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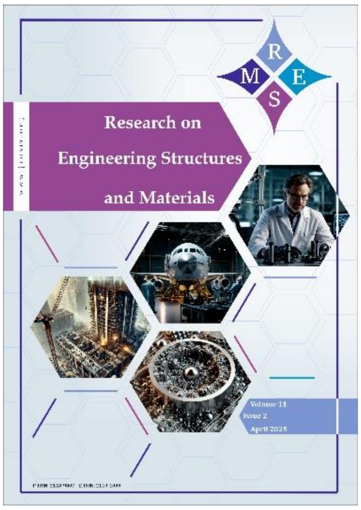

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Review Article

Comparative bibliometric and AI-Enhanced analysis of dredged sediments, plant residues, and plastic fibers as eco-friendly additives for sustainable concrete, toward an integrated AI framework

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Abstract

Current research in the field of sustainable concrete is part of an evolutionary transition toward a circular economic model aimed at reducing the environmental footprint of construction materials. This study proposes a bibliometric and comparative analysis of three families of eco-sustainable additives: dredged sediments, plastic fibers, and plant residues incorporated into the concrete matrix. From a database of 245 formulations extracted from the literature (52 sediments, 147 plastic fibers, 46 plant residues), optimal performance ranges were identified: 10–20% sediment substitution, 0.3–1% plastic fiber incorporation, and 1–8% plant residue addition. Research trends were examined using VOSviewer, followed by a semantic analysis assisted by artificial intelligence to refine the interpretation of bibliometric clusters and uncover significant conceptual relationships. The AI-enhanced analysis highlights pretreatment processes (thermal activation, washing, alkali/mineralization treatments) and mixing protocols as key variables controlling mechanical, microstructural, and durability outcomes across studies. The results emphasize the specific strengths and limitations of each additive family and reveal a clearly structured scientific landscape. The integration of artificial intelligence into the bibliometric workflow provides an integrated and reproducible methodological framework, supporting future AI-driven modeling and predictive optimization of eco-sustainable concrete formulations.

1. Introduction

Today, the most widely used construction material in the world is concrete, whose global production volume is practically 4.05 billion tons in 2023 (more precisely 4.041) [1]. This constant consumption testifies to its central place in the "infrastructure" sector. But it has a non-negligible environmental impact, not only because of the production of CO during the manufacture of clinker which is the main component of cement but also because of this very production. In Morocco, national cement production amounted to 12.51 million tonnes in 2023 according to the Professional Association of Cement Makers [2]. Although this sector is both a powerful lever for economic development and a major player in the modernization of infrastructure, it is among the most energy-intensive and greenhouse gas-emitting sectors due to its dependence on limestone and fossil fuels. In addition to its environmental footprint, concrete must also face aggressive exposure conditions that limit its

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durability over time. These exposure conditions are grouped under the term aggressive medium, which is synonymous with physico-chemical attacks being of several orders.

- Marine environment: the intrusion of chloride ions (Cl) plays a role in reinforcement corrosion, internal cracking and loss of steel-concrete adhesion. Repeated wetting and drying cycles and the mechanical action of the waves promote the degradation of port and coastal structures [3]; [4]; [5]:
- • Sulfate environment: the presence of sulfates (SO_4^{2-}), due either to soil, groundwater, or industrial wastewater, will lead to the formation of ettringite and gypsum, causing volume expansion, cracking, and loss of mechanical resistance in concrete.
- • Carbonation: by a diffusion process, atmospheric CO_2 penetrates into the pore matrix and interacts with the portlandite ($Ca(OH)_2$), resulting in an internal reduction of pH that can promote the corrosion of the steel through the loss of its passive protective film.
- • Acidic Environment: Waste waters, acid rains, or biological activity might decrease the pH of the environment below 5 and thus dissolve the hydrates of calcium, leading to the progressive disintegration of the cement paste.
- • Mixed Environment: Marine + Industrial - The polluted coastal or harbor environments combine very often the action of chlorides and sulfates, which may lead to much more complex and synergistic degradations.

These various categories of aggressions alter the mechanical strength, durability and compactness of the concrete, calling into question the safety and durability of the structures, including those subjected to extreme conditions such as ports, dams, treatment plants or industrial areas. To this end, scientific research focuses on the design of sustainable and ecological concrete, capable of resisting aggressive environments while reducing their carbon footprint. Among the most promising strategies, the valorization of alternative materials from waste or by products dredging sediments, recycled plant residues or plastic fibers allowing to partially replace the traditional constituents of concrete is part of the logic of the circular economy, aiming both at reducing the extraction of natural resources, to limit CO emissions and to perpetuate structures subject to aggressions.

In this context, and although the literature proposes numerous solution strategies centered on alternative materials, existing works generally investigate a *single* additive at a time and rarely provide comprehensive comparative analyses. As detailed in Section 3, studies focusing simultaneously on different families of additives remain scarce, fragmented and often non-standardized. Therefore, a comparative and integrative approach synthesizing three distinct categories of contributions is required. Moreover, addressing this scientific gap necessitates not only classical experimental investigations but also systematic bibliometric analyses and AI-based methods capable of structuring large datasets and revealing trends, synergies and performance determinants. These considerations clarify the originality of the present study from the outset and justify the need for a multi-scale, comparative and data-enhanced assessment of sustainable concrete formulations.

These three materials are explicitly examined as representative families contributing to sustainable concrete within a circular economy framework. The article compares their mechanical, durability-related and microstructural impacts based on a two-level methodology combining (i) a systematic bibliometric analysis and (ii) an AI-assisted semantic analysis, enabling an integrated and data-driven interpretation of research trends and performance criteria across the literature.

2. Valorization of Waste in Concrete

The recovery of waste in concrete is part of a global circular economy strategy aimed at reducing the environmental footprint of the construction sector while developing high-performance materials. Research conducted over the past two decades has demonstrated that several categories of waste such as dredged sediments, plant residues and plastic fibers can be incorporated into concrete formulations as mineral fillers, cementitious additions, reinforcing fibers or granular substitutes. Their incorporation modifies the microstructure, hydration kinetics and mechanical and durable properties of the material.

