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Tratamentos biopoliméricos sustentáveis em biocompósitos cimentícios: revisão integrada e perspectivas tecnológicas

Sustainable biopolymer treatments in cementitious biocomposites: integrated review and technological perspectives

Tratamientos sostenibles con biopolímeros en biocompuestos cementosos: revisión integrada y perspectivas tecnológicas

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Resumo: Motivado pela sustentabilidade, este estudo faz parte da tese de doutorado de Oliveira (2025), que desenvolveu um biotratamento para compósitos cimentícios reforçados com fibra de malva amazônica. Portanto, o presente estudo teve por objetivo combinar métodos de revisão exploratória e sistemática a fim de justificar a lacuna de conhecimento e temas emergentes com relação aos tratamentos biopoliméricos em biocompósitos cimentícios. Os resultados mostram que fibras tratadas de malva melhoram as propriedades mecânicas e durabilidade dos biocompósitos cimentícios. Contudo, a degradação das fibras na matriz e os impactos ambientais dos tratamentos usados não são sustentáveis, apresentando poucos estudos sobre tratamentos superficiais com uso de biopolímeros. O estudo conclui que a integração das revisões exploratórias e sistemáticas forneceu uma abordagem híbrida, essencial para a definição da pesquisa. Os resultados indicam que biopolímeros, como o látex de borracha natural e a nanocelulose bacteriana, representam oportunidades ecoeficientes para tratamentos superficiais com potencial de aplicação na superfície de fibras naturais utilizadas como reforço em matrizes cimentícias.

Palavras-chave: Biocompósitos cimentícios; Revisão exploratória; Revisão sistemática; Fibras lignocelulósicas; Tratamentos.

Abstract: Motivated by sustainability, this study is part of Oliveira's doctoral thesis (2025), which developed a biotreatment for cementitious composites reinforced with Amazonian mallow fiber. Therefore, the present study aimed at combining exploratory and systematic review methods to justify the knowledge gap and emerging themes concerning biopolymeric treatments in cementitious biocomposites. The results show that treated mallow fibers improve the mechanical properties and durability of cementitious biocomposites. However, the degradation of fibers in the matrix and the environmental impacts of the treatments used are not sustainable, with few studies on surface treatments using biopolymers. The study concludes that the integration of exploratory and systematic reviews provided a hybrid approach, essential for defining the research. The results indicate that biopolymers, such as natural rubber latex and bacterial nanocellulose, represent eco-efficient opportunities for surface treatments with potential application on the surface of natural fibers used as reinforcement in cementitious matrices.

Keywords: Cementitious biocomposites; Exploratory review; Systematic review; Lignocellulosic fibers; Treatments.

Author Contributions according to the CrediT Taxonomy

IRCO: conceptualization, data curation, formal analysis, methodology, project administration, validation, visualization, writing – original draft, review & editing.

LTC: writing – original draft, review & editing.

BMT: methodology, project administration, resources, supervision, validation, writing – original draft.

Resumen: Motivado por la sostenibilidad, este estudio forma parte de la tesis doctoral de Oliveira (2025), quien desarrolló un biotratamiento para compuestos cementosos reforzados con fibra de malva amazónica. Por lo tanto, el presente estudio tuvo como objetivo combinar métodos de revisión exploratoria y sistemática con el fin de justificar la brecha de conocimiento y los temas emergentes en relación con los tratamientos biopoliméricos en biocompuestos cementosos. Los resultados muestran que las fibras de malva tratadas mejoran las propiedades mecánicas y la durabilidad de los biocompuestos cementosos. Sin embargo, la degradación de las fibras en la matriz y los impactos ambientales de los tratamientos utilizados no son sostenibles, y hay pocos estudios sobre tratamientos superficiales con biopolímeros. El estudio concluye que la integración de las revisiones exploratorias y sistemáticas proporcionó un enfoque híbrido, esencial para la definición de la investigación. Los resultados indican que los biopolímeros, como el látex de caucho natural y la nanocelulosa bacteriana, representan oportunidades ecoeficientes para tratamientos superficiales con potencial de aplicación en la superficie de fibras naturales utilizadas como refuerzo en matrices cementosas.

Palabras clave: Biocompuestos cementosos; Revisión exploratoria; Revisión sistemática; Fibras lignocelulósicas; Tratamientos.

