the rapid development of renewable energy, countries worldwide are formulating and implementing strategies to combat climate change. These efforts are driving the reduction of greenhouse gas emissions and the transition towards more sustainable energy systems [4]. The Paris Agreement sets forth global targets for controlling temperature rise and encourages countries to adopt more proactive emission reduction measures [5]. Advancements and cost reductions in solar, wind, and energy storage technologies have gradually increased the market share of renewable energy [6]. Global investment in green energy and technological innovation is driving the widespread adoption of renewable energy. Green finance has become an integral part of the global financial market, with investors and financial institutions increasingly focusing on environmental, social, and governance (ESG) factors [7]. The rise of financial instruments such as green bonds and green funds has facilitated the financing and development of green and low-carbon projects. The application of technologies like smart grids, the Internet of Things (IoT), and big data has enhanced energy management and optimization. The integration of digital technologies in energy production, transmission, and consumption helps improve energy efficiency and reduce resource waste [8].

The development of the rural renewable energy industry is beneficial for promoting rural revitalization. It helps increase rural economic income, improve infrastructure, and drive comprehensive and sustainable development. By leveraging renewable energy sources such as solar, wind, and biomass, the rural renewable energy industry reduces dependence on traditional fossil fuels, improves the energy mix, and enhances energy security [9]. Moreover, rural renewable energy projects can effectively reduce greenhouse gas emissions and environmental pollution, improve rural environmental quality, and promote ecological conservation [10]. In addition, the implementation of rural renewable energy projects can create job opportunities, enhance residents' living standards, and promote harmonious social development.

Current literature on the rural renewable energy sector exhibits several significant shortcomings. Firstly, methodological limitations are prevalent, as most research tends to adopt a singular approach—either quantitative analysis or case studies—while neglecting the benefits of a mixed-methods strategy. This restricts the generalizability and applicability of the findings. Furthermore, many studies fail to adequately consider local characteristics, such as regional policies, socioeconomic contexts, and cultural differences, which can significantly influence the implementation of rural renewable energy initiatives. Lastly, there is a gap in addressing the integration of technological innovations with supportive policy

frameworks, as existing literature often highlights advancements in technology without systematically analyzing their promotion alongside policy support.

To address these literature gaps, this study offers several important contributions. First, by systematically collecting and analyzing data from diverse countries and regions, this research provides a comprehensive understanding of the rural renewable energy sector, revealing critical success factors and challenges encountered in real-world applications. Second, this study employs a mixed-methods approach, combining both quantitative and qualitative analyses to capture the complexities of rural renewable energy projects, thereby enhancing the depth and breadth of the research. Third, the study offers localized policy recommendations tailored to specific regional characteristics and needs, ensuring their feasibility and effectiveness across different socioeconomic contexts. Finally, by emphasizing the interaction between technological innovation and policy support, this research proposes effective benefit-linkage mechanisms that foster coordinated development within the rural renewable energy industry. Drawing on international experiences, this study aims to provide valuable insights for the innovative application of renewable energy technologies in China, contributing to the country's carbon neutrality goals and rural revitalization strategies.

2. Literature review and theoretical foundation

2.1. Green low-carbon and rural renewable energy industry concepts

Green low-carbon development refers to achieving sustainable economic, social, and environmental progress by enhancing resource efficiency, reducing greenhouse gas emissions, and minimizing environmental pollution. This concept emphasizes balancing economic growth with environmental protection and climate change mitigation, driving a societal transition toward low-carbon, eco-friendly, and resource-efficient practices [11]. Green development emphasizes reducing the consumption of natural resources and minimizing environmental impacts in economic activities. It achieves sustainable economic growth through the advancement of green technologies and the development of green industries [12]. A low-carbon economy focuses on reducing carbon dioxide and other greenhouse gas emissions, promoting the use of low-carbon energy sources and technologies to slow the pace of climate change.

The rural renewable energy industry involves the development and utilization of renewable energy resources in rural areas, such as solar, wind, biomass, and geothermal energy. These resources are characterized by their renewability, cleanliness, and environmental friendliness, helping to reduce reliance on traditional fossil fuels, achieve energy self-sufficiency, and promote environmental protection [13]. The rural renewable energy industry encompasses not only the research and application of new energy technologies but also the entire process of energy production, storage, distribution, and consumption. Its goal is to enhance energy efficiency and drive rural economic development by promoting the adoption of renewable energy technologies in rural areas.

2.2. Global development status of the renewable energy industry

Globally, the renewable energy industry has progressively become a crucial driver of economic growth. Advances in technologies such as wind, solar, biomass, geothermal, and hydrogen energy have led to continuous breakthroughs, decreasing costs, and expanding application ranges. According to data from the International Energy Agency (IEA), global investment in renewable energy has steadily increased in recent years, with wind and solar energy emerging as primary focus areas. Concurrently, the rapid development of electric vehicles and energy storage technologies has further enhanced the renewable energy industry chain, leading to a more integrated and mature industry ecosystem [14]. Global solar photovoltaic (PV) installed capacity has been steadily increasing, particularly in China, the United States, and European Union countries. Technological advancements and economies of scale have significantly reduced the cost of solar power generation. The wind energy market has seen rapid development in Europe and North America, with technological innovations driving down wind power costs. Offshore wind energy is emerging as a new growth area within the sector [15]. Although the development of biomass and geothermal energy has been slower compared to solar and wind energy, their utilization is gradually increasing in certain countries and regions, particularly those rich in agricultural and forest resources.