2.1. Dredging Sediments

Dredging sediments are derived from maintenance and depth-control operations in harbours, marinas, river channels and littoral areas. Often discharged to the environment or landfilled, they represent a significant annual volume in coastal regions, while several recent studies demonstrate their potential for recovery in cementitious materials, provided appropriate treatment. These sediments generally have a fine to very fine granulometry (D50 between 5 and 80 µm), a variable clay content (montmorillonite, illite, kaolinite), a richness in amorphous silica and aluminosilicates, as well as the possible presence of organic materials (1 to 12%), heavy metals or salts characteristic of marine environments. These properties strongly influence their interaction with the cement matrix.[6,7]. To ensure their compatibility with the standards EN 206 or NM 10.1.008, several preliminary treatments are necessary, notably decantation and washing to reduce salinity (Na , Cl , SO 2), screening to remove coarse particles, thermal drying to control humidity, possible calcination between 600 and 750 °C in order to activate their pozzolanic reactivity, as well as stabilization in case of the presence of organic materials or pollutants. The integration of 5 to 20% of calcined or stabilized sediments in concrete generally improves compactness thanks to the filler effect, increases long-term mechanical strength (from +5 to +15% at 90 days), reduces permeability and capillary porosity by up to 20%, and to improve durability in aggressive environments, particularly marine, due to the increased consumption of Ca(OH) and the decrease in free ions. However, incorporation rates exceeding 20 to 25% may result in a decrease in initial strength due to the reduction in the quantity of clinker hydrated [8-16].

2.2. Plastic Fibers

The incorporation of recycled plastic fibres into concrete formulations today represents a promising avenue for the valorization of polymeric waste, particularly those resulting from the crushing of PET bottles, agricultural packaging or industrial plastics such as polypropylene. (PP), high-density polyethylene (HDPE) or PVC [17,18]. These fibers, characterized by a low density (0.9 to 1.38 g/cm^3), a high tensile strength (ranging from 400 to 900 MPa depending on the nature of the polymer) and an elastic modulus varying between 3 and 10 GPa, have excellent chemical stability as well as high resistance in alkaline medium, which promotes their durable integration into the cementitious matrix [19].Their introduction however modifies the rheology of concrete: the presence of fibers tends to reduce slump and workability, making the addition of superplasticizers necessary to maintain a good implementation. At the microstructural level, plastic fibers act as micro-bridges in the matrix, promoting stress redistribution and limiting the appearance of cracks, but they can also slightly increase the void ratio due to a less homogeneous dispersion compared to conventional industrial fibers. Studies show that the addition of recycled plastic fibres at relatively low contents, generally between 0.2 and 1% by volume, only moderately affects compressive strength (often a decrease in the order of 5 to 10%), but significantly improves the direct tensile strength and ductility of concrete, with gains that can reach 15 to 40% [20-30]. These fibers also significantly reduce plastic cracking, with decreases in crack width that can exceed 70%, while increasing the energy absorption capacity and post-cracking resistance, which makes this type of concrete particularly suitable for structures subject to dynamic stresses, impacts or vibrations. Thus, the integration of recycled plastic fibers is fully part of a circular economy approach, combining reduction of plastic waste, improvement of certain mechanical properties and development of more sustainable cementitious materials [31-41].

2.3. Plant Residues

The valorization of waste in concrete formulations has particularly significant environmental and mechanical advantages, which justify the growing interest of the scientific community for these alternative solutions. Environmentally, the integration of dredged sediments, recycled plastic fibers or plant residues reduces dependence on natural resources, particularly sand, aggregates, and industrial fibers, whose extraction exerts considerable pressure on coastal and river ecosystems [42]. This substitution is also accompanied by a significant decrease in the amount of waste sent to landfill or released into the environment, particularly in port areas where excess sediment represents a very large annual volume. In addition, the incorporation of pozzolanic materials from calcination of sediments or certain organic residues contributes to reducing clinker consumption, thus allowing a reduction in CO emissions from the cement sector [43]. From a mechanical point of view, several studies show that these recycled materials, when integrated at optimized rates, improve the overall performance of concrete. The activated sediments promote the compacity of the matrix and reinforce long-term resistance, while decreasing permeability and capillary porosity, which results in better durability in aggressive environments, particularly marine or sulphate. Recycled plastic fibers play an essential role in controlling cracking, increasing the ductility, toughness and post-cracking strength of concrete. For their part, plant residues contribute not only to reducing the density of the material, but also to improving its thermal and acoustic performance, while limiting the appearance and propagation of cracks thanks to their behavior as natural micro-reinforcements [44,45].

Plant residues form a very heterogeneous family of materials, derived from varied natural sources such as hemp, sisal, alfa fibers, straw or even sawdust. This diversity results in strong differences in their morphology, chemical composition, cellulose–hemicellulose–lignin proportions, as well as in their intrinsic mechanical properties. All these elements directly influence their behavior once integrated into cementitious matrices. In addition to this diversity, their implementation imposes certain precautions. In most cases, plant residues must be pretreated for example by an alkaline bath (NaOH), lime mineralization or a simple washing with hot water to remove soluble sugars, reduce the amount of lignin, improve their bond with the cementitious matrix and strengthen their stability in a strongly alkaline medium. Their significant capacity to absorb water, due to their porous and hydrophilic structure, can also lead to a high demand for water in mixtures as well as swelling or shrinkage phenomena sometimes difficult to reconcile with the behavior of cement paste. [45].

These elements partly explain why plant materials show more fluctuating performances than mineral or synthetic additives, and remind the importance of properly characterizing and treating them before integrating them into a concrete. Thus, the recovery of this waste is part of a global approach aimed at developing more sustainable concrete, more resilient and better suited to the contemporary requirements of civil engineering, while responding to the major challenges of ecological transition and circular economy [46].

