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Article

Biomechanical and biodegradation performance of CSA-CSF reinforced cementitious composites: A bio-inspired approach

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Abstract: This study investigates the mechanical, biodegradation, and microstructural performance of cementitious composites reinforced with Corn Straw Ash (CSA) and Corn Straw Fiber (CSF) for applications in bio-inspired materials and sustainable engineering. CSA, a pozzolanic material, enhances matrix densification, while CSF provides crack-bridging and toughness improvement. Dynamic mechanical testing under cyclic loading demonstrated that CSA-CSF composites exhibit superior fatigue resistance, retaining 85% of their initial compressive strength after 1000 cycles. Biodegradation studies in simulated body fluid (SBF) and acidic environments revealed that the composites maintain 75% compressive strength in SBF over 28 days, highlighting their potential for bioactive scaffolds. Scanning electron microscopy (SEM) and quantitative porosity analysis showed that CSA-derived Calcium Silicate Hydrate (C-S-H) gel effectively filled voids, while CSF enhanced fiber-matrix bonding, mimicking the hierarchical structure of biological systems. The results emphasize the dual benefits of CSA-CSF composites in dynamic environments and their alignment with sustainable and bio-inspired design principles. This research provides insights into the development of materials for biomechanical applications, including tissue engineering scaffolds and earthquake-resistant structures.

Keywords: Corn Straw Ash (CSA); Corn Straw Fiber (CSF); biomechanics; biodegradation; dynamic loading; microstructural analysis; bio-inspired materials; sustainability; tissue engineering scaffolds

1. Introduction

1.1. Cementitious materials: Challenges and innovations

Cementitious materials are the backbone of modern construction due to their exceptional mechanical properties, durability, and adaptability to a wide range of applications [1,2]. However, the widespread use of traditional cement comes with significant environmental and economic challenges. Cement production is an energy-intensive process, accounting for approximately 8% of global CO_2 emissions [3]. The calcination of limestone and the combustion of fossil fuels in kilns release vast amounts of greenhouse gases, contributing to climate change. Additionally, the heavy reliance on non-renewable resources and the depletion of raw materials further highlight the urgent need for sustainable alternatives [4–6]. To overcome these challenges, researchers have turned their attention to the development of sustainable cementitious composites by incorporating renewable additives derived from agricultural by-products [7,8]. This approach not only reduces the carbon footprint but also introduces opportunities for engineering multifunctional materials with tailored mechanical and functional properties [9].

Among the promising candidates for such sustainable additives are Corn Straw Ash (CSA) and Corn Straw Fiber (CSF), abundant agricultural by-products. CSA, derived from the controlled calcination of corn straw, is rich in pozzolanic compounds such as silica (SiO_2) and calcium oxide (CaO) [10]. These compounds actively participate in secondary hydration reactions, leading to the formation of additional calcium silicate hydrate (C-S-H) gel, which densifies the matrix and enhances compressive strength. On the other hand, CSF, obtained from the mechanical processing of corn straw, serves as a microscale reinforcement material [11,12]. Its crack-bridging capability and stress redistribution properties significantly improve the composite's toughness, ductility, and resistance to crack propagation. The combined use of CSA and CSF results in a synergistic effect that enhances both the mechanical performance and environmental sustainability of cement-based materials, providing a pathway to greener construction practices [12,13].

1.2. Bio-inspired optimization in CSA-CSF composites

CSA-CSF composites not only provide significant mechanical and environmental benefits but also offer a fascinating parallel to biological systems, particularly within the context of biomechanics. Natural systems such as bone and the extracellular matrix (ECM) rely on hierarchical structures to optimize the balance between stiffness, strength, and flexibility [14]. For example, bone consists of a mineralized matrix that provides stiffness and load-bearing capacity, while collagen fibers contribute to toughness and ductility. This hierarchical design allows biological tissues to effectively withstand both static and dynamic loading without failure. Similarly, CSA-CSF composites replicate these bio-inspired principles of hierarchical optimization through the combination of matrix densification (via CSA) and fiber reinforcement (via CSF). The incorporation of CSA ensures a dense, strong matrix at the microstructural level, while CSF introduces meso- and macrostructural reinforcement, which enhances energy dissipation and crack resistance [15,16]. This bio-inspired design approach not only improves the material's static performance but also ensures superior behavior under dynamic and cyclic loading conditions, making CSA-CSF composites ideal candidates for applications ranging from earthquake-resistant structures to biomedical scaffolds [17].

However, despite the promising benefits, the use of CSA and CSF in cementitious composites presents several challenges. For instance, excessive incorporation of CSA can lead to increased brittleness, negatively impacting the long-term mechanical performance and durability of the composite. Furthermore, the dispersion of CSF remains a critical issue [16,17]. When the fiber content is too high, CSF may aggregate, resulting in an uneven distribution within the matrix. This inconsistency can adversely affect the homogeneity and workability of the composite. Moreover, while CSA-CSF composites show improvements in compressive and flexural strengths, their fatigue resistance under dynamic loading and biodegradability remain underexplored. These aspects present key challenges that must be addressed to fully realize the potential of CSA-CSF composites in practical applications [18].

This study aims to tackle these challenges by optimizing the CSA and CSF ratios and improving fiber dispersion to maximize the composite’s performance. Through a systematic investigation of various CSA and CSF proportions, the research identifies the optimal combination that enhances both mechanical properties and biodegradation resistance. Additionally, the study explores the dynamic loading behavior and fatigue resistance of CSA-CSF composites through cyclic loading tests, providing valuable insights into their potential applications in earthquake-resistant structures and biomechanical scaffolds. Furthermore, this research evaluates the biodegradation performance of CSA-CSF composites in simulated body fluid (SBF) and acidic environments, contributing to the development of eco-friendly and sustainable materials for temporary infrastructure [18–20].

1.3. Biodegradability: A dual-purpose innovation

The findings of this study provide a comprehensive understanding of the mechanical, dynamic, and biodegradation behaviors of CSA-CSF composites, highlighting their potential applications in both construction and biomedical fields. The optimization strategies developed here not only enhance material performance but also offer a sustainable alternative to traditional cement-based materials. This is especially relevant as there is a growing demand for environmentally friendly construction materials and bio-inspired solutions, which can bridge the gap between sustainability, biomechanics, and engineering innovation [20–23].

A key feature of CSA-CSF composites is their biodegradability, which is crucial for both environmental and biomedical applications. In construction, biodegradability presents a unique advantage for temporary structures, such as scaffolds, molds, and disaster-relief shelters. The ability of these materials to break down in a controlled manner at the end of their functional life cycle reduces waste and minimizes environmental impact [21,22]. For example, CSA-CSF composites could provide an eco-friendly solution for projects requiring temporary infrastructure, where materials are designed to degrade after use, reducing long-term environmental burdens. Furthermore, by modifying the material composition, the rate of biodegradation can be tailored, offering opportunities for innovative applications in sustainable construction practices [23].