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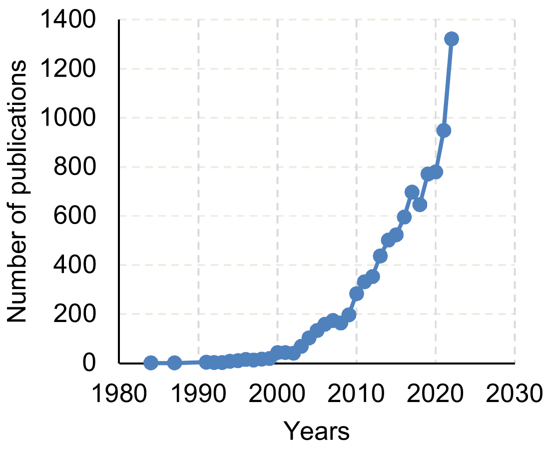
1 INTRODUCTION

Researchers worldwide have sought to implement green strategies in civil engineering, linking interests across different fields of study with the goal of promoting environmental sustainability (ANKUR; SINGH, 2021; BALEA et al., 2021; DE BRITO; KURDA, 2021; FERRARA et al., 2018).

In this context, Olawumi and Chan (2018) mapped 2,094 bibliographic records from the Web of Science database, identifying global research patterns on sustainability. Their study revealed that countries such as the United States, China, the United Kingdom, and Canada primarily focus on subject categories such as environmental sciences, green and sustainable technology, civil engineering, and construction technology. Emerging trends include sustainable urban development, sustainability indicators, water management, environmental assessment, and public policies, among others.

Sustainable buildings are characterized by materials offering recyclability, low cost, environmentally friendly features, non-toxicity, biodegradability, and satisfactory mechanical performance (VANTADORI; CARPINTERI; ZANICHELLI, 2019). Furthermore, they incorporate alternative, more eco-friendly materials, such as biocomposites (AHMAD et al., 2022). Over the years, publications on this topic have increased significantly (Figure 01), influencing several development sectors, including construction.

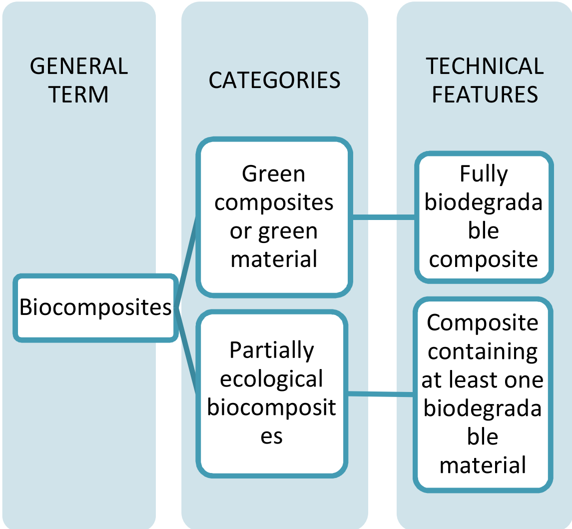
Figure 1 – Publications on biocomposites according to the Engineering Village database in recent years. Source: prepared by the authors



Source: prepared by the authors.

The term *biocomposite* encompasses a variety of biomaterials, thereby offering flexibility to adapt different materials according to specific needs (AHMAD et al., 2022). Originally, the term was applied to compositions containing at least one natural material, not necessarily because of biodegradability (BISMARCK et al., 2005). Currently, however, the definition requires at least one biodegradable component to qualify as a biocomposite, unlike "green composites" or "green materials," in which both the matrix and the reinforcement are biodegradable (AHMAD et al., 2022; MANU et al., 2022; ZINI; SCANDOLA, 2011). Based on these definitions, biocomposites can be subdivided into two categories, as shown in Figure 02.

Figure 2 – General scheme of biocomposite subdivision



Source: prepared by the authors.

Among partially ecological biocomposites are fiber-reinforced cementitious composites (FRCs), in which the cementitious matrix acquires more ductile behavior. With advancing research, inorganic and synthetic fibers are gradually being replaced by bio-based reinforcements, transforming cementitious composites into cementitious biocomposites (BALEA et al., 2021; KUMAR et al., 2012). The most common substitution involves the use of cellulose pulp from reforested wood (BALLESTEROS et al., 2017).

Nevertheless, the use of chemical processes to obtain cellulose pulp presents environmental disadvantages, as pulping generates polluting effluents, including sulfur- and chlorine-based compounds (SERRA-PARAREDA et al., 2021). In addition, untreated bio-reinforcements degrade within the cementitious matrix due to three main aging mechanisms: dimensional instability, alkaline hydrolysis, and mineralization of the cell wall (DOS SANTOS et al., 2019).

In order to improve the environmental aspects of FRCs, protect bio-reinforcements against degradation mechanisms, and enhance the mechanical properties and durability of both reinforcement and biocomposite, other biomaterials can be employed. These show potential applications in diverse areas of civil engineering, ranging from the production of precast elements (LIMA et al., 2018) to the development of novel mortar mixtures in three-dimensional printing technologies (BOHUCHVAL et al., 2021).

Examples include lignocellulosic fibers from the Amazonian mallow (*Urena Lobata Linn.*) and natural biopolymers used as surface treatments, such as natural rubber latex (NRL) and bacterial nanocellulose (BNC).