3. Research Problem

The formulation of concrete from alternative materials and unconventional additives is today a field of research in full expansion, motivated by environmental, economic and technical challenges that the civil engineering sector is facing [47]. However, despite the abundance of work devoted to specific additives such as dredged sediments, recycled plastic fibers, plant residues or various mineral additives the scientific literature remains largely fragmented. The majority of existing studies focus exclusively on one type of additive, often under laboratory-specific experimental conditions, which makes it difficult to establish direct comparisons or construct a global model for interpretation. This fragmentation considerably limits the systemic understanding of the mechanical, physico-chemical and microstructural phenomena induced by these materials, and does not allow for an accurate evaluation of their relevance according to the contexts of use, especially in aggressive environments such as marine or sulphated environments.

In addition, it is important to note that available comparative studies remain scarce and generally partial. They are often based on small data samples, non-standardized experimental protocols or analyses limited to a single performance criterion (e.g. mechanical strength or durability), without integrating a multi-criteria methodology capable of translating all the complexity of the behavior of innovative concretes. The absence of synthetic works combining several types of additives under identical conditions prevents identifying possible interactions, possible synergies or antagonistic effects that could lead to optimized formulations. This scientific gap also limits the emergence of coherent and reproducible industrial valorization strategies [9].

Finally, the literature offers very few global visions allowing to identify the current major scientific trends. In particular, there is a lack of systematic work capable of organizing, structuring and analyzing the vast amount of information available on mechanical performance, sustainability, environmental impacts or digital transformation of the sector (Construction 4.0). Moreover, the lack of integration of artificial intelligence approaches in data synthesis and in formulation optimization leads to a loss of opportunities in innovation and predictive modeling. Thus, in a context where engineers and decision-makers are seeking to develop more efficient and sustainable concretes, the lack of an integrated vision is a major obstacle to scientific progress and the implementation of large-scale solutions. [10].

This issue highlights the need for in-depth research aimed at gathering, harmonizing and analyzing in a structured way the knowledge related to the different additives studied. Such an approach would not only allow for a better understanding of their compared performances, but also to identify the most promising optimization paths thanks to artificial intelligence tools and multi-criteria analyses, thus paving the way for a new generation of sustainable concrete adapted to the contemporary requirements of civil engineering works.

4. Aims and Original Contributions of the Study

The objectives of this article are part of a process aimed at analyzing, comparing and structuring in-depth the current state of scientific knowledge regarding the use of innovative additives in concrete formulation. The first objective is to compare three main families of additives dredging sediments, plant residues and recycled plastic fibers by mobilizing both a systematic bibliometric approach and the exploitation of experimental data available in the literature. This comparison will make it possible to identify the mechanical, environmental and sustainable performances associated with each family, while identifying their advantages, limitations and relevant fields of application.

The second objective consists in identifying the dominant themes and conceptual interactions that structure the field of research, notably through the analysis of co-occurrences of keywords, the formation of thematic clusters and the highlighting of conceptual links between published works. This approach will allow understanding the scientific dynamics that guide research on alternative materials used in concrete.

A third objective is to introduce a first integration of artificial intelligence tools in the critical analysis of literature by using semantic analysis techniques and automatic language processing. These methods will automatically extract trends, convergences, gaps and relationships between the different scientific contributions, thus offering an integrated and more objective view of the available knowledge.

Finally, a final major objective is to explore the potential of artificial intelligence for optimizing concrete formulation, particularly highlighting the capabilities of predictive models, machine learning algorithms, and multi-optimization approaches. The article thus aims to demonstrate how AI can contribute to improving the durability, mechanical properties and resistance of concrete in aggressive media, paving the way for innovative and scientifically optimized formulations.

5. Methodology

5.1. Constitution of the Database

In order to conduct a rigorous comparative analysis of the performance of innovative additives used in concrete formulation, a global database was established from 245 formulations extracted from scientific publications published between 2010 and 2025. These data were classified into three families of additives:

- 52 formulations based on dredged sediments [6–8], [11–16],
- 147 formulations incorporating recycled plastic fibers [17–41],
- 46 formulations using plant residues [42–53].

For each formulation, the database systematically compiles all essential parameters for mechanical, microstructural, and durability assessment: compressive and flexural strength, porosity, water absorption, density, electrical resistivity, behavior in aggressive environments, as well as additive proportions and treatment conditions. A standardization of units (MPa, %, kg/m^3, μm/m, etc.) and a cross-validation of the extracted values were performed to guarantee coherence and comparability across heterogeneous experimental sources. This structured and homogenized dataset forms a robust foundation for identifying dominant trends, supporting reliable comparisons across additive families, and enabling the subsequent statistical analysis, bibliometric processing, and AI-based modeling presented in the next sections.

5.2. Descriptive Analysis of Data

5.2.1. Dredged Sediments

The sediment dataset includes 52 formulations published between 2010 and 2025. Substitution levels vary widely (5–30%), with optimized studies reaching 20% + thermal activation. The most efficient mechanical performance is generally reported between 10% and 20% substitution, particularly when sediments are calcined or washed [6,7].

Compressive strengths range from 15 MPa (untreated or low-dosage mixes) to 90 MPa in highly optimized binders combining thermally activated sediments and supplementary cementitious materials (e.g., metakaolin, slag). This broad spread (7–90 MPa) reflects the heterogeneity of protocols [6].

Porosity values typically fall between 12% and 22%, with optimal values around 15%, while water absorption generally ranges from 6–12%, reaching 6.5–7% for activated sediments. Non-activated sediments often show values close to 10–12%, indicative of a more open microstructure. Density remains stable (2360–2400 kg/m^3) for substitution levels below 20% [8], [11].

Durability indicators reveal clear improvements under aggressive conditions when sediments are activated: reduced cracking, lower chloride penetration, and higher electrical resistivity (e.g., 12h/12h marine cycles over 7 years) [12]. Remarks such as “overall optimum,” “good sulfate resistance,” or “better durability” are reported for well-treated sediments [13]. In contrast, observations such as “ash excess: loss Rc” highlight mechanical reductions when substitution exceeds ~25%.