The rural renewable energy industry is gaining increasing attention globally, with many countries implementing policy support and market mechanisms to promote renewable energy development in rural areas. In the United States, both federal and state-level policies, such as tax incentives and subsidies, have driven the growth of solar and wind energy projects in rural regions [16]. The European Union encourages the adoption of renewable energy in rural areas, fostering the development of community energy projects and green energy cooperatives. In China, national policies and subsidies have driven the implementation of rural renewable energy projects, achieving significant results, particularly in the fields of solar photovoltaics and wind energy.

2.3. Benefit-linkage mechanisms in rural renewable energy industries

Benefit-linkage mechanisms refer to the cooperation and coordination methods among different stakeholders in renewable energy projects, aimed at achieving resource sharing, risk distribution, and equitable benefit-sharing [17]. Benefit-linkage mechanisms in renewable energy projects can be categorized into several models.

(1) Cooperative Model. Farmers collectively invest in, build, and operate renewable energy projects through cooperatives. They share both the benefits and risks associated with the projects. While this model promotes farmer participation and equitable benefit distribution, it may encounter challenges related to management and operational efficiency [18].

(2) Enterprise + Farmer Model. Enterprises take the lead in investing in and developing renewable energy projects, while farmers contribute land or labor. Both parties share the generated benefits. This model can significantly boost rural economic development but requires well-defined agreements to manage risk

distribution and benefit-sharing.

(3) Public-Private Partnership (PPP) Model. This model involves collaboration between government entities and private companies to jointly invest in and manage renewable energy projects. The success of this model depends on effective cooperation between the public and private sectors, highlighting the importance of strong partnership mechanisms for project success [19]. These are frameworks designed to ensure that the economic, social, and environmental benefits of renewable energy projects are equitably distributed among all stakeholders, including local communities, project developers, and governments. Effective benefit-sharing mechanisms are crucial for the success and sustainability of rural renewable energy projects. They help to align the interests of various stakeholders, foster community support, and ensure that projects contribute positively to local development.

2.4. Theoretical foundation

Based on cooperation theory, benefit-sharing mechanisms coordinate the interests of different stakeholders to create mutually beneficial outcomes. Cooperation theory emphasizes that by building trust and sharing resources, the success rate and overall benefits of projects can be enhanced [20]. Game theory is used to analyze the behavior and strategies of various stakeholders in renewable energy projects, helping to understand the impact of different benefit-linkage mechanisms on each party. Policy tools theory explores the role of government in promoting green low-carbon development, including incentives, regulations, and market mechanisms. In green low-carbon policies, the government can drive the development of green technologies and industries through financial incentives, technical support, and regulatory constraints [21]. Multilevel governance theory emphasizes the interactions and cooperation among various levels of government, markets, and society in global climate governance. In the context of rural renewable energy industries, this theory helps to understand the roles and coordination mechanisms of local governments, central governments, and international organizations. It highlights the importance of collaborative efforts across different governance levels to effectively manage and advance renewable energy initiatives.

3. Evolution of benefit-linkage mechanisms in China's rural renewable energy industry

3.1. Development progress

Emergence Stage (Around 2000): The rural renewable energy industry began to attract attention, with the promotion of renewable energy sources such as biogas, solar water heaters, and small hydro power stations in rural areas.

Preliminary Development Stage (2000–2010): The government started to implement relevant policies to support the construction and promotion of renewable energy projects, such as the "Renewable Energy Law." Advanced foreign technologies were introduced, and demonstration projects were launched to accumulate experience.

Rapid Development Stage (2010–2020): Large-scale promotion of solar photovoltaics, wind energy, and biomass energy projects in rural areas. The variety and application scope of renewable energy continued to expand, covering agricultural production, daily energy supply, and more.

Innovation Development Stage (2020–Present): Ongoing advancements in renewable energy technology to improve energy efficiency and economic benefits. Exploration of various benefit-sharing models, such as agro-solar complementary and agro-wind complementary, to enhance endogenous economic development in rural areas.

3.2. Major innovative models and mechanisms

Regarding the models, the cooperative model organizes farmers into cooperatives to participate in new energy projects and share the benefits. The enterprise + farmer model involves enterprises investing in the construction of new energy projects, while farmers contribute land and labor, resulting in mutual benefits. The government guidance model entails the government directing farmers and enterprises to engage in new energy projects through policy support and subsidies.

In terms of mechanisms, market-oriented approaches are employed to attract social capital for the construction and operation of rural new energy projects. A technical service system is established to provide technical support and training for these projects. Additionally, diversified financial products and services are developed to facilitate the financing of new energy projects in rural areas.

3.3. Policy support and complementary measures

In terms of policy support, the Renewable Energy Law offers legal protection for the development of the new energy industry. The government provides financial subsidies to lower the costs of participation in new energy projects for both farmers and enterprises. Preferential tax policies will be implemented to encourage investment in and operation of these projects.

Regarding supporting measures, there will be increased investment in the construction of rural power grids, roads, and other infrastructure to support new energy projects. Technical training programs will be conducted to enhance the technical skills and management capabilities of farmers and enterprises. Additionally, support will be provided for the development of demonstration projects, with successful experiences and models promoted to guide further initiatives.

3.4. Current status and challenges

Currently, the scale of rural new energy projects is steadily expanding, with applications becoming increasingly diverse. These projects have stimulated rural economic development, enhanced farmers' incomes, reduced environmental pollution, and advanced ecological protection. However, challenges remain: the low level of technology in some areas affects project efficiency; substantial investment requirements highlight a notable shortage of funds; insufficient management capacity impacts the long-term viability of projects; and inadequate policy implementation in some regions hampers progress. In summary, while China's rural new energy

industry has made significant strides through policy support and technological innovation, it continues to face challenges related to technology, capital, and management.