However, as in other scientific fields, a significant portion of the research on these biomaterials in civil engineering is published in national dissertations and theses. This underscores the need for an alternative bibliographic review approach that integrates exploratory methods with both national and international research sources, in order to identify such studies more effectively (NORONHA, 1998).

Exploratory reviews enable a broad, preliminary understanding of the field, identifying emerging trends and gaps in the literature. In contrast, systematic reviews provide a more rigorous and detailed analysis, consolidating evidence from previous studies and establishing a solid foundation for future research. By combining these approaches, a comprehensive perspective can be achieved to advance scientific and technological development.

Therefore, this study aimed to integrate exploratory and systematic bibliographic review methods to analyze the use of lignocellulosic fibers from Amazonian mallow (F), surface treatments with natural rubber latex (L), and bacterial nanocellulose (BNC) applied to FRCs, as well as to identify emerging trends and gaps in the existing literature. This methodological process is herein defined as a Simplified Systematic Review (SSR).

It is important to emphasize that the exploratory review was used solely to provide the initial foundation of the study. As the research developed, additional national and international literature was analyzed and incorporated. The next section presents the detailed methodological procedures adopted in this review.

2 METHODOLOGICAL PROCEDURES

To achieve the proposed objective, the bibliographic review was divided into two search strategies: exploratory and systematic methods.

To gain familiarity and visualize broader scenarios of studies on lignocellulosic fibers from Amazonian mallow in cementitious materials, an exploratory review of national literature (dissertations and theses) was conducted. This process yielded relevant terms (keywords) to be subsequently used in the systematic review, which focused on international articles.

Research protocols for document analysis and synthesis were applied, with methodologies adapted from Medeiros et al. (2015), Ferenhof and Fernandes (2016), Page et al. (2021), and Carbonari and Librelotto (2022). In general, for both methods, the protocol consisted of the following steps:

(a) Construction of the main review question to be investigated;

(b) Definition of search strategies and document selection criteria;

(c) Verification and analysis of documents using inclusion and exclusion criteria;

(d) Systematization, mapping, and specification of information.

In the first stage of the exploratory search protocol, the aim was to answer the following question: *What treatments are being used on lignocellulosic mallow fibers in cementitious composites?* Once this initial question was addressed, the subsequent stage focused on the systematic review, guided by the following question: *What biopolymeric surface treatments are being applied to lignocellulosic fibers in cementitious composites to improve the physical and mechanical properties, as well as the durability of cementitious biocomposites?* The purpose was to identify gaps and novel approaches in these treatments for potential future applications not only to mallow fibers but also to other plant-based fibers.

After defining the research question, exploratory search strategies were established using national literature databases: the *Biblioteca Digital de Teses e Dissertações* (BDTD), the *Catálogo de Teses e Dissertações* (Capes), and additional dissertations and theses previously consulted. These sources were chosen because they are nationally recognized and allowed the selection of studies involving mallow produced in Brazil. The exploratory search had no time restrictions, adopting the terms "fibra" (fiber) and "malva" (mallow). This stage identified 10 studies out of an initial 65.

Table 1 – Parameters adopted and defined in the research

Combinations of terms					Bibliographical Bases			Total
General term	**+**	**Matrix**	**+**	**Addition type**	**Eng. Village**	**Scopus**	**WoS**	**161**
*durab**	AND	*cement**	AND	*natural latex*	26	2	2	30
*durab**	AND	*cement**	AND	OR *lignocellulosic*	22	26	36	84
*durab**	AND	*cement**	AND	OR *nanocellulose*	18	15	14	47

Source: prepared by the authors.

From these studies, a knowledge matrix was developed to analyze how Amazonian mallow fiber bio-reinforcement was incorporated into the cementitious matrix, including the treatments applied. Treatments were classified as: simple (washing with tap water), surface (application of a material onto the fiber surface), thermal (temperature cycles and time intervals using water as the main fluid), biological (use of fungi or bacteria), and chemical (use of chemical solutions to modify the fiber surface).

For the international literature (papers), searches were also conducted without year restrictions in the databases Compendex (Engineering Village), Web of Science (WoS), and Scopus—selected for their international and interdisciplinary scope related to engineering. The search string applied was: "durab" AND "cement" AND ("natural latex" OR "lignocellulosic" OR "nanocellulose")**, as shown in Table 01. This resulted in 161 studies. The first column of the query focused on the general research field (durability); the second narrowed the scope to studies related to the type of matrix (cementitious); and the third targeted the specific additions of interest (natural rubber latex, lignocellulosic fiber, and nanocellulose). All searches were conducted up to February 15, 2023.

For the document selection criteria, all identified studies were first added to folders in the reference manager software Mendeley. Titles, abstracts, and keywords were reviewed to assess relevance to the research area. Documents unrelated to the topic, duplicates, works lacking DOI registration, book chapters, studies without keywords, or inaccessible documents were excluded. The remaining studies were subjected to an eligibility criterion: the introduction and conclusion were examined to determine whether they contained essential information to address the protocol's main question. At each filtering stage, documents were organized into subfolders in Mendeley to facilitate classification and quantification. This process ultimately yielded 12 studies closely aligned with the research objectives.