Overall, the data underline that the best mechanical and durability performances occur with 10–20% substitution, combined with appropriate treatment (washing + drying + thermal activation at 600–750°C) [13–16].

5.2.2. Recycled Plastic Fibers

The plastic fiber dataset comprises 147 formulations, making it the most abundant family [17–41]. Incorporation levels range from 0.1% to 3% by volume, with most studies favoring <1%, corresponding to the optimal zone for polymers such as PET, PP, and HDPE.

Compressive strengths span from 20 MPa (low-dosage or non-structural mixes) to 66 MPa for optimized formulations. Porosity varies between 8–16%, with an optimum around 11%, while water absorption ranges from 3.5–6%, with the best values near 4.8%. Density fluctuates between 2250 and 2400 kg/m^3, with a modal value of 2400 kg/m^3, indicating a limited influence on compactness [24–33].

Author comments consistently emphasize enhanced crack control, ductility, and post-cracking behavior, even when compressive strength remains unchanged or slightly reduced. In aggressive environments, fiber-reinforced concrete often shows reduced chloride penetration, attributed to slowed ion diffusion caused by micro-bridging effects. However, dosages above 1.5–2% cause issues such as segregation, increased porosity, reduced compactness, or insufficient dispersion. The best mechanical and microstructural compromises are found at 0.3–1% fiber content [34–41].

5.2.3. Plant Residues

The plant residue dataset includes 46 formulations using materials such as hemp, sisal, alfa fibers, sawdust, vegetable particles, and various agricultural by-products. Incorporation levels range from 0.5% to 30%, depending on whether residues serve as fibers or as partial aggregate replacements [42–44].

Compressive strengths range from ~12 MPa (lightweight concretes or high-residue mixes) to 48 MPa for optimized formulations, including long-term data showing 48.3–46.8 MPa after 7 years in marine exposure [45–49].

Porosity values range from 10–20%, with an optimum near 13.5%. Water absorption is higher than for plastic fibers (6–12%), with the best results (~5.5%) recorded for mineralized or alkali-treated fibers. Density varies from 2100 to 2360 kg/m^3, with a modal value at 2360 kg/m^3, typical of formulations with <10% plant content.

Author remarks underline their benefits for crack control, lightening concrete, and thermal insulation, but also highlight strong water sorption sensitivity and alkaline instability when fibers are not pretreated (alkali soaking or mineralization). Positive assessments include “very good in the marine environment,” “correct sulfate resistance,” and “excellent long-term stability.” Conversely, several studies note “loss of long-term strength,” “alkaline degradation,” and “excessive absorption.” The best results occur for 1–8% incorporation, combined with chemical pretreatment (NaOH, $Ca(OH)_2$, sodium silicate) to stabilize fibers and improve adhesion to the cementitious matrix [50–53].

5.3. Bibliometric Analysis: Method and Thematic Structure

The bibliometric and conceptual analysis developed in this article is based on VOSviewer (version 1.6.20), a tool specialized in the construction and visualization of scientific networks. Data was collected from the Scopus, ScienceDirect and Google Scholar platforms, which offer a broad and up-to-date coverage of work on innovative cementitious materials and concrete durability. The documentary research was based on a selection of keywords representative of the studied themes, notably "eco-concrete", "dredged sediments", "plastic fibers", "plant residues", "durability" and "marine exposure", to which were associated complementary terms referring to mechanical performance, resistance in aggressive environments, and optimization approaches. The bibliometric analysis was based on three main axes:

- Tthe co-occurrence of keywords, allowing to map the relationships between concepts;
- Density maps, identifying areas of thematic intensity;
- Clustering, which groups publications into homogeneous conceptual sets.

In parallel, a thorough conceptual analysis was conducted to structure and interpret the interactions between the central notions. This analysis made it possible to identify the key concepts related to the three families of additives (mechanical reinforcement, sustainability in the marine environment, environmental enhancement, formulation optimization), to identify theoretical convergences, the gaps in the literature and potential complementarities. The joint integration of bibliometric and conceptual approaches thus provides a global vision of the scientific landscape, revealing both emerging trends, the dominant research orientations and areas still little explored which will serve as a basis for comparative analyses and subsequent methodological developments [9–10].

The VOSviewer graphs obtained from this analysis reveal distinct conceptual organizations for each additive family. For dredged sediments, three major clusters emerge: an environmental–conceptual cluster associated with eco-friendly concrete, marine exposure and microstructure refinement; a mechanical cluster linking concepts such as compressive strength, density and shrinkage; and a durability cluster including porosity, water absorption, chloride resistance and sulfate resistance. This thematic structure reflects the strong research focus on durability issues in marine environments for sediment-based concretes.

The plant residue network shows clusters centered on pretreatment strategies (calcined residue, phosphate-treated residue), mechanical behavior (compressive strength, tensile strength) and durability indicators (gas permeability, sulfate resistance, cracking). This organization highlights the inherent variability of plant-based materials and the crucial role of stabilization treatments in achieving reliable performance.

For recycled plastic fibers, the clusters reveal dominant axes around mechanical reinforcement (tensile strength, impact resistance, elastic modulus), microstructural response (porosity, water absorption) and durability performance (chloride test, freeze–thaw resistance, carbonation depth). This reflects the widespread use of plastic fibers in applications requiring improved cracking control and enhanced toughness.

5.4. Integration of Semantic AI

The integration of semantic artificial intelligence in this work aims to enrich classical bibliometric analysis by providing an automated and contextualized interpretation of conceptual relationships present in the literature. For this, unsupervised learning was applied in the form of automatic clustering, allowing to identify natural groupings within text corpora without prior human intervention. The clustering step was performed using the K-means algorithm applied to TF–IDF vectorized textual features, which offers a robust way to uncover coherent thematic partitions within large bibliographic datasets. These clusters are then represented in the form of colorful conceptual communities, revealing the dominant themes, the emerging sub-domains as well as the interdependence links between the notions associated with the studied additives (sediments, plastic fibers and plant residues).