4. Lessons from international experience in rural renewable energy

4.1. United States practices in rural renewable energy development

4.1.1. Historical evolution

The development of rural renewable energy in the United States has evolved significantly over the decades. During the early development phase (1970s–1990s), the energy crisis of the 1970s prompted a focus on renewable energy, with pilot projects for solar, wind, and biomass technologies starting in rural areas. The rapid development phase (2000s–2010s) saw significant advancements in photovoltaic, wind, and biomass technologies, leading to substantial cost reductions and broader adoption. This period was marked by strong policy support from federal and state governments, including the Energy Policy Act and the American Recovery and Reinvestment Act, which facilitated the expansion of rural renewable energy projects. In the diversified development phase (2010s-Present), the range of renewable energy applications in rural areas has expanded to include distributed photovoltaic systems, wind power, and biogas projects. Innovative benefit-sharing models have emerged, enhancing the integration of renewable energy with rural economic development.

4.1.2. Support mechanisms

At the federal level, support includes direct financial subsidies, tax credits, and favorable loans to reduce investment costs for rural renewable energy projects. Funding is also provided for research and demonstration projects to drive technological advancements. At the state level, requirements for utility companies to obtain a certain percentage of their power from renewable sources stimulate market demand. Dedicated green banks offer low-interest loans and venture capital to support rural renewable energy projects. Market mechanisms include the establishment of carbon trading markets to encourage companies to reduce carbon emissions and invest more in renewable energy. Additionally, long-term power purchase agreements between companies and farms ensure sustained project revenue.

4.1.3. Benefit-linkage models

In the Cooperative Model, rural renewable energy cooperatives organize farmers to jointly invest in, build, and operate renewable energy projects, sharing the profits and reducing the investment risk for individual farmers.

In the Enterprise + Farmer Model, enterprises invest in the construction of rural renewable energy projects, while farmers provide resources such as land and labor. The profits are shared between the two parties according to an agreed-upon ratio.

In the Community Supported Agriculture (CSA) Model, community members pre-purchase products or services from renewable energy projects, providing financial support while enjoying the economic and environmental benefits generated by the projects.

4.1.4. Performance trends

In terms of economic benefits, rural renewable energy projects have significantly increased income in rural areas and stimulated local economic development. The expansion of these projects has also driven the growth of related industries, creating additional job opportunities.

From an environmental perspective, the large-scale adoption of renewable energy has reduced reliance on fossil fuels and lowered greenhouse gas emissions. This shift has improved the ecological environment in rural areas and promoted sustainable development.

Socially, renewable energy projects have enhanced the quality of life for rural residents by providing more reliable and cleaner energy supplies. The promotion of these projects has also strengthened community cohesion and supported the autonomous development of rural areas.

4.1.5. Policy insights

The U.S. experience underscores the importance of continuous policy support for rural renewable energy development, including financial subsidies, tax incentives, and research funding. This suggests that other countries should ensure the continuity and systematic nature of their policies. Additionally, the U.S. employs a multi-layered support system involving federal, state, and local governments, demonstrating that a multi-tiered, multi-channel approach can more effectively advance rural renewable energy projects. Market mechanisms, such as carbon trading markets and power purchase agreements, play a decisive role in resource allocation and promote sustainable development. Innovative benefit-linkage models, such as cooperative and community-supported agriculture models, have integrated rural economies with renewable energy sectors, providing a valuable reference for other nations to stimulate endogenous growth in rural areas. In summary, continuous policy support, multi-layered mechanisms, market-oriented operations, and innovative models are crucial for the successful development of rural renewable energy industries.

4.2. EU practices in rural renewable energy development

4.2.1. Historical evolution

In the early 1990s, the EU began focusing on climate change and gradually introduced renewable energy policies, with the 1997 Energy White Paper marking the first formal commitment to renewable energy targets. During the mid-2000s to early 2010s, the Renewable Energy Directive of 2001 set development targets for member states, and funding programs such as the Sixth and Seventh Framework Programmes (FP6, FP7) supported research and application of new energy technologies. The rapid development phase from the mid-2010s to early 2020s saw the 2010 Climate and Energy Package establish ambitious targets for renewable energy, greenhouse gas reduction, and energy efficiency by 2020. Technological advancements in photovoltaic and wind energy significantly lowered costs, leading to widespread adoption in rural areas. Since 2020, the European Green Deal has set a goal for carbon neutrality by 2050, and post-COVID-19, the EU has significantly invested in green energy projects through the Recovery and Resilience Facility,

further driving energy transformation in rural regions.

4.2.2. Support mechanisms

At the EU level, the Renewable Energy Directive and the Climate and Energy Package establish clear targets and requirements for renewable energy development. Multiple funding programs, such as Horizon 2020, the Innovation Fund, and the Structural and Investment Funds, support research, demonstration, and promotion of rural renewable energy projects. At the national level, member states develop their own renewable energy plans and policies in accordance with EU guidelines, offering various economic incentives like financial subsidies, tax breaks, and low-interest loans to encourage rural renewable energy projects. Market mechanisms, including the carbon emission trading system and the renewable energy certificate (green certificate) trading system, further promote investment and application in renewable energy by increasing market transparency and supporting sector growth.