In the final stage, the selected documents were systematized, and their main data were extracted and analyzed to populate the knowledge matrix in Excel. This included identification data (authors, year, title, institution, and document type) and complementary data (structure, objective, application, research problem, proposed solution, type of matrix, reinforcement and treatment, composite configuration, tests applied to matrix, reinforcement and composite, main results, and research gaps).

In addition, for the international literature, the *Bibliometrix* package in R was used to identify word clouds of the most frequent terms employed by the authors, annual publication trends, and thematic networks of the selected documents. These were based on statistical and mathematical dynamic indicators of scientific information generated through the software's data extraction process. The results are presented and discussed in the following section.

3 RESULTS AND DISCUSSIONS

In the review of national literature, after systematizing and inserting data from the documents into the knowledge matrix, the national research landscape on mallow fiber was mapped. It was observed that the State of Amazonas stood out with the highest number of documents produced on mallow fibers, totaling 18. This is related to the fiber's importance in the region, with the peak in publications occurring in 2015.

Over the past 20 years, most Brazilian scientific production on mallow fiber has been slightly concentrated in the fields of Social Sciences, Economics, Agrarian Sciences, Politics, and Environmental Management, with nearly 50% focusing on civil engineering and materials. This indicates that studies have aimed to expand technological alternatives and processes in the application of Amazonian mallow fiber.

Among the studies applied to civil engineering and materials, the work of Cunha (2020) stood out because the fiber treatment process adopted was more sustainable. By contrast, the other selected studies applied synthetic treatment processes, cementitious matrix modification techniques, and supplementary ecological binders such as metakaolin to replace ordinary Portland cement, along with analyses of physical, mechanical, and durability properties through accelerated aging tests.

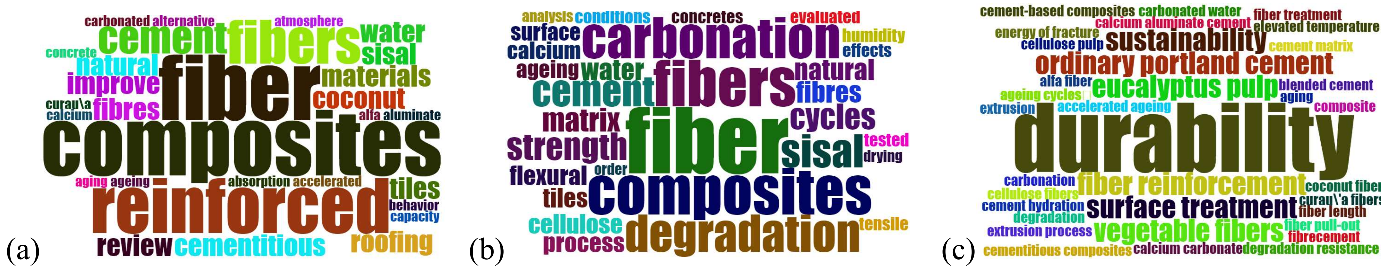
It is well established that the modification of the cementitious matrix is one of the strategies to reduce fiber vulnerability in the alkaline environment, producing a matrix with lower—sometimes even negligible—calcium hydroxide content, without compromising the composite's final strength.

Oikawa (2019), Oliveira (2013), and Savastano Júnior (2000) identified that when incorporated into the cementitious matrix, mallow fibers enhanced strength and ductility, improving impact resistance and thereby representing a viable bio-reinforcement alternative. However, in the absence of treatment, these mechanical properties decrease over time.

Furthermore, treatments can be applied at different stages of cementitious biocomposite production, either in isolation or in combination, using physical and/or chemical principles. These studies aimed to directly improve mechanical properties and indirectly enhance the durability of cementitious biocomposites.

Before analyzing the 12 selected international studies, a bibliometric analysis of the 161 documents was conducted to identify the main terms occurring in the titles, abstracts, and keywords of international literature, as shown in Figures 03a, 03b, and 03c.

Figure 3 – Word clouds of terms used in: a) titles, b) abstracts, and c) Keywords



Source: prepared by the authors.