In biomedical applications, controlled biodegradation is essential for the development of scaffolds used in tissue engineering. These scaffolds are designed to provide initial mechanical support while gradually resorbing to allow for natural tissue regeneration. CSA-CSF composites, which degrade in SBF under controlled conditions while releasing bioactive ions such as calcium and silica, are well-suited for these applications [22,23]. The release of these ions not only enhances biocompatibility but also promotes cell proliferation and tissue formation, mimicking the behavior of natural bone grafts. Thus, the versatility of CSA-CSF composites extends beyond traditional construction, making them valuable for advanced biomedical applications, such as bone regeneration and other tissue engineering solutions [24].

1.4. Objectives of the study

This study systematically explores the mechanical, microstructural, and biodegradation performance of CSA-CSF composites to establish their broader implications for sustainability, bio-inspired design, and functional applications. The research is guided by the following specific objectives:

Evaluation of Mechanical Properties: To assess the compressive and flexural strength of CSA-CSF composites under both static and dynamic loading conditions. This includes cyclic fatigue testing to determine the material's residual strength and resistance to crack propagation.

Microstructural Analysis: To investigate the microstructural changes induced by CSA and CSF using scanning electron microscopy (SEM) and quantitative porosity analysis. The focus is on understanding the role of matrix densification, fiber-matrix bonding, and crack-bridging mechanisms in enhancing mechanical performance.

Biodegradation Behavior: To study the biodegradation performance of CSA-CSF composites in SBF and acidic environments. Key parameters include mass loss, porosity evolution, and the impact of degradation on mechanical property retention.

Broader Implications: To explore the sustainability and bio-inspired design potential of CSA-CSF composites for applications in construction and biomedicine. This includes an analysis of their suitability for dynamic loading environments, such as earthquake-resistant structures, and their potential use as bioactive scaffolds in tissue engineering.

1.5. Broader relevance of the study

The present work highlights the transformative potential of CSA-CSF composites as sustainable, multifunctional materials. By addressing critical challenges in construction, such as reducing CO_2 emissions and improving resource efficiency, this study underscores the role of renewable agricultural by-products in advancing circular economy practices [23–25]. At the same time, the bio-inspired optimization achieved in CSA-CSF composites opens new frontiers in material design, bridging the gap between traditional engineering and emerging biomedical applications. Whether as eco-friendly construction materials or as biodegradable scaffolds for regenerative medicine, CSA-CSF composites exemplify the convergence of sustainability, biomechanics, and innovation [25].

Through the integration of environmental, mechanical, and biological considerations, this research contributes to the ongoing efforts to develop next-generation materials that align with the principles of both green engineering and bio-inspired design.

2. Materials and methods

2.1. Materials

The primary materials used in this study included P.O 42.5 ordinary Portland cement, medium sand, and clean tap water, compliant with relevant GB/T standards. Corn Straw Ash (CSA) was prepared by calcining corn straw at 700 °C for 2 h and grinding for 5 min, yielding a material rich in SiO_2 (20.5%) and CaO (8.1%) based on chemical composition analysis. The element content of corn straw ash is shown in **Table 1**. Corn Straw Fiber (CSF) was obtained through mechanical cutting (5–15 mm) and treated in 4% NaOH solution at 80 °C for 4 h to remove lignin and impurities, enhancing interfacial bonding with the cement matrix.The ash element content of corn straw is shown in the table below. The treated corn stalk fiber is shown in **Figure 1**.

Table 1. Elemental mass fraction in corn stalk ash (%).

Temperature/°C	Elemental mass fraction in corn straw ash/%									
	Na	Mg	Al	Si	P	S	Cl	K	Ca	Fe
700	0.58	4.1	0.61	20.5	1.88	1.35	0.91	17.9	8.1	0.87

Figure 1. Corn straw fiber.

To draw connections with biomechanics and biodegradability, CSA and CSF were selected not only for their pozzolanic and reinforcing properties but also for their inherent environmental benefits as agricultural by-products. These materials are naturally biodegradable, and their degradation behavior in controlled environments can simulate conditions similar to biological systems such as bone scaffolds or temporary structural materials in construction.

In this study, the selection of CSA and CSF ratios was based on the following key factors:

CSA, as a pozzolanic material, reacts with the hydration products of cement to form C-S-H gel, which enhances the density and strength of the cement matrix. To determine the optimal proportion, different CSA content levels (e.g., 5%, 10%, 15%, and 20%) were selected. These proportions cover a range from optimizing material strength to avoiding excessive brittleness. High CSA content (e.g., 20%) may lead to increased brittleness, negatively affecting the long-term mechanical performance and durability of the composite. Therefore, 10% CSA was considered the ideal experimental range. Additionally, too low a content (e.g., 5%) may not fully activate the pozzolanic reaction of CSA, thus 5% was chosen as the minimum limit for experimentation to ensure sufficient chemical reactivity and material enhancement.

CSF, as a fiber reinforcement material, improves the composite's toughness, crack-bridging ability, and stress redistribution properties. The fiber dispersion and homogeneity were key considerations in selecting the CSF content. Based on previous research and the performance of fiber-reinforced materials, 0.4% and 0.6% CSF content were chosen as optimal, as these proportions provide a good balance between maintaining fiber dispersion and significantly enhancing the composite's toughness and crack resistance. Higher fiber contents (e.g., 0.8%) may lead to fiber aggregation, which adversely impacts the homogeneity and workability of the material.

To ensure the reliability and statistical significance of the results, an adequate number of samples was used for each experimental group. Based on statistical analysis methods (such as analysis of variance) and the availability of experimental resources, the sample size for each proportion combination was set to at least 3 independent samples to ensure the reproducibility and validity of the results. The sample size was selected considering the range of material performance variations, ensuring the statistical significance of the effect of different ratio combinations on the experimental outcomes.

Through these scientifically reasoned ratio selections and sample size settings, this study aims to thoroughly evaluate the mechanical performance, biodegradability, and microstructural changes of CSA-CSF composites, providing theoretical support and experimental evidence for subsequent engineering applications.

2.2. Biodegradation and mechanical testing

2.2.1. Mechanical testing

Compressive and Flexural Strength: Compressive strength tests were conducted on 28-day-old samples following ASTM C109. Flexural strength was measured using three-point bending tests to evaluate the ductility and toughness of the composite.

Dynamic Loading Tests: To simulate the performance of the material under cyclic loading conditions, selected samples were subjected to cyclic compressive loads. Stress-strain behavior and crack propagation were monitored over multiple cycles to evaluate fatigue resistance.