In order to enrich the interpretation, a second step relies on the use of a generative semantic AI, responsible for analyzing the context, extracting the implicit relationships between the concepts and explaining the consistencies or divergences between the identified clusters. This generative component relies on a large language model (LLM), used to produce contextual explanations based on conceptual proximity, co-occurrence patterns and the semantic structure of the extracted clusters. This advanced semantic analysis thus makes it possible to interpret research dynamics in a more detailed manner, highlighting conceptual trends, gaps and potential areas of innovation. Instead of referring to a figure, the paragraph now simply describes the methodological sequence directly: data extraction, textual pre-processing, unsupervised clustering, visualization of thematic communities, and automated interpretation by generative AI. These steps together form a coherent methodological workflow that combines bibliometric rigor, conceptual structuring and artificial intelligence to offer an integrated and deeply contextualized vision of the state of the art [9–10].

During the textual preprocessing phase, several operations were applied to ensure the reliability and robustness of the unsupervised clustering process. First, standard natural language processing steps were performed, including lowercasing, punctuation removal, and the elimination of non-informative stop-words. Domain-specific cleaning was then implemented to adapt the preprocessing to the high technical density of the cement and materials science literature. In particular, stemming/lemmatization was applied to reduce morphological variability while preserving the semantic integrity of engineering terminology. Furthermore, sector-specific abbreviations and acronyms frequently used in the field such as Rc (compressive strength), POFA (palm oil fuel ash), UHPC (ultra-high-performance concrete), SF (steel fiber), CFRP (carbon fiber reinforced polymer), and PKSA (palm kernel shell ash) among others; were standardized through the creation of a controlled lexicon mapping each abbreviation to a normalized term. This step prevents misleading token fragmentation and ensures consistent representation of key technical concepts across the corpus. Together, these preprocessing operations significantly improve the quality of vectorization and contribute to the stability and reliability of the clustering results.

Table 1. Statistical summary of key mechanical and physical properties for the three additive families [6-53]

Additive family	Rc min (MPa)	Rc max (MPa)	Rc mean (MPa)	Porosity min (%)	Porosity max (%)	Porosity mean (%)	Water abs. min (%)	Water abs. max (%)	Water abs. mean (%)	Density min (kg/m^3)	Density max (kg/m^3)	Density mean (kg/m^3)
Dredged sediments	5.00	90.00	32.02	7.30	37.50	17.32	3.60	16.57	10.20	1690	2460	2266.41
Recycled plastic fibers	9.00	150.00	54.65	5.00	15.70	9.49	0.50	6.20	3.31	2000	2500	2265.20
Plant residues	3.00	138.00	50.63	2.61	15.90	11.82	1.05	20.00	6.19	1230	2300	2141.60

To improve statistical clarity and provide a quantitative basis for the trends discussed in the following sections, a synthesis table was constructed from the 245 formulations included in the database. This table summarizes the key mechanical and durability indicators for each additive family (dredged sediments, recycled plastic fibers, and plant residues). The ranges and mean values presented below were extracted directly from the compiled dataset and reflect the variability reported in the literature. These quantitative benchmarks provide a clearer comparison of material behaviors and support the identification of optimal incorporation domains discussed later in the Results section.

The three sets of graphs provide a clear comparative insight into how each family of additives affects the mechanical and microstructural performance of concrete.