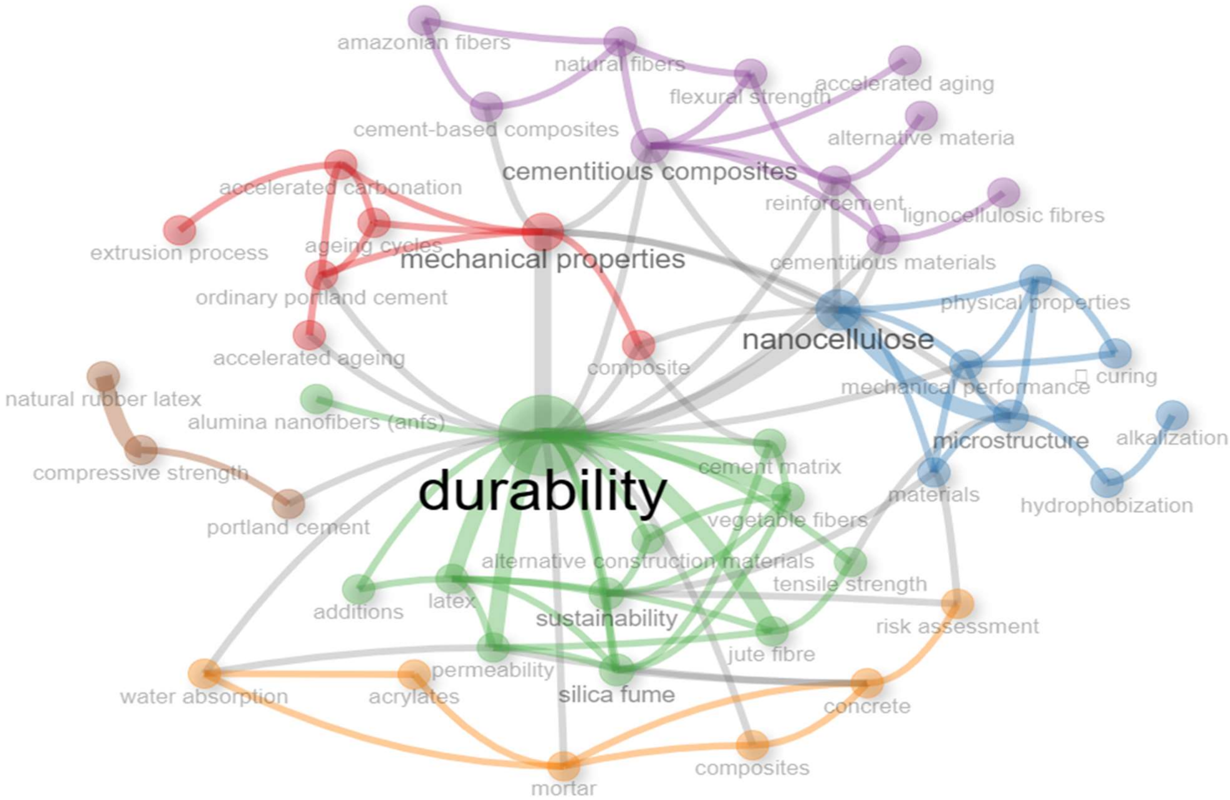
As observed, the main terms associated with these studies were identified. In titles, the words *fiber* and *reinforced* appeared most frequently, closely associated with the core term *composites*. Other terms such as *cement, accelerated aging, behavior, kaolin, sisal*, and *water* appeared less often.

In keywords, the dominant term used by researchers was *durability*, followed by *fiber surface treatment*, *pulp*, *cement*, and *sustainability*, cementitious composites, along with testing procedures such as flexural strength and accelerated aging cycles involving wetting and drying.

Additionally, a thematic network of the most frequent terms related to the broader research field was visualized, as shown in Figure 04.

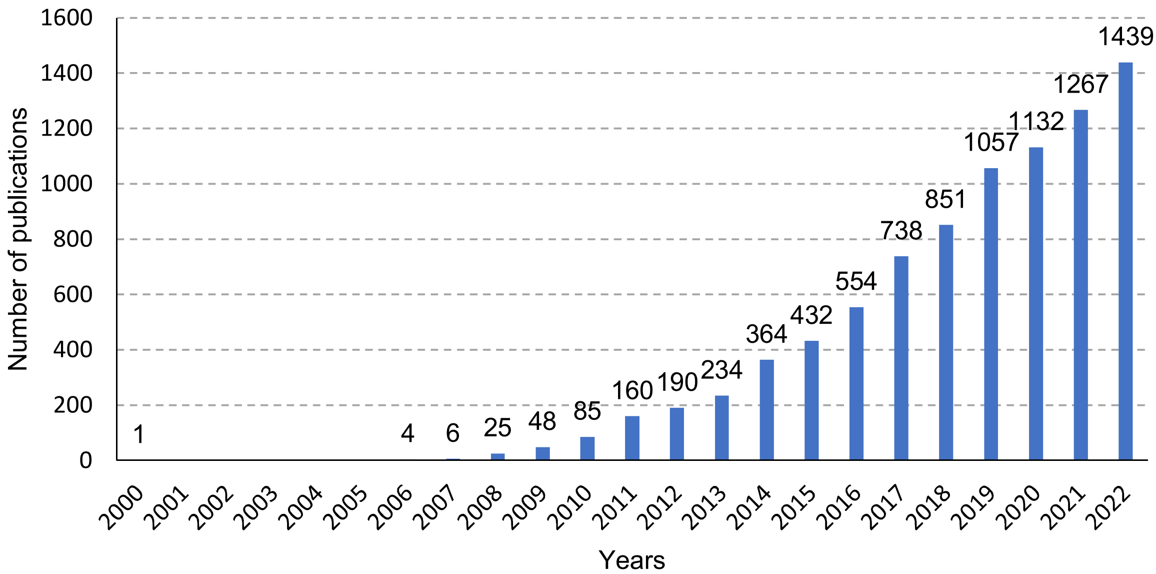
Six interconnected research areas were identified within the field of cementitious biocomposite durability. In proximity to the term *durability*, the most frequent associated terms were *nanocellulose*, *mechanical properties*, and *sustainability*. Notably, in the Engineering Village database, searches for the term *nanocellulose* yielded 1,439 publications between 2000 and 2022 (Figure 05).