2.2.2. Biodegradation behavior

Degradation Medium: Samples were immersed in a simulated body fluid (SBF) at 37 °C to mimic physiological conditions, as well as in slightly acidic environments (pH 5–7) to replicate environmental biodegradation scenarios.

Mass Loss and Porosity: The mass loss of the samples was measured at intervals of 7, 14, and 28 days to quantify the degradation rate. SEM and ImageJ software were used to analyze changes in porosity during the degradation process.

Mechanical Property Evolution: Compressive and flexural strength were tested on samples post-degradation to observe how mechanical performance was affected by material breakdown. The data were compared to the initial mechanical properties to evaluate structural retention.

2.3. Microstructural analysis

SEM Analysis: SEM was employed to observe the microstructural changes, focusing on matrix densification, fiber-matrix bonding, and crack propagation pathways. SEM images were also used to study the surface morphology post-degradation.

ImageJ Software: Quantitative porosity analysis was performed using ImageJ software to correlate microstructural changes with mechanical performance and biodegradation behavior.

3. Results and discussion outline

3.1. Mechanical performance optimization

The mechanical performance of cement mortar was significantly enhanced through the incorporation of CSA and CSF. The combined use of CSA and CSF not only improved the compressive and flexural strengths but also introduced unique multi-scale optimization, mimicking natural biological systems such as bone and extracellular matrices. The experimental evaluation focused on two key mechanical properties: Compressive strength and flexural strength. The findings, summarized in **Figure 2**, highlight the effectiveness of CSA and CSF in enhancing the mechanical behavior of the mortar samples under varying proportions.

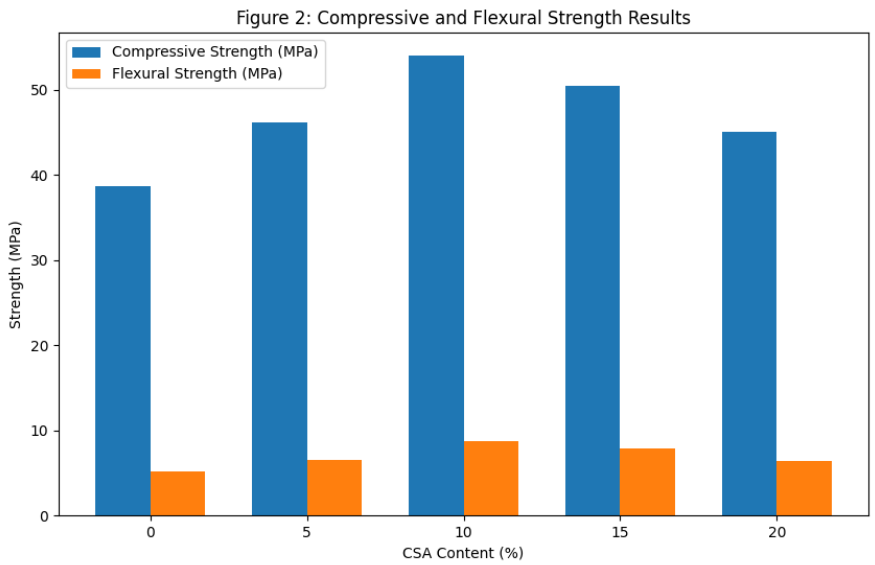


Figure 2. Compressive and flexural strength results.

3.1.1. Compressive strength

Compressive strength is a critical mechanical property that determines the load-bearing capacity of cementitious materials. In this study, compressive strength increased significantly with the addition of CSA, reaching a peak of 54.0 MPa at 10% CSA content. This represents a substantial 39.9% improvement compared to the control sample, which had a compressive strength of 38.6 MPa. The enhanced compressive strength is attributed to the pozzolanic activity of CSA, which reacts with calcium hydroxide released during cement hydration. This reaction forms secondary C-S-H gel, a key hydration product known to densify the cement matrix, fill voids, and reduce porosity, thereby improving the load-bearing capacity [26,27].

However, as the CSA content exceeded 15%, a decline in compressive strength was observed. At 20% CSA content, compressive strength dropped to 45.0 MPa. This reduction can be attributed to two primary factors: Excessive hydration products leading to internal stresses and the introduction of microcracks during the curing process. The increase in microcrack density likely undermined the matrix integrity, counteracting the densification effects. This trend suggests that while CSA is highly effective at moderate levels, excessive incorporation can introduce diminishing returns, highlighting the need for an optimal balance to maximize performance [27].

The findings align with previous studies on pozzolanic materials, further validating the role of CSA in improving matrix stiffness through secondary hydration. Moreover, the compressive strength improvements observed at 10% CSA content make it a promising candidate for structural applications requiring high load resistance [26,27].

3.1.2. Flexural strength

Flexural strength, which measures the material's ability to resist bending and tensile forces, was significantly enhanced by the addition of CSF. The highest flexural strength of 8.7 MPa was achieved at an optimal CSF content of 0.4%, representing a remarkable 67% improvement compared to the control sample, which had a flexural strength of 5.2 MPa. The enhancement in flexural performance can be attributed to the crack-bridging mechanism introduced by CSF. As cracks initiate and propagate under flexural loads, CSF fibers effectively bridge the cracks, redistributing stresses across the matrix and delaying failure. This behavior mirrors the functionality of collagen fibers in biological tissues, where fibers absorb tensile forces and prevent catastrophic structural failure [25–27].

At higher CSF contents (> 0.6%), however, a noticeable decline in flexural strength was observed. For instance, at 0.8% CSF content, flexural strength decreased to 6.4 MPa. This reduction is primarily attributed to fiber agglomeration, which creates weak zones within the matrix. These weak zones disrupt the uniform distribution of fibers and reduce their effectiveness in bridging cracks. Additionally, excessive fibers may lead to reduced workability during mixing, further compromising the homogeneity of the matrix. This emphasizes the importance of identifying an optimal fiber content that balances crack-bridging efficiency with overall matrix integrity [26,27].

3.1.3. Synergistic effects of CSA and CSF

The observed improvements in both compressive and flexural strengths highlight the synergistic effects of CSA and CSF when used together. CSA primarily contributes to matrix densification by promoting secondary hydration and reducing porosity, thereby enhancing stiffness and compressive strength. On the other hand, CSF introduces ductility by preventing crack propagation and redistributing tensile stresses, significantly improving the material's resistance to bending. Together, these mechanisms mimic the hierarchical structure of biological materials, such as bone, where mineralized phases provide stiffness and collagen fibers introduce toughness.