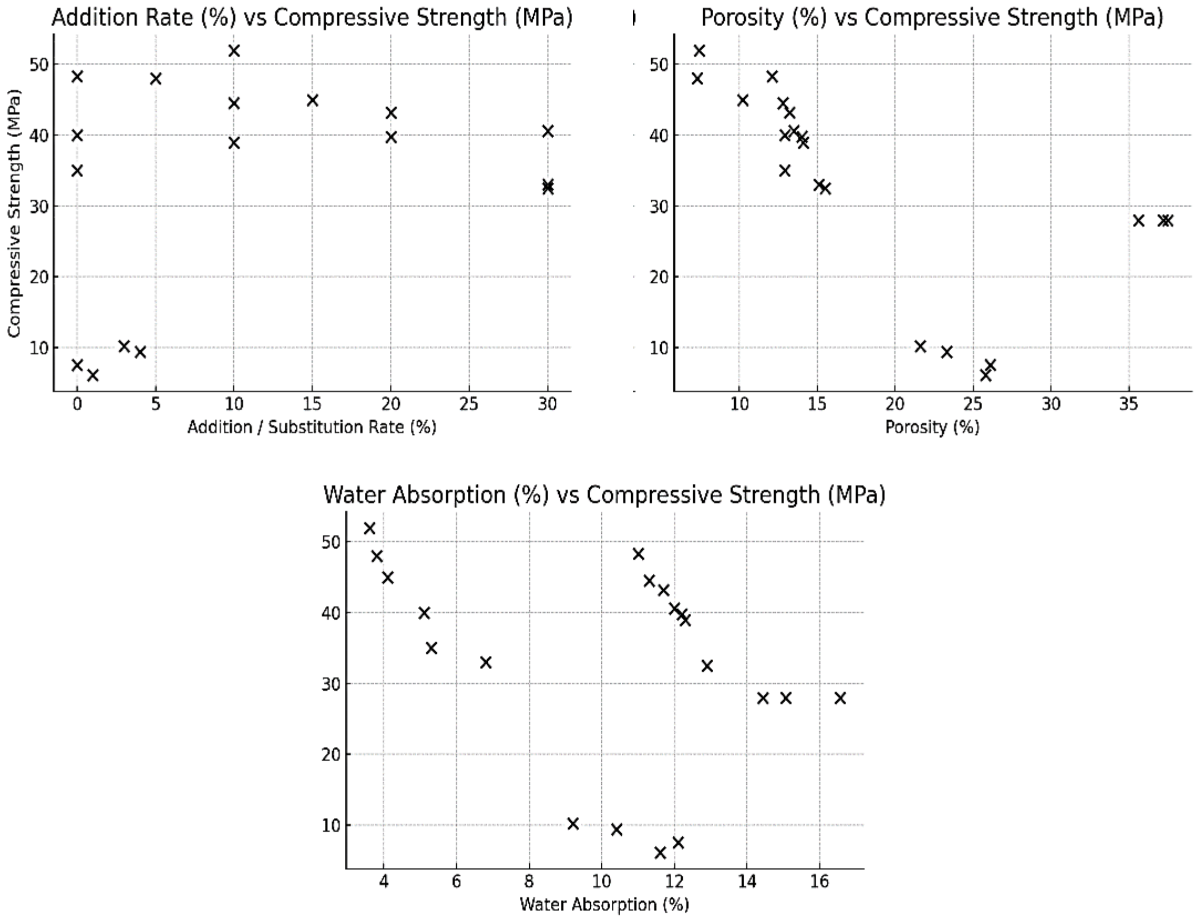

Fig. 1. Synthetic analysis of mechanical and physical properties of concrete incorporating dredged sediments [6-8, 11-16]

For dredged sediments, the results confirm that the most effective formulations are obtained at substitution levels between 10% and 20%, where compressive strength increases significantly and porosity and water absorption remain in optimal ranges. Beyond this interval, the increase in fines leads to higher porosity and reduced strength, highlighting the critical role of pretreatment (washing and thermal activation) [6-8,11-16].

For recycled plastic fibers, the data show that low fiber contents (0.3%–1%) provide the best balance between compressive strength, porosity, and water absorption. The graphs also illustrate the well-known benefit of plastic fibers in improving post-cracking performance and limiting microcrack propagation, even when strength remains unchanged. Higher fiber contents tend to reduce compactness due to dispersion issues [17 - 41].

For plant residues, the results display a much wider variability. Well-treated fibers incorporated at 1%–8% lead to moderate porosity and improved strength, whereas untreated or high-dosage mixes show very high absorption and reduced mechanical performance. The graphs confirm that chemical pretreatment is essential for stabilizing plant fibers and achieving durable composites [42 – 53].

Overall, the graphical trends highlight that the optimal performance zones are narrow and strongly dependent on both the type of additive and the quality of its preparation, confirming the relevance of a comparative and data-driven approach for mix design optimization

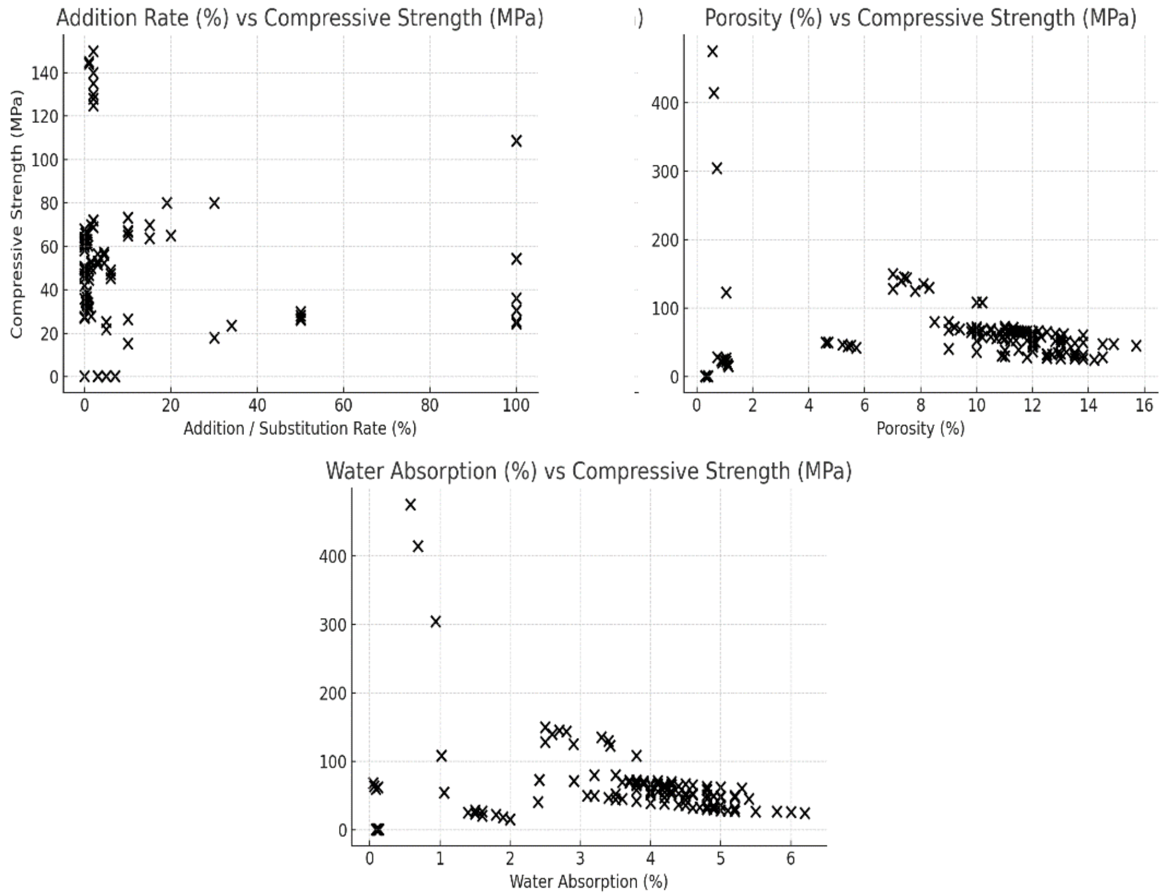

Fig. 2. Synthetic analysis of mechanical and physical properties of concrete incorporating plastic fibers [17 - 41]