Figure 4 – Thematic network mapping of terms related to the general research field



Source: prepared by the authors.

Figure 5 – Number of publications on nanocellulose in the Engineering Village database (2000 to 2022)



Source: prepared by the authors.

Interest in nanocellulose has grown because it is a biodegradable and renewable material with high strength and surface area, making it suitable for diverse research areas developing new materials. Nasir et al.

(2022), after conducting a literature review on nanostructured celluloses in cementitious matrices between 2014 and 2021, identified that 53% of publications focused on cellulose nanofibrils (CNF), 35% on cellulose nanocrystals (CNC), and only 12% on bacterial nanocellulose (BNC). All categories show growth trends and positive perspectives for future implementation in engineering applications.

In thematic mapping, the term *natural rubber latex* emerged due to its natural production, efficiency, lower energy consumption, and reduced environmental impact. This biopolymer is currently used in more than 50,000 commercialized products across different industrial sectors (ABRAHAM et al., 2012; CHERIAN; RYU; CORNISH, 2019; PEREIRA; LEAL; RAMOS, 2018; WICHAITA et al., 2021), with *Hevea brasiliensis* being the main commercially important source (SILVA et al., 2021).

Other terms in the thematic network included *Amazonian fibers*, *natural fibers*, *lignocellulosic fibers*, *vegetable fibers*, *jute fiber*, and *nanofibers*. These are directly related to the Amazonian context, with emphasis on biodiversity. In states such as Amazonas and Pará, lignocellulosic fibers from jute (*Corchorus capsularis L.*) and mallow (*Urena lobata L.*) are among the main crops with socioeconomic relevance, with production exceeding 2,876 tons in 2023 alone (IBGE, 2023). Table 02 presents some lignocellulosic fibers produced in the Amazon region and their properties.

Table 2 – Selected lignocellulosic fibers produced in the Amazon region and their properties

Name of Fibers (Brazil)	**Curauá**	**Juta**	**Malva**	**Açaí**	**Capim-navalha**	**Piaçava**
Scientific name (Botanical)	*Ananas erectifolius*	*Corchorus capsularis L.*	*Urena Lobata L..*	*Euterpe oleracea*	*Echinochloa polystachya*	*Leopoldinia piassaba*
Chemical properties (%)						
Cellulose	58,8	66,3	69,4	46	86,9	51,4
Hemicellulose	8,4	24,8	21,3	18	8,4	1,7
Lignin	8,4	10,5	13,6	32	0,8	45,7
Crystallinity	76	71	-	-	60	40
Physical Properties						
ρ. (g/cm³)	0,97	0,85	0,91	1,37*	1,31*	1,00*
CAA (%)	350	325	156	-	400	150
A_f (mm²)	0,0012	0,005	0,004	-	0,80	0,50
Mechanical Properties						
σ_r (MPa)	688 – 991	234 – 900	390	18	70	34
E (GPa)	27 – 42	10 – 30	31	16	1	-
ε_L (mm/mm)	2 – 3	1 – 2	1	-	-	-
References	Ferreira *et al*., (2017); Tomczak, Satyanarayana e Sydenstricker (2007)	Ferreira *et al*. (2017), Oliveira (2013) e Soltan *et al*., (2017)	Oliveira (2013) e Savastano e Agopyan (1999)	De Azevedo *et al.* (2021)	Da Fonseca, Rocha e Cheriaf (2021)	Ferreira *et al*., (2017); Tomczak, Satyanarayana e Sydenstricker (2007)

Note: ρ – Apparent density; WAC – Water absorption capacity; A_f – Total cross-sectional area of the fibre; σ_r – Breaking stress; E –Modulus of elasticity; ε_L – Longitudinal deformation. Source: prepared by the authors

Source: prepared by the authors.