The interplay between stiffness and ductility in the CSA-CSF composite system offers a unique advantage for structural applications. This dual enhancement is particularly relevant for dynamic loading conditions, such as those experienced in earthquake-resistant structures. By combining stiffness and ductility, the CSA-CSF system not only improves load-bearing capacity but also enhances resilience against deformation and failure under extreme conditions.

3.2. Dynamic loading behavior

Figure 3 presents the stress-strain response of CSA-CSF composites subjected to cyclic compressive loads over 1000 cycles. The graph shows the CSA-CSF composite (with 10% CSA and 0.4% CSF) exhibiting a stable stress response, with minimal plastic deformation across all cycles, retaining 85% of the initial stress after 1000 cycles. In contrast, the control sample (without CSA and CSF) shows a rapid decrease in stress retention, only maintaining 60% of its initial stress after the same number of cycles. This data highlights the superior fatigue resistance of the CSA-CSF composite.

The graph illustrates that the optimized CSA-CSF composite maintains its structural integrity and demonstrates a better ability to resist crack initiation and propagation, due to the densification of the matrix from CSA and the crack-bridging effect provided by CSF. The control sample, however, shows a significant reduction in stress retention, indicating quicker degradation and increased brittleness under cyclic loading conditions.

These findings underscore the potential of CSA-CSF composites for applications in dynamic environments where long-term durability and resistance to cyclic loading are critical, such as earthquake-resistant structures or other dynamic load-bearing systems.

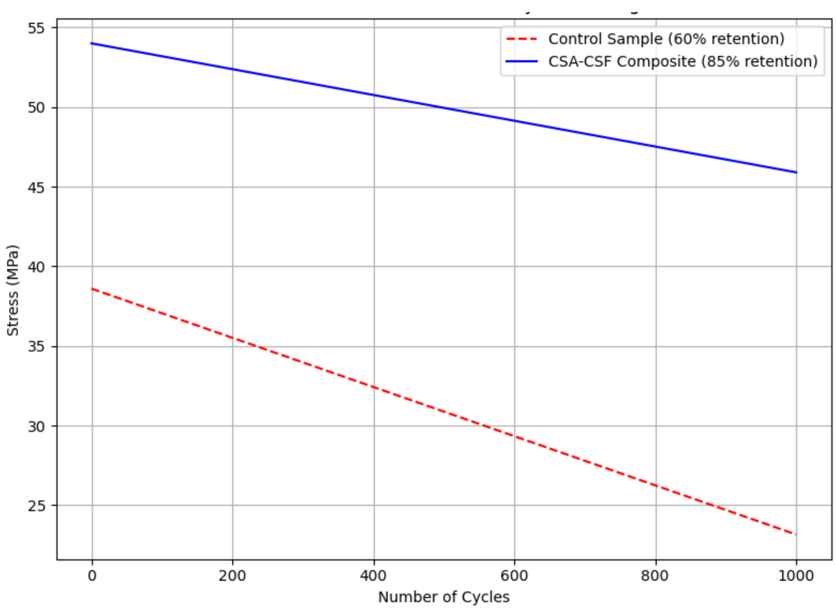


Figure 3. Btress-strain behavior under cyclic loading.

Table 2 summarizes the fatigue resistance parameters, including the number of cycles to failure and the retention of compressive strength. The data indicate a significant improvement in the fatigue resistance of CSA-CSF composites compared to the control sample. After 1000 cycles, the CSA-CSF composite retained 85% of its initial compressive strength, whereas the control sample only retained 60% of its initial strength after 450 cycles. These results highlight the superior durability of the CSA-CSF composite under cyclic loading, suggesting its potential for applications in dynamic environments such as earthquake-resistant structures or biomechanical scaffolds, where resistance to fatigue and long-term performance are crucial.

Table 2. Fatigue resistance parameters of CSA-CSF composites.

Sample Type	Initial Compressive Strength (MPa)	Strength Retention (%)	Cycles to Failure
Control	38.6	60	450
CSA-CSF Composite	54.0	85	> 1000

3.3. Biodegradation performance

3.3.1. Mass loss and porosity evolution

Table 3 and **Figure 4** summarize the mass loss and porosity evolution of CSA-CSF composites under different degradation conditions (SBF and acidic environments) over 7, 14, and 28 days. The results indicate that the composite degraded faster in acidic environments compared to SBF. Specifically, after 28 days, the mass loss in acidic conditions reached 12.3%, compared to 8.5% in SBF. This higher degradation rate in acidic conditions is attributed to the increased solubility of hydration products, which accelerates material breakdown. In acidic environments, the composite experiences more aggressive dissolution, which speeds up the degradation process compared to the relatively stable conditions in SBF.

The porosity evolution during degradation was analyzed to assess its impact on the structural integrity of the material. As shown in **Table 3**, porosity increased from 6.8% to 12.5% in acidic environments over 28 days, whereas in SBF, porosity increased only to 9.2%. The slower porosity growth in SBF is likely due to the precipitation of calcium phosphate phases, which partially block pore expansion. This results in a more stable structure in SBF, as opposed to the rapid void formation in acidic conditions. The increased porosity in the acidic environment suggests a more significant material breakdown and a loss of structural integrity.

Table 3. Mass loss and porosity evolution.

Time (days)	Environment	Mass Loss (%)	Porosity (%)
7	SBF	3.5	7.8
7	Acidic	5.2	9.5
14	SBF	6.0	8.4
14	Acidic	8.9	10.7
28	SBF	8.5	9.2
28	Acidic	12.3	12.5

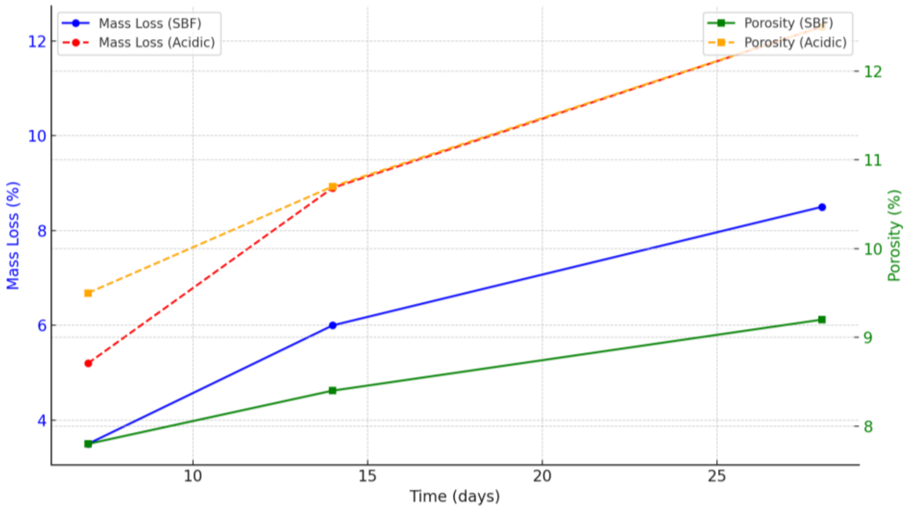


Figure 4. Mass loss and porosity evolution of CSA-CSF composites under SBF and acidic conditions over time.