4.2.3. Benefit-linkage models

Cooperative Model: In this model, farmers and community residents jointly invest in, build, and operate renewable energy projects, such as wind farms and photovoltaic stations. They share the benefits and enhance community cohesion.

Public-Private Partnership (PPP) Model: This model involves collaboration between the government and private enterprises to jointly invest in and manage rural renewable energy projects. It aims to improve the sustainability and economic efficiency of the projects.

Energy Community Model: Community members participate together in the planning, construction, and operation of renewable energy projects. Through democratic decision-making mechanisms, they achieve shared benefits and promote collective development.

4.2.4. Performance trends

Technological advancements and economies of scale have significantly reduced the costs of renewable energy projects such as photovoltaics and wind power, enhancing their economic benefits. The promotion of renewable energy projects has also stimulated the development of related industry chains and increased employment opportunities in rural areas.

The large-scale adoption of renewable energy has reduced the use of fossil fuels and lowered greenhouse gas emissions, contributing to climate change mitigation. The expansion of renewable energy projects has also supported ecological conservation in rural areas and reduced environmental pollution.

In rural areas, the development of renewable energy has improved energy self-sufficiency and reduced reliance on external energy sources. Cooperative and energy community models have enhanced residents' sense of participation and responsibility, fostering community development.

4.2.5. Policy insights

In terms of comprehensive policy systems, the European Union has ensured the stable development of rural renewable energy industries by establishing a thorough legal framework and policy objectives. This suggests that other countries should consider developing systematic and comprehensive policy frameworks when

formulating renewable energy policies. Regarding multi-layered support mechanisms, the EU's approach spans multiple levels, including EU-wide, national, and local supports, effectively advancing rural renewable energy projects through diverse and multi-channel support. Other countries can adopt such multi-layered support mechanisms to enhance policy implementation effectiveness. In terms of market operations and innovation, the EU promotes renewable energy development through market-based approaches like carbon trading and green certificate trading, while innovative models such as cooperatives and energy communities enhance the sustainability of rural renewable energy projects. Other nations could leverage these market-based operations and innovative models to stimulate market vitality. Lastly, the EU emphasizes community involvement and shared benefits through models like cooperatives and energy communities, which boost residents' sense of participation and responsibility. This highlights the importance of stimulating community engagement to ensure the sustainable development of rural renewable energy projects. Overall, the EU's integrated policy system, multi-layered support mechanisms, market-based operations, innovative models, and focus on community participation and shared benefits provide a robust framework for advancing the healthy development of rural renewable energy industries.

4.3. Brazil practices in rural renewable energy development

4.3.1. Historical evolution

In the early development phase (1970s–1990s), Brazil began seeking alternative energy sources due to the 1970s oil crisis, leading to the gradual rise of ethanol fuel projects. During this period, rural areas started to pilot and promote renewable energy projects such as small hydropower, wind energy, and solar energy. In the policy guidance phase (early 2000s to early 2010s), Brazil enacted the Electricity Law in 2002 and related policies to encourage the development of renewable energy. The Renewable Energy Incentive Program (PROINFA) launched in 2002 aimed to promote the growth of wind energy, small hydropower, and biomass energy. The rapid development phase (mid-2010s to early 2020s) saw significant advancements in photovoltaic and wind energy technologies, with costs decreasing substantially, leading to widespread adoption of rural renewable energy projects. Brazil actively engaged in international renewable energy cooperation, importing advanced technologies and funding to accelerate the development of rural renewable energy projects. In the comprehensive development phase (2020–present), Brazil set ambitious goals to significantly increase the proportion of renewable energy by 2030 in its National Energy Plan, further advancing the rural renewable energy industry. Following the COVID-19 pandemic, Brazil has intensified investment in rural renewable energy projects through a green recovery plan, promoting economic recovery and sustainable development.

4.3.2. Support mechanisms

In terms of policy support, laws such as the Electricity Law and the Renewable Energy Law provide policy guarantees and clearly define the goals and requirements for renewable energy development. Financial subsidies, tax incentives, and low-interest loans are offered to reduce the investment costs of rural renewable energy

projects and encourage the development of renewable energy in rural areas. For funding support, low-interest loans and financing assistance are provided through the National Development Bank to help finance rural renewable energy projects. Additionally, international aid and cooperation are actively sought to attract foreign investment and technology, promoting the development of rural renewable energy projects. In terms of market mechanisms, electricity auction mechanisms are used to determine the prices of renewable energy projects, promoting market competition and improving project efficiency. Participation in international carbon trading markets allows for funding support through carbon trading, further advancing the development of renewable energy.

4.3.3. Benefit-linkage models

In the cooperative model, farmers form energy cooperatives to jointly invest in, build, and operate renewable energy projects, sharing the profits and reducing individual investment risks.

In the public-private partnership (PPP) model, the government collaborates with private enterprises to jointly invest in and manage rural renewable energy projects, enhancing the sustainability and economic benefits of the projects.

In the community support model, community residents are encouraged to participate in the planning, construction, and operation of renewable energy projects, using democratic decision-making mechanisms to achieve shared benefits and mutual development.

4.3.4. Performance trends

In terms of economic benefits, advancements in photovoltaic and wind energy technologies have significantly reduced project costs, improving their economic viability. The development of rural renewable energy projects has stimulated the growth of related industry chains and created additional employment opportunities in rural areas.

Regarding environmental benefits, large-scale application of renewable energy has reduced dependence on fossil fuels and lowered greenhouse gas emissions. The promotion of renewable energy projects has also contributed to ecological protection and reduced environmental pollution in rural areas.