According to Batista dos Santos et al. (2022), simulations of using lignocellulosic mallow fibers in cementitious composites near cultivation areas showed a 95% reduction in environmental impact. As corroborated by other studies, this implies a lower ecological footprint in the production chain compared to lignocellulosic fibers produced in Asia (OLIVEIRA et al., 2022), while also contributing to mechanical property improvements (OLIVEIRA et al., 2022).

Correia et al. (2018) highlighted that lignocellulosic fibers have been used as reinforcement at macro-, micro-, and nanoscale levels in cementitious materials. To aid the analysis, studies were categorized by reinforcement length: nanoscale (<1 mm), microscale (1–50 mm), and macroscale (>50 mm).

Table 03 shows the selected studies with cellulose reinforcement at the nanometric scale (nanocellulose) in various contents, origins, treatments, refinements, types of cementitious matrices adopted, and the main results.

Table 3 – Comparison of treatments applied to mallow fibers

References	Reinforcement percentages	Fiber type, and treatment	Matrix and process	Main results
Diamanti *et al.* (2022)	0,3%, 0,6%, 1,2% e 2,4%	Cotton, Mechanic and Chemist	OPC, mortar	44% increase in compressive strength for contents above 0.6% and 30% decrease in water absorption at contents of 2.4%
Akhlaghi, Bagherpour e Kalhori (2020)	0,1%, 0,3% e 0,5%	Bacteria / Mechanical (gel) and thermal (powder)	OPC, mortar	100% increase in flexural strength for 0.3% content, 20% increase in compression for 0.1% content and 25% decrease in water absorption for 0.1% content
Gonçalves *et al. (*2019)	0,05 a 5,0%	Commercial cellulose nanofibers (CNF)	OPC, mortar	CNF at a concentration of 0.3 to 0.5% reduced the penetration of sulfate ions, decreased the production of ettringite and increased resistance
Hisseine *et al. (*2019)	Distribuição randomizada em 0,0% a 0,30%	Commercial kraft wood pulp, chemical	OPC, mortar	As the cellulose addition rate increased, more polycarboxylate-based additives were used, reaching a slump flow of 240 mm. Strength improvements of up to 26% in compression, 18% in elastic modulus, 21% in flexion, and 74% in toughness were obtained, distinct in the different contents

Source: prepared by the authors.

Akhlaghi, Bagherpour, and Kalhori (2020) and Diamanti et al. (2022) both identified a significant reduction in water absorption of composites after nanocellulose addition, regardless of dosage. Similar behavior was observed in mechanical properties such as flexural and compressive strength. Diamanti et al. (2022) argued that these improvements indicate reduced porosity and an increased proportion of capillary pores, both key indicators of greater material durability.

Hisseine et al. (2019) studied commercial cellulose pulp incorporated at dosages from 0.0% to 0.30% in cement paste and found that maximum flexural strength was achieved at relatively low levels (0.05–0.10%), while maximum energy absorption occurred at 0.30%. The authors attributed these effects to the hydrophilic and hygroscopic properties of cellulose pulp, which retains and gradually releases water during curing, thereby promoting further hydration of anhydrous cement grains and achieving a 15% increase in hydration at 28 days.

Table 04 below presents the selected studies on cellulose reinforcement at the micro and macro scales.

Table 4 – Studies on cementitious biocomposites reinforced with cellulose at micro- and macroscale levels

References	Reinforcement percentages	Fiber type, and treatment	Matrix and process	Main results
Machado, Ferreira, Motta (2020)	Randomized distribution into 14.94% cellulose pulp and 1.40% natural latex	Eucalyptus, mechanical	Replaced 13.55% of OPC with silica fume, paste	Cellulose reduced the modulus of elasticity. Latex reduced modulus of rupture, modulus of elasticity and absorption after aging at 180 days. The combination of silica fume and latex reduced portlandite
Texeira *et al.* (2020)	Randomized distribution at 5%	Eucalyptus, banana stem, coconut and coffee, mechanical	Replaced 30% OPC with limestone powder, paste	All composites absorbed less than 37% of water. After 400 aging cycles, all composites met category 2 of the strength standard (4 MPa)
Texeira *et al.* (2019)	Randomized distribution in 1% and 2% of lignocellulosic macro fibers and unbleached cellulose pulp	Curauá manual process and eucalyptus pulp with chemical process	Replaced approximately 30% of OPC with limestone powder, paste	Composites with 10 mm fibers showed better mechanical results. Composites with curauá fibers after 200 cycles of accelerated aging were better than non-aged
Reixach *et al. (*2019)	Randomized distribution at 0% to 2.0%	Pin sawdust, mechanical and chemical process	OPC, paste	The flexural strength after 28 days of curing of the samples improved when the amount of fibers increased, resulting in 16 MPa
Silva *et al.(* 2018)	25 mm length, randomly distributed at 10% content	Coconut, process with manual cutting	OPC, mortar	The combined effect of reinforcing coconut fibers treated with silica fume and natural latex increased tensile strength in flexural strength (5.5 MPa) by 19.2% compared to the control composite (4.5 MPa)
Mohammadkazemi, Aguiar e Cordeiro (2017)	1.13 mm lignocellulosic fibre pulp, randomly distributed at 6% content	Bagasse, mechanical process treated with 50% bacterial nanocellulose (BNC) gel	OPC, mortar	The incorporation of BNC coating the fibers decreased fiber mineralization by 48% and increased surface area. Resulting in lower porosity and higher surface roughness
Silva et al. (2017)	25 mm length, unidirectional distributed	Coconut, mechanical process	OPC, mortar	The combined effect of reinforcing coconut fibers treated with silica fume and natural latex increased tensile strength in flexural strength (8.5 MPa) by 42% compared to the control composite (5 MPa)
Teixeira *et al.* (2014)	Lignocellulosic and synthetic fiber pulp randomly distributed in the content of 2% and 4%	Newsprint, sisal fibre and polypropylene fibre, mechanical and chemical processes	Replaced approximately 20% of OPC with limestone powder, paste	The hybrid reinforcement of newsprint and polypropylene increased tensile strength in bending by 215% than the reinforcement of newsprint and sisal fiber. With the accelerated aging process, this gain was more significant