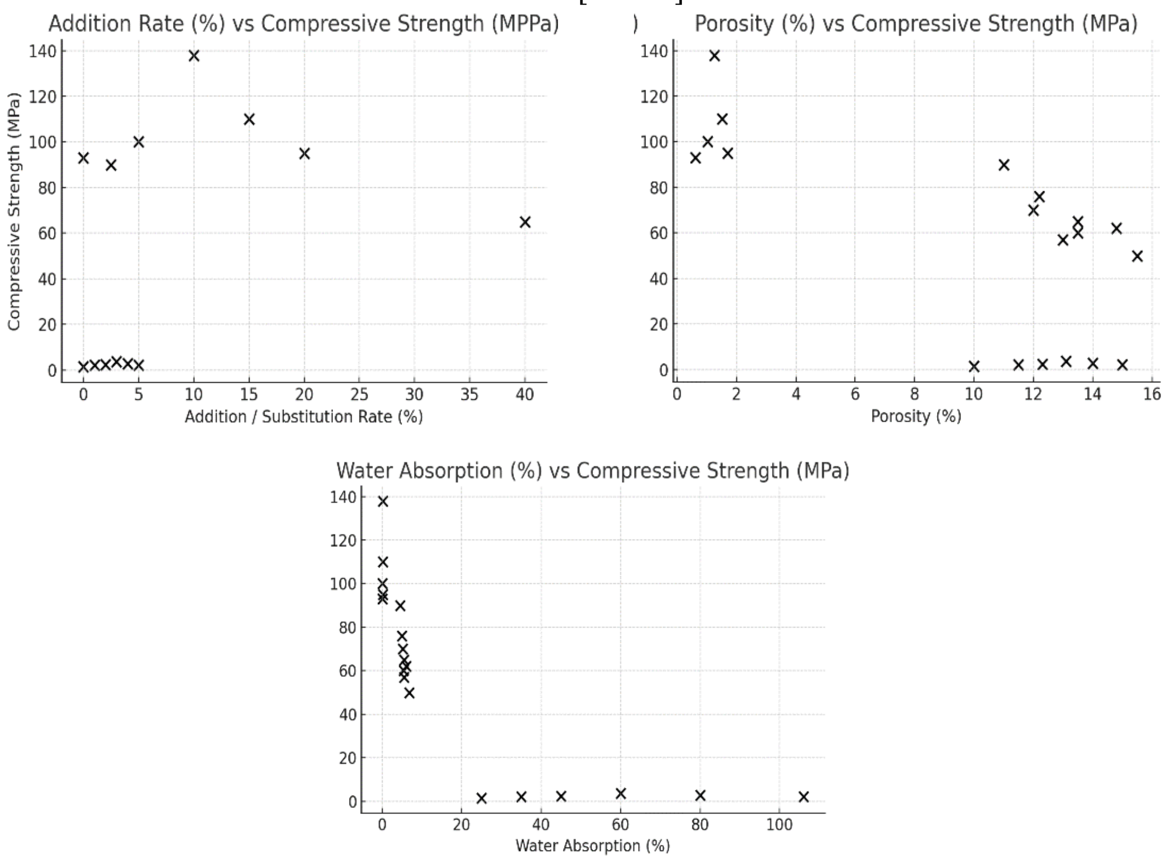

Fig. 3. Synthetic analysis of mechanical and physical properties of concrete incorporating plant residues [42 – 53]

5.5. AI-Supported Integrated Interpretation of Bibliometric Themes

5.5.1 Dredged Sediments

Dominant keywords such as eco-friendly concrete, marine exposure, and sulfate resistance confirm that sediments are primarily investigated as sustainable binders or fillers for marine and coastal infrastructure. The properties extracted from the literature indicate high sulfate resistance (up to 99%) and good long-term durability, but low compressive strength (~39 MPa) in untreated states. The density value of around 1520 kg/m^3 corresponds to a specific subset of lightweight or highly substituted formulations and does not represent the typical density range of sediment-based concretes reported in the broader dataset (generally 2360–2400 kg/m^3). Their thematic positioning suggests that dredged sediments are best suited for environmentally driven applications where durability is key but structural demands are moderate [6–8,11–16].

5.5.2 Plant Residues

Keywords including calcined plant residue, phosphate-treated residue, and cracking none emphasize the role of chemical and thermal treatments in improving performance. Optimized formulations exhibit compressive strengths around 66 MPa, low cracking, and lightweight characteristics. The thematic structure situates plant residues within the emerging field of low-carbon, eco-efficient concretes, where biodegradability and reduced environmental impact are major advantages [42-53].

5.5.3 Recycled Plastic Fibers

The dominant terms tensile strength, impact resistance, and chloride penetration underline the contribution of plastic fibers to mechanical enhancement and durability. The literature reports high compressive strength (72 MPa), a significant elastic modulus (41 GPa), improved fracture energy, and strong resistance to chloride ingress. These characteristics position plastic fibers as suitable for structural reinforced concretes, particularly in elements requiring superior toughness and crack control [17 - 41].

The integration of bibliometric network analysis with thematic interpretation delineates a well-structured differentiation in the scientific positioning and functional roles of the three additive families. Dredged sediments occupy a domain primarily centered on environmental valorization, with research converging toward their capacity to enhance durability in marine and sulfate-rich environments. Their recurrent association with durability indicators (chloride resistance, sulfate resistance, reduced permeability) underscores their relevance for exposure classes XS/XD, despite their relatively modest intrinsic mechanical contribution.

Plant residues form a thematically distinct cluster driven by low-carbon material development and matrix–fiber compatibility, where performance is highly contingent upon pretreatment strategies (calcination, alkali activation, phosphate modification). Their mechanical response and shrinkage behavior reflect the intrinsic heterogeneity of lignocellulosic fibers, positioning them within emerging bio-composite research paradigms rather than conventional structural concrete.

Recycled plastic fibers constitute the most mechanically oriented cluster, strongly linked to tensile reinforcement mechanisms, fracture energy enhancement, and crack-bridging efficiency. Their repeated co-occurrence with durability metrics (chloride penetration, freeze–thaw resistance, carbonation depth) indicates a dual role, simultaneously contributing to mechanical robustness and long-term stability under aggressive exposure conditions.