In terms of social benefits, developing renewable energy has enhanced energy self-sufficiency in rural areas and reduced reliance on external energy sources. Cooperative and community support models have increased residents' sense of involvement and responsibility, promoting sustainable community development.

4.3.5. Policy insights

In terms of multi-layered support mechanisms, Brazil has advanced rural renewable energy projects through a combination of national, local, and international support channels. Other countries can adopt this multi-layered approach to enhance policy implementation effectiveness. For market-based operations, Brazil has used mechanisms like power auctions and carbon trading to promote renewable energy, increasing project efficiency and economic benefits. Other countries can replicate this market-driven model to invigorate market activity. Regarding social participation and shared development, Brazil emphasizes community involvement

through cooperatives and community support models, enhancing residents' sense of participation and responsibility. This suggests that other countries should focus on stimulating community engagement to promote the sustainable development of rural renewable energy projects. Additionally, Brazil's success in developing rural renewable energy projects through international cooperation and technology importation provides a valuable example for other nations to strengthen international partnerships, acquire advanced technologies and funding, and accelerate renewable energy growth. Overall, Brazil's approach—combining multi-layered support mechanisms, market-based operations, community involvement, and international cooperation—demonstrates an effective strategy for fostering the healthy development of the rural renewable energy sector.

5. Comparative analysis of rural renewable energy development practices

5.1. Similarities and differences in benefit-linkage mechanisms

Table 1 is the similarities and differences in benefit-linkage mechanisms.

(1) Similarities: The Cooperative Model is utilized in Brazil, the United States, the EU, and China, where farmers form cooperatives to jointly invest in, construct, and operate renewable energy projects. This model enables them to share profits and mitigate individual investment risks. The Public-Private Partnership (PPP) Model is employed by Brazil, the United States, and the EU, involving collaboration between governments and private enterprises to invest in and manage rural renewable energy projects, thereby enhancing their sustainability and economic benefits. Additionally, the Community Participation Model is encouraged in the United States, the EU, and Brazil, where community members are involved in the planning, construction, and operation of renewable energy projects through democratic decision-making processes, fostering shared benefits and collective development.

(2) Differences: The Enterprise + Farmer Model is particularly prevalent in China, where enterprises invest in renewable energy projects while farmers contribute land, labor, and other resources, sharing the benefits. This model is less common in other countries and regions. In contrast, the Energy Community Model is widely applied in the EU, where community members collectively engage in renewable energy projects. This model enhances community cohesion and self-development capabilities, reflecting a distinct approach compared to the models used in other regions.

Table 1. Similarities and differences in benefit-linkage mechanisms.

Mechanism	Brazil	United States	EU	China
Cooperative model	Yes	Yes	Yes	Yes
Public-private partnership (PPP)	Yes	Yes	Yes	No
Community participation	Yes	Yes	Yes	No
Enterprise + farmer model	No	No	No	Yes
Energy community model	No	No	Yes	No

5.2. Similarities and differences in policy support

Table 2 is the similarities and differences in policy support.

(1) Similarities: Brazil, the United States, the EU, and China have all established comprehensive legal frameworks through legislation to support renewable energy development goals and policies. Governments in these regions provide various financial incentives, such as subsidies, tax benefits, and low-interest loans, to lower investment costs in rural renewable energy projects. Additionally, they fund research and demonstration projects for renewable energy technologies, fostering technological advancement and innovation.

(2) Differences: The United States and the EU have extensively implemented market mechanisms such as carbon emission trading systems and green certificate trading mechanisms, which promote market competition and enhance project efficiency. In contrast, China and Brazil have less developed market mechanisms; China primarily depends on national policies and subsidies, while Brazil incorporates these mechanisms to a lesser extent. Additionally, Brazil actively seeks international assistance and cooperation to attract foreign investment and technology for its rural renewable energy projects. China, although also engaged in international cooperation, primarily relies on domestic resources and technology, promoting renewable energy projects through its "Belt and Road" initiative.

Table 2. Similarities and differences in policy support.

Policy support aspect	Brazil	United States	EU	China
Comprehensive legal framework	Yes	Yes	Yes	Yes
Financial incentives (subsidies, tax benefits)	Yes	Yes	Yes	Yes
Funding for research and demonstration projects	Yes	Yes	Yes	Yes
Market mechanisms (carbon trading, green certificates)	Limited	Extensive	Extensive	Limited
International assistance and cooperation	Active seeking foreign investment	Limited	Limited	Engaged in but resource-reliant
Domestic resource utilization	Moderate reliance	High reliance	Moderate reliance	High reliance

5.3. Performance and trend comparisons

Table 3 is the similarities and differences in policy support.

(1) Performance Comparison: In the United States and the EU, advanced market mechanisms and technological progress have significantly reduced project costs, resulting in high economic benefits. Conversely, China and Brazil, despite achieving cost reductions, experience relatively lower economic benefits due to less mature market mechanisms. Environmentally, the EU has realized substantial reductions in greenhouse gas emissions and pollution through stringent policies and carbon limits. While the United States, China, and Brazil also see notable environmental benefits, their policies' enforcement and effectiveness vary compared to the EU. Socially, the United States and the EU have fostered greater community involvement and responsibility through community participation models, promoting sustainable development. In contrast, China and Brazil primarily reflect social benefits in improved rural living standards and energy independence, with relatively less

emphasis on community engagement.