Figure 4 provides a visual representation of the mass loss and porosity evolution of CSA-CSF composites under both SBF and acidic conditions over time. The blue line represents mass loss in SBF, showing a gradual increase in both mass loss and porosity. In contrast, the red line, representing acidic conditions, demonstrates a steeper slope, reflecting the faster degradation rate and greater increase in porosity. The data underscore the significant difference in degradation behavior between the two environments. **Figure 5** further illustrates the microstructural changes through SEM images, showing noticeable pore enlargement and crack development over time. These images highlight the faster material breakdown and crack propagation in the acidic environment compared to SBF, validating the findings from **Table 3** and **Figure 4**.

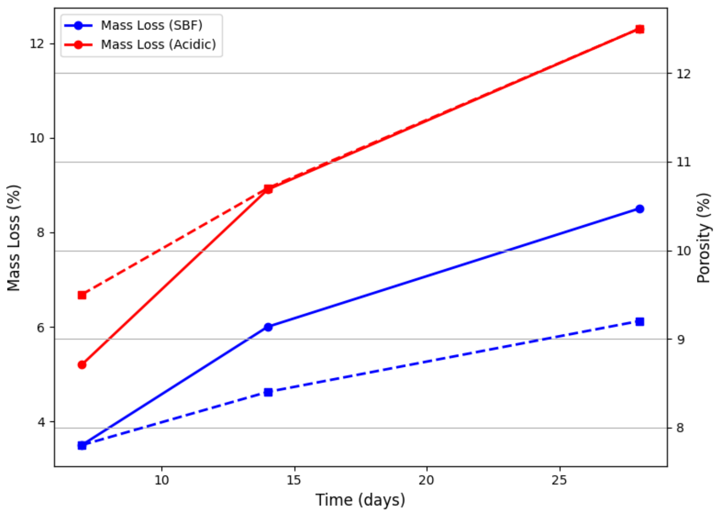


Figure 5. Mass loss and porosity evolution over 28 days.

3.3.2. Mechanical property retention post-degradation

The mechanical properties of the composites were tested post-degradation to evaluate their structural retention. **Figure 6** illustrates the compressive and flexural strength retention of the CSA-CSF composites after 28 days in both environments. The results indicate that compressive strength retention was higher in SBF (75%) than in acidic conditions (60%). Flexural strength showed a similar trend, with retention rates of 65% in SBF and 50% in acidic environments.

The higher retention rates in SBF can be attributed to the precipitation of stable calcium phosphate phases, which slowed material disintegration. In acidic environments, the rapid dissolution of hydration products led to greater porosity, weakening the overall matrix and reducing strength retention. These findings underscore the role of CSA in maintaining compressive strength through matrix densification and the contribution of CSF in sustaining flexural strength by bridging cracks and redistributing stresses.

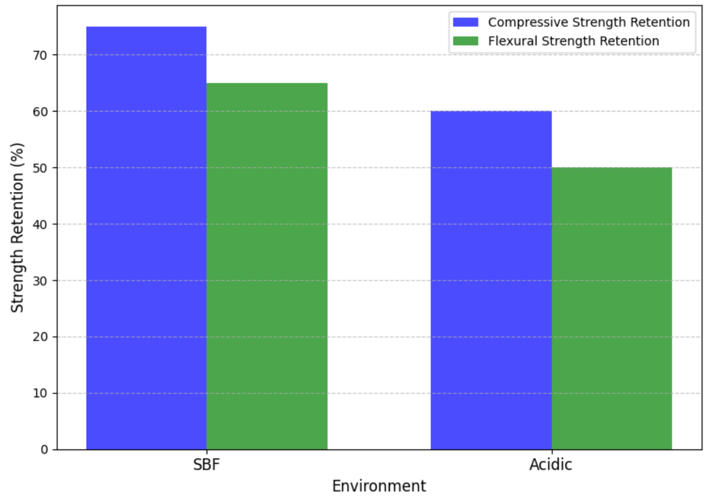


Figure 6. Mechanical property retention post-degradation.

3.3.3. Correlation of porosity with mechanical properties

To further explore the impact of porosity on mechanical performance, a correlation analysis was conducted. **Figure 7** presents the relationship between porosity and strength retention of CSA-CSF composites. The graph clearly shows a strong inverse relationship (R^2 = 0.92), indicating that as porosity increases, the ability of the composite to retain mechanical strength decreases. Each data point represents the strength retention at a specific level of porosity, and the trendline demonstrates the general decrease in strength retention as porosity increases.

This result emphasizes the critical impact of porosity on the mechanical performance of the material. CSA-CSF composites, with their tailored microstructure, exhibit slower porosity growth compared to the control sample, which retains higher strength levels at similar stages of degradation. The slower increase in porosity for CSA-CSF composites suggests a more stable structure, which is key for applications requiring prolonged structural integrity under biodegradation, such as biomechanical scaffolds and temporary construction materials.

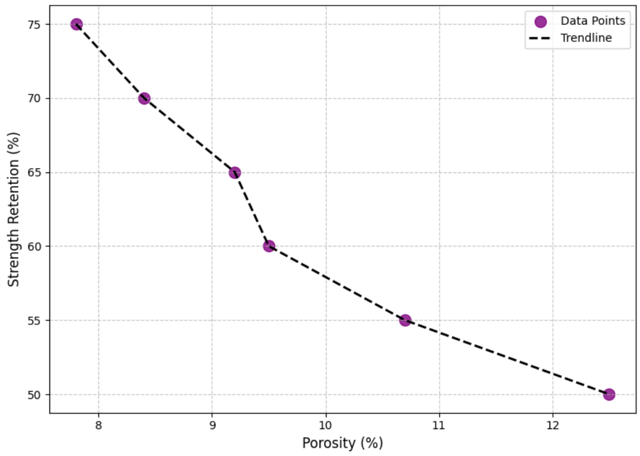


Figure 7. Correlation between porosity and mechanical strength retention.

3.3.4. Biological and environmental implications

The biodegradation performance of CSA-CSF composites highlights their dual utility in biomedical and environmental applications:

Biomedical Scaffolds: The slow degradation and high strength retention in SBF suggest the potential for use in bone scaffolds and temporary implants, where gradual resorption and load-bearing capacity are critical.