Source: prepared by the authors.

Among these, the studies by Machado, Ferreira, and Motta (2020), Mohammadkazemi, Aguiar, and Cordeiro (2017), and Silva et al. (2018) are noteworthy for employing manufacturing processes and treatments with lower energy consumption, using more sustainable materials while still achieving gains in final strength.

In the work of Machado, Ferreira, and Motta (2020), mechanical and physical tests, scanning electron microscopy (SEM), X-ray diffraction (XRD), and contact angle measurements were conducted after 28 days and again after natural aging of 90 and 180 days. The composites, containing 2.9% microsilica, 1.40% latex (by mass), and 13.5% cellulose (by volume), exhibited mechanical properties such as a modulus of rupture of 12.38 ± 1.98 MPa and a modulus of elasticity of 18.76 ± 2.22 GPa.

Mohammadkazemi, Aguiar, and Cordeiro (2017) found lower porosity and greater surface roughness when bacterial nanocellulose was incorporated into mortars reinforced with 1.13 mm cellulose pulp at 6% content. However, they reported that the addition of bacterial nanocellulose biopolymer did not prevent mineralization of the cellulose-based reinforcement.

Silva et al. (2018) evaluated the random incorporation of 25 mm coconut fibers treated with natural latex and pozzolanic materials, analyzing their effect on physical properties and durability. The combined effect of silica fume and natural latex increased flexural tensile strength by 19.2% (5.5 MPa) compared to the control composite (4.5 MPa), followed by the metakaolin–latex treatment. According to the authors, this treatment effectively protected the bio-reinforcement against degradation mechanisms, including calcium hydroxide [$Ca(OH)_2$].

From the reviews, the following general knowledge gaps were identified:

- Lack of studies in civil engineering on the physical and mechanical properties of natural rubber latex (NRL) and bacterial nanocellulose (BNC) biopolymeric surface treatments applied to Amazonian mallow lignocellulosic fibers and their effects on cementitious matrices;
- Absence of complementary studies on these combined biopolymeric treatments regarding the durability of cementitious biocomposites during curing (initial, intermediate, and post-accelerated aging cycles), employing industrial techniques already implemented in the production of fiber-cement boards and roofing sheets.

4 FINAL CONSIDERATIONS

This study underscores the effectiveness of combining exploratory and systematic reviews to investigate the application of bio-reinforcements in cementitious composites, specifically lignocellulosic fibers from Amazonian mallow treated with natural biopolymers. Exploratory reviews provided a broad, preliminary perspective—identifying emerging trends and gaps in the literature—whereas systematic reviews enabled a more rigorous analysis, consolidating evidence from prior studies.

The findings indicate that lignocellulosic mallow fibers treated with biopolymers such as natural rubber latex and bacterial nanocellulose can enhance the mechanical properties and durability of cementitious biocomposites. Nevertheless, degradation of bio-reinforcements within the cementitious matrix and the environmental challenges associated with treatment processes remain critical issues that warrant further investigation.

Moreover, the analysis revealed that most studies focus on modifying the cementitious matrix to mitigate fiber vulnerability in alkaline environments, while fewer address surface treatments applied directly to mallow fibers. This highlights the need for future research on biopolymeric surface treatments to strengthen the durability and performance of biocomposites.

This article serves as a valuable methodological guide for researchers in the field of cementitious biocomposites, encouraging a hybrid review approach to accelerate scientific and technological progress. The identified gaps point to opportunities for innovation and sustainable development in construction, particularly through the use of more eco-friendly and efficient materials.

In sum, integrating exploratory and systematic reviews emerges as a promising strategy for advancing research on cementitious biocomposites, promoting both sustainability and efficiency in the built environment.

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