(2) Trend Comparison: Technologically, the United States and the EU lead in advancements in photovoltaic, wind, and energy storage technologies. China is rapidly advancing, particularly in photovoltaics and wind energy, but still has room for growth in high-end technologies and innovations. Brazil's technological focus is mainly on biomass and wind energy, balancing technology importation with local development. Policy-wise, the United States and the EU are shifting from subsidies and incentives to market mechanisms like carbon trading and green certificates. In China and Brazil, policies remain largely subsidy-driven and government-led, with gradual introductions and refinements of market mechanisms. On the international stage, the United States and the EU actively promote global cooperation through technology exports and project investments, expanding their influence. China enhances its international impact through the "Belt and Road" initiative, while Brazil is increasing its role in renewable energy cooperation within Latin America and gradually expanding its international collaboration.

Table 3. Similarities and differences in policy support.

Aspect	United States	EU	China	Brazil
Performance: economic benefits	High due to advanced mechanisms.	High due to advanced mechanisms.	Lower due to less mature mechanisms.	Lower due to less mature mechanisms.
Performance: environmental benefits	Notable reductions but variable enforcement.	Substantial reductions via stringent policies.	Notable benefits, variable enforcement.	Notable benefits, variable enforcement.
Performance: social benefits	Greater community involvement.	Greater community involvement.	Improved rural living standards.	Improved rural living standards.
Trend: technological advancements	Leading in PV, wind, and storage.	Leading in PV, wind, and storage.	Rapid advances in PV and wind.	Focused on biomass and wind.
Trend: policy direction	Shifting to market mechanisms.	Shifting to market mechanisms.	Largely subsidy-driven.	Largely subsidy-driven.
Trend: international cooperation	Actively promoting global cooperation.	Actively promoting global cooperation.	Enhanced impact via belt and road.	Increasing role in Latin America.

6. Insights and policy recommendations

6.1. Insights for China's rural renewable energy industry

To foster the innovative development of China's rural renewable energy industry, it is crucial to establish a comprehensive policy system. (1) Establish a Comprehensive Policy System. To drive the innovative development of China's rural renewable energy industry, it is essential to establish a comprehensive policy framework. China should learn from the EU and the United States by setting clear medium- and long-term development goals and roadmaps to ensure policy coherence and stability. This includes refining the "Renewable Energy Law" and related legislation, as well as defining specific renewable energy targets for rural areas to guide implementation effectively. (2) Implement Multi-Level Support Mechanisms. A robust multi-level support mechanism is crucial for lowering investment costs and enhancing the feasibility of renewable energy projects. By providing various economic incentives, such as subsidies, tax benefits, and low-interest loans, China can create an environment conducive to the growth of its rural renewable energy

sector. Additionally, introducing market-based approaches like carbon trading and green certificates, modeled after successful strategies in the U.S. and EU, will further enhance economic benefits and market competitiveness. (3) Promote Technology Innovation and Community Engagement. Strengthening technology innovation and community involvement is vital for enhancing China's competitiveness in renewable energy. Increasing funding for research and development, particularly in emerging technologies like energy storage and smart grids, will improve technological standards. Moreover, encouraging international cooperation to attract advanced technologies and fostering community participation in renewable energy projects will enhance public support and promote sustainable development.

6.2. Improving benefit-linkage mechanisms in rural renewable energy

To improve benefit-linkage mechanisms in rural renewable energy, developing cooperative models is key. (1) Develop Cooperative Models. To improve benefit-linkage mechanisms in rural renewable energy, developing cooperative models is key. Supporting the establishment of renewable energy cooperatives where farmers jointly invest in, build, and operate projects will enable them to share both benefits and risks. By providing policy support and training, cooperatives can enhance their management and operational capabilities, ensuring the sustainability of their projects. (2) Optimize Enterprise + Farmer Models. Optimizing the enterprise + farmer models is essential for protecting the interests of both parties. This can be achieved by clearly defining cooperation terms and benefit-sharing methods, which will help prevent disputes. Strengthening supervision of these cooperations will further safeguard farmers' rights by preventing unfair contracts and unreasonable benefit distribution, ensuring equitable outcomes for all stakeholders involved. (3) Promote Public-Private Partnerships and Energy Community Models. Promoting Public-Private Partnership (PPP) models is crucial for leveraging the strengths of governments and private enterprises in the investment and management of rural renewable energy projects. Establishing clear policy frameworks and cooperation norms will facilitate smooth implementation and project sustainability. Additionally, implementing energy community models that allow communities to participate in renewable energy projects through democratic decision-making will increase community involvement and responsibility, ensuring successful project outcomes.

6.3. Policy recommendations

To advance the rural renewable energy industry, several policy recommendations should be considered. (1) Formulate and Refine Policies. To advance the rural renewable energy industry, it is crucial to formulate and refine comprehensive policies. Developing a national "Rural Renewable Energy Development Plan" will outline clear development goals, policy measures, and implementation steps. Additionally, creating "Rural Renewable Energy Project Management Measures" will regulate project planning, construction, and operation to ensure quality and effectiveness, providing a solid framework for project success. (2) Enhance Financial Support and Introduce Market Mechanisms. Enhancing financial support through the establishment of a special fund for rural renewable

energy will facilitate research, construction, and operational activities. Optimizing subsidy policies based on project types and regional characteristics will improve targeting and effectiveness. Furthermore, introducing market mechanisms, such as a national carbon trading market and renewable energy certificate trading, will encourage investment, increase market transparency, and create a more competitive environment for renewable energy projects. (3) Promote International Cooperation and Social Participation. Promoting international cooperation by engaging in global renewable energy projects will facilitate technology transfer and enhance domestic competitiveness through the introduction of advanced technologies and management practices. Additionally, fostering social participation by encouraging rural communities to engage in renewable energy projects will drive community development and yield social benefits. Strengthening public awareness and education on renewable energy will further improve recognition and support for the industry. Through these measures, China can enhance benefit-linkage mechanisms, improve policy effectiveness, and drive innovative development toward sustainable goals.