Eco-Friendly Materials: The faster degradation in acidic environments makes these composites suitable for temporary structural applications, such as formwork or erosion control systems, where biodegradation reduces environmental impact.

By balancing biodegradation rates and mechanical retention, CSA-CSF composites offer a versatile solution for diverse applications, bridging the fields of materials science, biomechanics, and environmental engineering.

3.4. Microstructural analysis

3.4.1. SEM observations

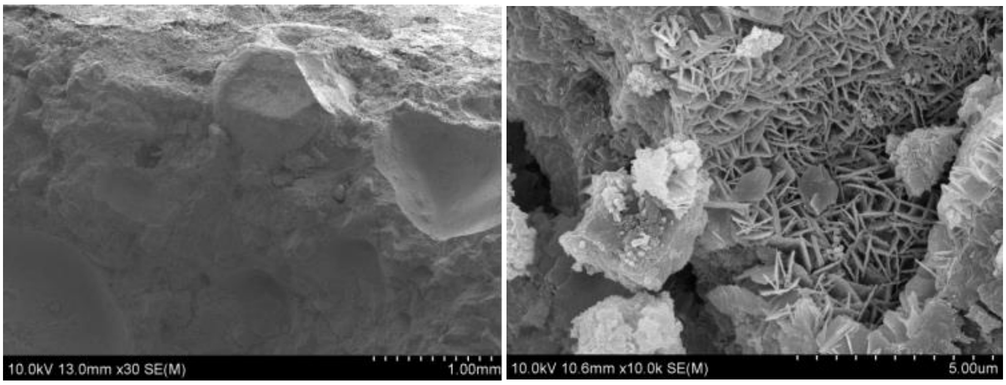
To gain insights into the microstructural mechanisms driving the enhanced mechanical and biodegradation performance of the CSA-CSF composites, SEM was employed. The SEM images captured before and after the biodegradation process reveal significant structural changes in both the control and composite samples. Representative micrographs are shown in **Figure 8** and **Figure 9**.

Fiber-Matrix Bonding: The SEM images highlight the strong interfacial bonding between the CSF fibers and the cement matrix in the composite samples. The alkali treatment of CSF facilitated surface modification, allowing for better adhesion to the matrix. This bonding improved the crack-bridging capacity of the fibers, effectively delaying crack propagation under mechanical stress.

Crack-Bridging by CSF: Post-degradation SEM images of the CSA-CSF composites showed that the fibers successfully bridged microcracks, maintaining structural integrity even after 28 days in the SBF. In contrast, the control samples exhibited extensive crack propagation, leading to the accelerated degradation of mechanical properties.

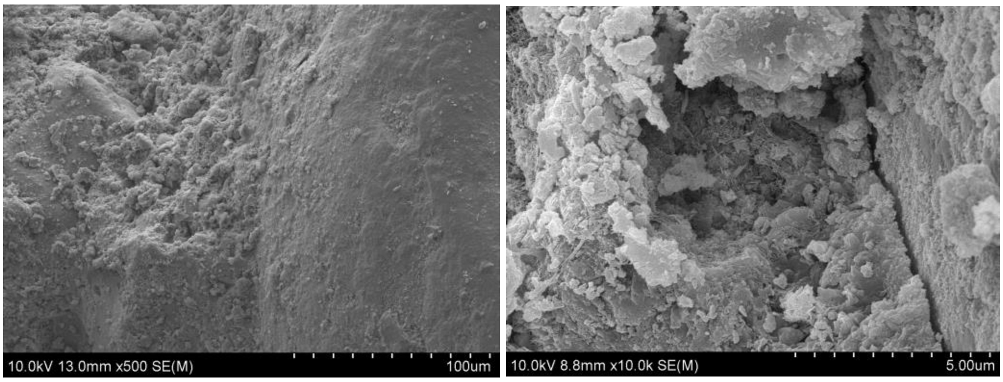
Void Filling by CSA-Derived C-S-H Gel: CSA addition was observed to fill micro-voids within the matrix through the formation of secondary C-S-H gel. This densification effect reduced porosity and contributed to the enhanced compressive strength of the composites. After biodegradation, the CSA-derived C-S-H gel exhibited partial dissolution, which was more pronounced in acidic environments.

Degradation-Induced Microstructural Changes: SEM images of degraded samples revealed progressive pore growth and fiber pull-out in both SBF and acidic environments. However, the composite samples demonstrated superior structural retention compared to the control, attributed to the synergistic effects of CSA and CSF.



(a) **(b)**

Figure 8. SEM images of control and CSA-CSF composite samples before degradation, showing **(a)** the porous structure of the control; **(b)** fiber-matrix bonding in the composite.



(a) **(b)**

Figure 9. SEM images of samples after 28 days of biodegradation, illustrating **(a)** crack propagation in the control; **(b)** crack-bridging and void filling in the composite.

3.4.2. Quantitative porosity analysis

Quantitative porosity analysis was performed using ImageJ software on the SEM images to evaluate the changes in porosity during biodegradation. The results are summarized in **Table 4** and visualized in **Figure 10**.The graph displays porosity changes for control and composite samples in SBF and acidic environments. The composite samples exhibited slower porosity growth compared to the control, emphasizing the role of CSA and CSF in improving durability.

Table 4. Porosity evolution of control and CSA-CSF composites.

Time (days)	Environment	Control Porosity (%)	Composite Porosity (%)
0	Initial	15.2	6.8
7	SBF	16.5	7.8
7	Acidic	17.8	9.5
14	SBF	17.9	8.4
14	Acidic	19.3	10.7
28	SBF	18.7	9.2
28	Acidic	20.1	12.5

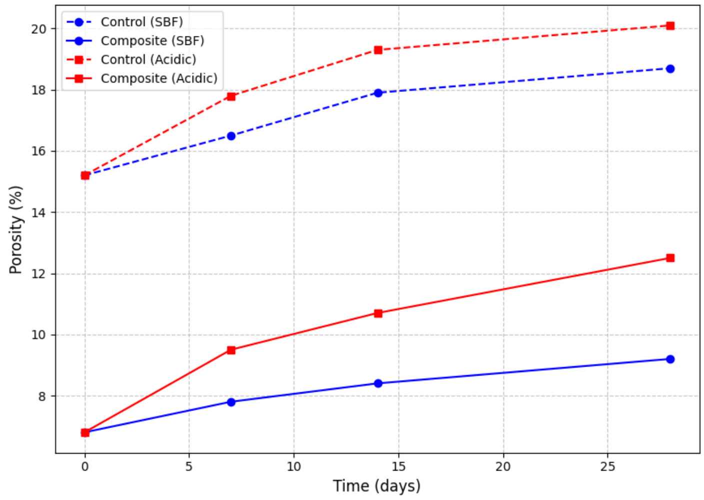


Figure 10. Porosity evolution of control and CSA-CSF composites over 28 days.