7. Conclusion

The study concludes as follows: Countries and regions demonstrate diverse practices in rural renewable energy benefit-linkage mechanisms. The United States and the EU widely employ cooperative and community support models; Brazil emphasizes enterprise-farmer collaboration, while China primarily relies on enterprise-led and government-supported models. These various models contribute differently to the promotion of rural renewable energy projects. In terms of policy support, systematic legal frameworks and financial incentives are established across countries, but the extent and methods of introducing market mechanisms vary. The EU and the United States have developed mature market mechanisms for carbon and green certificate trading, whereas China and Brazil have less developed or newer market mechanisms.

Performance differences are evident, with the United States and the EU leading in technological advancement and market-based operations, demonstrating significant economic and environmental benefits. China and Brazil have made notable progress in policy support and technology introduction but require further development in market mechanisms and international cooperation. Social participation and community support have shown substantial benefits globally, with the EU's energy community model and the United States' community participation model effectively enhancing community cohesion and project sustainability. This study's focus on select countries and regions may overlook unique practices and policies in others, potentially leading to an incomplete understanding of global rural renewable energy development. Future research should encompass a broader range of countries and regions, including developing nations and emerging markets, to offer a more comprehensive global perspective on rural renewable energy industry development.

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Commentary

Climate change and economic growth: Some critical reflections

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Abstract: Global warming may affect the economic development and, thus, the welfare of people around the world. Therefore, the economic effects of a changing climate should be known in order to be able to design appropriate policy responses. In the economics literature, one research field empirically analyzes the growth effects of global warming. But often those studies do not account for economic variables that have turned out to be significant in explaining economic growth. In addition, they frequently fail to check for the robustness of their outcomes. This can give rise to biased results regarding the growth process and, therefore, does not necessarily reflect the true data-generating process. Hence, the question comes up: how valid and reliable the results are. Therefore, economic analyses should be undertaken that study the robustness of the results as regards the integration of fundamental economic variables. When policy recommendations are made on how to deal with global warming, we argue that they should be based on robust results only. If that does not hold, economic policy risks being inadequate, giving rise to substantial welfare losses.

Keywords: global warming; economic development; robustness; policy recommendations
JEL: O40; Q50

1. Introduction

The question of which factors cause economic growth has been as old as economics as a scientific discipline (for a short survey, see, e.g., Greiner [1]). Using modern econometric methods to detect the forces of economic growth started in the 1950's with a seminal paper written by Solow [2], who implicitly builds on Tinbergen [3], who was the first to integrate a time index in the aggregate production function. Solow's great merit was to show how a measure of the technical progress can be estimated from real-world data accounting for that part of GDP growth that is not explained by increases in capital and labor input.

In the following decades, numerous empirical studies have been undertaken aiming to enhance our understanding of the process of economic growth. But researchers often limit their analyses to only a limited number of explanatory variables so that the question arises how reliable and valid their results are. As regards that problem, Leamer states that "We must insist that all empirical studies offer convincing evidence of inferential sturdiness. We need to be shown that minor changes in the list of variables do not alter fundamentally the conclusions, nor does a slight reweighting of observations, nor correction for dependence among observations, etcetera, etcetera" [4]. Thus, Levine and Renelt [5] perform an extreme-bounds analysis based on Leamer [6], where they investigate which variables always exert a statistically significant effect, independent of which other variables are included in the regression in explaining economic growth (for details as to that analysis, see Levine and Renelt [5]). They find that only a few variables are robust as defined by them, such as the investment share, trade, and the initial level of GDP. The economist Sala-i-Martin [7]

argues that the extreme-bounds analysis is too restrictive since it allows only a zero-one labeling, i.e., a variable is either robust or it is not. Rather, he suggests to call a variable robust if 95% of the density of an estimated coefficient lies to the right or to the left of zero. Proceeding like that, he finds additional variables to be robust, like political variables, for example. Bruns and Ioannidis [8] analyze whether the forces of economic growth change over time or whether they remain the same, independent of which time period is considered. They find that inferences on growth determinants are not stable across time periods. Nevertheless, variables such as the investment share and trade are statistically significant in the more recent growth period until 2010, too.

2. Climate change and economic growth

The accumulation of greenhouse gases (GHGs) like carbon dioxide and methane in the atmosphere will affect the global climate, and changes in the climatic conditions are likely to influence the economic system of societies. For example, more extreme weather events may cause economic damages and require resources that cannot be used for consumption and/or for investment. However, even if there is very strong evidence that the accumulation of GHGs raises the average surface temperature on the earth and can lead to more extreme weather events (see e.g., Arias [9]), it must be stated that the climate system is an extremely complex system such that there is strong uncertainty as regards its sensitivity, see e.g., Meinshausen et al. [10] and Sherwood et al. [11]. An example is provided by Greiner and Semmler [12], who have shown that feedback mechanisms affecting the Albedo of the earth can lead to multiple equilibria in a standard growth model where a simple zero-dimensional climate model has been integrated.