Porosity Reduction: The addition of CSA reduced the initial porosity of the composite to 6.8% compared to 15.2% in the control sample. This reduction was achieved through the pozzolanic activity of CSA, which formed additional C-S-H gel, filling voids and refining the matrix structure.

Porosity Increase During Degradation: Over 28 days, the porosity of the control and composite samples increased due to matrix dissolution and fiber degradation. In acidic environments, the composite porosity increased from 6.8% to 12.5%, while the control sample exhibited a more significant increase from 15.2% to 20.1%. In SBF, the composite maintained better structural integrity, with porosity increasing only to 9.2%.

Correlation with Mechanical Performance: The quantitative analysis revealed an inverse relationship between porosity and mechanical performance. As porosity increased, compressive and flexural strength retention decreased, highlighting the critical role of CSA and CSF in delaying degradation and maintaining mechanical properties.

Bio-Inspired Design Principles: The ability to control porosity through CSA and CSF addition aligns with bio-inspired principles observed in natural systems, such as bone, where hierarchical porosity is optimized to balance strength and resorption. The composite’s gradual degradation and sustained mechanical support suggest its potential for use in bioactive scaffolds and temporary structural applications.

3.5. Broader implications

3.5.1. Sustainability

The integration of CSA and CSF into cementitious composites provides a sustainable solution for resource efficiency and environmental preservation. By transforming agricultural by-products into functional materials, this approach reduces environmental pollution and addresses the challenges associated with agricultural waste disposal. Specifically, CSA and CSF help lower greenhouse gas emissions by mitigating the incineration of corn straw while minimizing reliance on virgin construction materials. Additionally, the biodegradable nature of these composites ensures an eco-friendly end-of-life cycle, leaving minimal environmental impact. A preliminary life cycle analysis suggests that replacing 10% of cement with CSA could reduce CO_2 emissions by 8%, while CSF eliminates the need for synthetic fibers, reducing petroleum-based material dependence.

3.5.2. Bio-inspired design

The CSA-CSF composite design draws inspiration from the hierarchical optimization observed in biological systems, such as bone and the ECM. CSA enhances matrix densification at the microstructural level, while CSF provides crack-bridging and energy dissipation at the meso- and macrostructural levels, mimicking the interplay between collagen fibers and mineral components in natural tissues. This bio-inspired approach enables the composite to adapt to dynamic environments, resist crack propagation, and degrade predictably. The synergy between CSA and CSF results in optimized compressive strength, flexural toughness, and fatigue resistance, demonstrating the potential of biomimetic principles in material design.

3.5.3. Applications in biomechanics and construction

The mechanical properties and biodegradability of CSA-CSF composites highlight their applicability in both civil engineering and biomedical fields. For dynamic loading environments, such as earthquake-resistant structures, the fatigue resistance and crack-bridging capacity of these composites provide superior residual strength retention. In biomedical applications, the biocompatibility and bioactivity of CSA-CSF composites make them ideal candidates for tissue engineering scaffolds. These composites mimic natural bone grafts by providing mechanical support, releasing bioactive ions, and gradually degrading to promote tissue regeneration. Furthermore, the unique combination of structural integrity, environmental safety, and biodegradability enables their use in hybrid applications, such as eco-friendly hospitals and orthopedic implant coatings.

3.5.4. Future directions

Future research should focus on the long-term durability and degradation behavior of CSA-CSF composites under various environmental and physiological conditions. Further exploration of bio-inspired strategies, such as the incorporation of biopolymers or nanomaterials, could enhance the mechanical and biological properties of the composite. Additionally, developing scalable manufacturing processes will be crucial for commercializing CSA-CSF composites in construction and biomedical markets. These advancements will pave the way for innovative materials that bridge sustainability, biomechanics, and engineering.

4. Discussion

This study has demonstrated the significant potential of CSA-CSF composites in improving mechanical properties, enhancing biodegradability, and aligning with bio-inspired design principles. The following discussion contextualizes these findings by linking them to existing literature and highlighting their broader implications in materials science, biomechanics, and sustainability.

4.1. Mechanical performance

The incorporation of Corn Straw Ash (CSA) and Corn Straw Fiber (CSF) significantly enhances the mechanical performance of the composite material. Specifically, the compressive strength of the CSA-CSF composite increased by up to 39.9%, attributed to the pozzolanic reaction of CSA. This reaction generates additional C-S-H gel, which contributes to the densification of the cement matrix, leading to improved strength and durability. On the other hand, the flexural strength improved by up to 67%, demonstrating the efficacy of CSF in bridging cracks and redistributing stresses within the composite material. The fiber's ability to delay crack propagation significantly enhances the composite's resistance to bending and improves its overall toughness.

The compressive strength improvements observed in this study align with findings from previous research on pozzolanic materials, such as fly ash and silica fume, both of which are known for their ability to enhance matrix integrity through secondary hydration reactions. CSA's performance is comparable to these materials, particularly in the way it promotes matrix densification and enhances the material's overall structural integrity. Previous studies have demonstrated that pozzolanic materials like fly ash can help reduce porosity and improve strength, a mechanism that CSA appears to mirror, offering similar benefits in terms of enhancing the material's durability.

Similarly, the crack-bridging mechanism of CSF is akin to the role of natural collagen fibers in biological systems like bone. Just as collagen fibers resist crack propagation and maintain structural stability under loading, CSF fibers similarly prevent crack growth in the composite, contributing to improved toughness and resistance to flexural stresses. This bio-inspired feature highlights the innovative nature of CSA-CSF composites, offering the potential for materials that mimic the durability and strength of biological tissues, a feature that has not been fully explored in previous fiber-reinforced cementitious materials.

While the optimized CSA-CSF composite exhibited superior performance, there are some limitations that warrant further investigation. One of the main challenges is evaluating the long-term durability of the composite under varying environmental conditions, such as freeze-thaw cycles, elevated temperatures, and high humidity. These factors could affect the composite's performance in real-world applications, particularly for construction and biomedical uses, where materials need to withstand extreme environmental stresses. Additionally, fiber agglomeration at higher CSF contents remains a challenge, as increased fiber concentration can lead to uneven distribution within the matrix, which may negatively impact the material's homogeneity and mechanical properties. This issue can be addressed by optimizing fiber treatment and dispersion techniques, ensuring uniform fiber distribution and maximizing the reinforcing benefits of CSF. Future studies should focus on refining these methods to improve the material's consistency and performance.

4.2. Biodegradation behavior

The biodegradation tests revealed distinct differences in mass loss and porosity evolution between SBF and acidic environments. In SBF, the composite showed slower degradation, with porosity increasing from 6.8% to 9.2% after 28 days. In contrast, acidic conditions accelerated degradation, with porosity reaching 12.5%. These results highlight the tunability of the material's degradation rate, which can be tailored for specific applications, depending on the desired degradation behavior.

The gradual increase in porosity and controlled degradation in SBF mimics the resorption behavior of biodegradable scaffolds used in tissue engineering. The release of bioactive ions such as calcium and silicon during degradation further enhances the composite's potential for promoting bone regeneration. This bio-inspired degradation profile makes the CSA-CSF composite an ideal candidate for biomedical applications where controlled resorption is crucial.

Similar to scaffolds made from polylactic acid or hydroxyapatite, CSA-CSF composites exhibit a balance between mechanical support and gradual degradation. However, unlike synthetic polymers, CSA-CSF composites are derived from renewable resources, offering superior environmental sustainability. This distinction further supports the composite's potential for eco-friendly applications, both in biomedical and temporary construction materials.

4.3. Microstructural insights

SEM analysis provided valuable insights into the microstructural changes associated with CSA and CSF. The reduction in porosity and the densification of the matrix due to CSA-derived C-S-H gel were consistent with the compressive strength enhancements. These microstructural changes facilitated the formation of a more robust material, contributing to the improved mechanical performance. Similarly, the crack-bridging behavior of CSF, observed as fibers spanning microcracks, was directly linked to the improved flexural toughness, highlighting the reinforcing role of the fibers in preventing crack propagation.

The porosity control achieved through CSA addition aligns with bio-inspired design principles, where structural optimization occurs at multiple scales. For instance, bone achieves its mechanical properties through the interplay of a dense mineral phase and a collagen matrix, a behavior mirrored in the CSA-CSF composite. This hierarchical structure, composed of both the dense C-S-H gel and the reinforcing CSF fibers, mimics the natural composite structures found in biological tissues, enhancing the material's durability and performance.

To further enhance the microstructural properties of CSA-CSF composites, advanced techniques such as nanoindentation or X-ray tomography could be employed to study the material's behavior at smaller scales. These methods would provide deeper insights into the local mechanical properties and microstructural characteristics, enabling the development of more efficient composites. Additionally, incorporating nanomaterials like graphene oxide or carbon nanotubes could further refine the composite's mechanical and biodegradation performance, offering new avenues for optimizing the material's overall functionality and application potential.

4.4. Broader implications

The findings of this study extend beyond the immediate mechanical and biodegradation performance of CSA-CSF composites, offering broader implications for sustainability, bio-inspired materials design, and practical applications. The use of agricultural by-products such as CSA and CSF aligns with the global push towards a circular economy. By converting waste materials into valuable construction products, this approach not only helps reduce environmental pollution but also decreases dependence on non-renewable virgin resources, making it an eco-friendly solution for sustainable development.

The composite's biodegradability ensures minimal long-term environmental impact, making it highly suitable for temporary structures or scaffolds that naturally decompose after their functional life. This characteristic is particularly advantageous for construction applications where materials are needed to fulfill their purpose and then degrade without leaving harmful residues. This aligns with global sustainability goals, emphasizing materials that contribute to a circular lifecycle, minimizing waste and pollution.

The hierarchical optimization achieved in the CSA-CSF composite mirrors biological systems, such as bone or the extracellular matrix (ECM), demonstrating the potential of biomimetic strategies in material design. CSA's reinforcement at the matrix level and CSF's crack-bridging behavior illustrate the advantage of combining multiple reinforcement mechanisms in one material. This bio-inspired approach not only addresses engineering challenges by combining strength, toughness, and adaptability, but also offers solutions for biomedical applications. In construction, the composite's fatigue resistance and biodegradability make it ideal for earthquake-resistant structures, temporary shelters, or eco-friendly infrastructure. In biomedicine, its biocompatibility and bioactivity position it as a promising candidate for load-bearing scaffolds in tissue engineering, particularly for bone regeneration.

4.5. Challenges and future directions

Despite the promising results, several challenges remain in the development of CSA-CSF composites. Long-term performance under extreme conditions, such as high humidity, freeze-thaw cycles, or marine environments, requires further investigation. Understanding how biodegradation impacts the mechanical performance of these composites over extended periods is critical for applications in both construction and biomedicine. Evaluating how these factors influence durability will provide valuable insights into the composite's reliability for long-term use.

One of the current challenges lies in the agglomeration of fibers at higher CSF contents, which limits the composite's scalability. Improved dispersion techniques, such as surface functionalization or the use of dispersing agents, could potentially address this issue, ensuring better fiber distribution within the matrix. Additionally, exploring the addition of other natural fibers or nanoparticles could further enhance both the mechanical and biological properties of the composite, making it more versatile for various applications.

While the use of CSA and CSF is environmentally sustainable, scaling up these materials for industrial applications remains a significant challenge. Developing cost-effective processing techniques and establishing efficient supply chains for agricultural by-products is essential for the commercial success of these composites. Additionally, interdisciplinary applications such as using CSA-CSF composites as coatings for orthopedic implants or eco-friendly materials for medical device manufacturing could open new markets, bridging the gap between materials science, biomechanics, and sustainable engineering.

5. Conclusion

This study demonstrated the potential of CSA-CSF composites in enhancing mechanical performance, biodegradability, and sustainability. The following key findings summarize the work:

5.1. Mechanical performance

The incorporation of 10% CSA and 0.4% CSF improved compressive strength by 39.9% and flexural strength by 67%. CSA contributed to matrix densification through pozzolanic reactions, while CSF enhanced toughness by bridging cracks and redistributing stresses.

5.2. Biodegradation behavior

The composite exhibited controlled degradation in simulated body fluid (SBF), making it suitable for biomedical scaffolds. Faster degradation in acidic environments highlighted its potential for eco-friendly, temporary construction materials.

5.3. Microstructural insights

SEM analysis confirmed CSA’s ability to refine matrix porosity and CSF’s crack-bridging function, contributing to the composite’s mechanical and degradation performance.

5.4. Broader implications

The use of agricultural by-products aligns with sustainability goals, reducing waste and promoting circular economy practices. The biomimetic design of CSA-CSF composites makes them applicable to dynamic environments, such as earthquake-resistant structures and tissue engineering scaffolds.

5.5. Future directions

Future work should focus on: Long-term performance under extreme environmental conditions.Optimization of CSF dispersion and integration with nanomaterials.Expanding applications to hybrid biomedical and eco-friendly infrastructure solutions.By combining environmental sustainability with bio-inspired design, CSA-CSF composites provide a promising pathway for advanced materials in both engineering and biomedical fields.

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