The uncertainty regarding the economics of climate change may be still larger, which is reflected by the wide range for the estimates of climate-related damages. This holds for specific sectors in the economy (see, e.g., Nocera et al. [13] and Neumann et al. [14]) and for the macroeconomy as well [15–17]. Newell et al. [18] estimate 800 specifications with the GDP growth rate and, alternatively, the level of GDP as the dependent variable that is explained by the temperature, by the change of the temperature, by precipitation, by time-fixed effects, and by country-specific time trends. They find that growth models are associated with large uncertainties, reflected by the fact that the 95% confidence interval for GDP impacts in 2100 ranges from GDP losses of 84% to gains of 359%. GDP level models, however, go along with less uncertainty and have a smaller 95% confidence interval between −8.5% and +1.8%, centered around losses between 1%–3%. Despite that uncertainty, it can be expected that changes in climatic conditions may have effects on the growth rates of aggregate GDP, and empirical studies should deal with that problem.

However, studies that empirically analyze the relation between climate change and economic growth often focus on only physical factors, such as temperature and precipitation, and neglect economic variables that have turned out to be important in generating economic growth, thus giving rise to the problem of omitted variables. From an econometric point of view this can lead to inconsistent estimations of the coefficients when the explanatory variables are correlated with the residuals. Even if that problem can be overcome technically in fixed effects panel regression models by introducing dummies, the problem of missing economic variables remains such that the estimated model may not be a good proxy for the true data-generating process and may not yield the true effect of climate variables. Thus,

Barker [19] points out that the relation between economic growth and the temperature change, detected in growth regressions, does not turn out to be robust. He tests the outcome of the paper by Colacito et al. [20] and shows that the removal of a small number of observations drastically changes the qualitative effect of climate change on economic growth. Hence, removing data before 1990 would have raised the estimate by almost three times, meaning that global warming would almost eliminate economic growth in the USA. In addition, taking into account non-linearities can alter the result, too, and may generate positive growth effects of higher temperatures. This shows that the estimation outcome is sensitive with respect to the data and as concerns the estimation method. The same holds for missing economic variables. In market economies, the growth of GDP is the outcome of decisions of individuals and of firms that act intentionally to achieve economic goals. Therefore, econometric models that intend to explain growth should be based on sound economic theory and contain economic explanatory variables, as demanded by Rosen [21]. When economic variables exert a statistically significant effect on economic growth and are not included in the estimation, their effect may be reflected by the coefficients of the climate-related variables and, thus, distort their true effects.

The scholars Dell et al. [22] and Burke et al. [23] represent two other frequently cited papers that study the relation that exists between economic growth and climate change. Dell et al. [22] regress annual growth on annual average temperatures for 127 countries from 1961 to 2003 and obtain a statistically significant negative effect of higher temperatures on economic growth in poor countries where the income falls short of the median, whereas the outcome for rich countries turns out to be insignificant. Burke et al. [23] analyze 166 economies from 1961 to 2010 and conclude that 77 percent of all countries would be poorer with temperature increases than without increases, and 5 percent of countries would be poorer in 2100 than they are today because of a rise of global temperatures. But the economist Barker [24,25] shows that those papers are characterized by flaws, just as the paper by Colacito et al. [20]. Hence, the paper by Dell et al. [22] resorts to an untenable method of classifying countries by income, and the results are influenced by arbitrary methodological choices and by a small number of observations with unusual characteristics [24]. As regards the paper by Burke et al. [23], Barker [25] demonstrates that the paper leaves out inconvenient results, presents misleading charts to confuse readers, and fails to report obvious robustness checks. In addition, it is shown by simulations that the statistical significance of their results is inflated.

Similarly, Greiner et al. [26] have demonstrated for European economies that climate change is not a robust statistically significant variable in explaining economic growth, while institutional and economic variables, such as the rule of laws, the fiscal variable, and the output gap, are statistically significant and robust. However, that study does not distinguish between northern and southern countries, which may affect the outcome, as shown by Jacob et al. [27] and by Pala [28]. Hence, more elaborate estimation strategies that allow for heterogeneity may turn out to be necessary, as applied, for example, by Owusu et al. [29] in estimating public debt sustainability for European countries.

Further, it should be noted that resorting to fossil sources of energy is promoting economic growth and development, and many countries, therefore, refuse to stop their use. For example, the G20 countries could not agree to phase out fossil fuels [30], and the African Energy Chamber (AEC) pointed out that oil and gas play an instrumental role in the development of African economies, and African producers of those resources will not agree

to a phase-out of those resources [31]. An et al. [32] point out that oil cooperation between economies has great potential and will be pursued in the future. Mutalimov et al. [33] show with the help of a mathematical model that Eastern Russian small enterprises will continue to raise their emissions over the next 20 years. This results from the fact that the enterprises benefit a lot from mineral extraction and from the fact that they have to increase their profits.

3. Conclusion

The philosopher Kant has stated that theory without empirics is empty and empirics without theory is blind: "Gedanken ohne Inhalt sind leer, Anschauungen ohne Begriffe sind blind" [34]. In market economies, the growth of aggregate GDP is the result of decisions of individuals and of firms that act intentionally to achieve economic goals. Hence, econometric models explaining growth should be based on sound economic theory and contain economic explanatory variables. Neglecting the latter and positing that growth solely depends on climatic factors can lack important aspects and may yield a biased picture of the real world. Thus, the outcomes of such models should be considered with care. That holds in particular when the emphasis is put on the exact numerical values of the estimated coefficients rather than on their qualitative contents, e.g., whether an explanatory variable exerts a positive or negative effect on the dependent variable. Focusing on the exact numbers would imply a perception of knowledge and precision that the models cannot deliver and may generate inadequate policy measures and, in the end, huge welfare losses.

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