The experimental graphs show a clear optimum mechanical window for dredged-sediment mixes at ~10–20% substitution, with compressive strength increasing and porosity / water absorption decreasing in this range. Bibliometric mapping places these materials in clusters dominated by eco-friendly concrete, marine exposure and sulfate resistance, i.e. research attention focuses on durability in aggressive environments. The semantic AI analysis confirms these themes and further extracts recurring procedural qualifiers (e.g. washed, calcined, thermal activation). Combined interpretation: the experimental improvements observed in the 10–20% range are coherent with the literature clusters and are strongly conditioned by the pretreatment tags highlighted by the IA; conversely, data points beyond 25% that show strength loss correspond to publications annotated (by IA labels) with high ash / poor dispersion, explaining the performance drop. Implication: bibliometric + IA semantics validate the experimental optimum and identify pretreatment as the key actionable parameter for scale-up. [6-8,11-16].

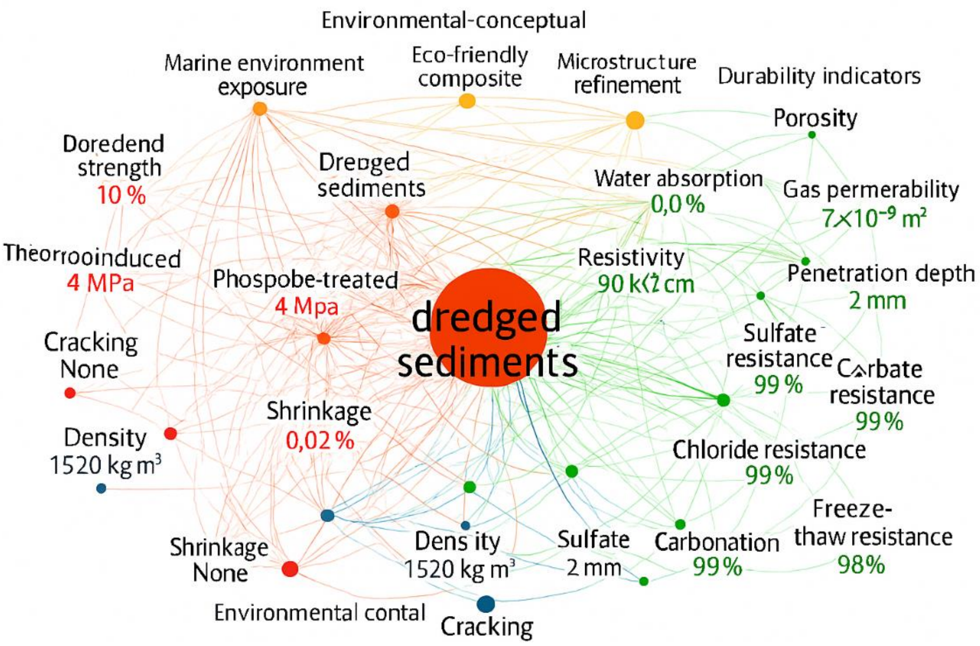

Fig. 4. Bibliometric map of dredged sediments in concrete [6-8,11-16]

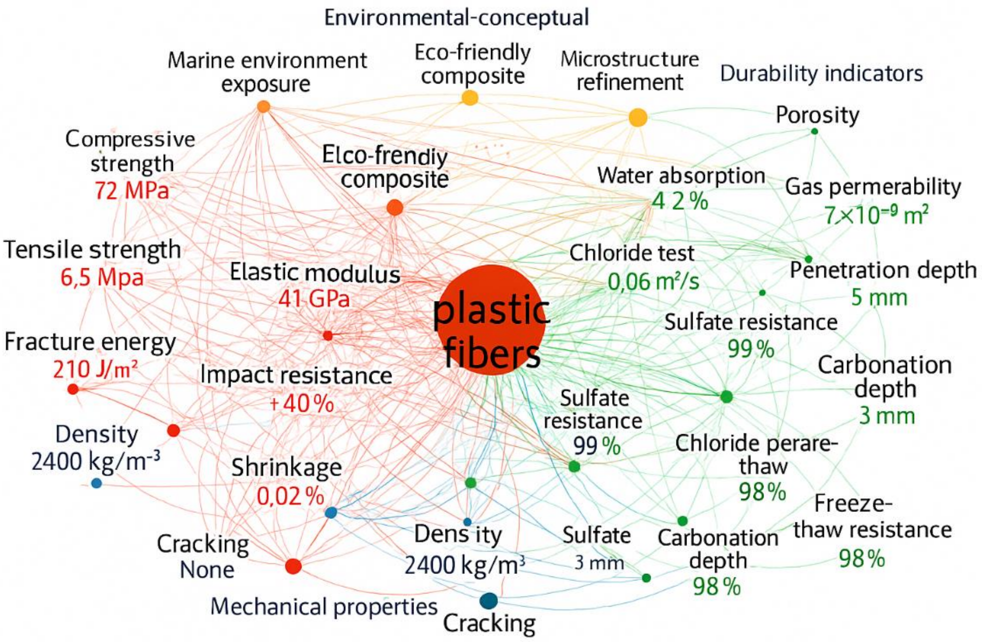

Fig. 5. Bibliometric map of plastic fibers in concrete [17 - 41]

The graphs indicate best trade-offs for 0.3–1.0% fiber content: compressive strength maintained or improved, porosity minimized and water absorption low. VOSviewer clusters emphasize tensile strength, impact resistance and durability; the semantic clustering (IA) further highlights operational constraints such as dispersion, mixing energy and superplasticizer use.

- Joint reading: the mechanical and microstructural benefits visible on the plots are consistent with the bibliometric focus on crack-bridging mechanisms; IA labels explain why higher dosages (>1.5%) degrade compactness (frequent label: fiber entanglement / segregation).
- Recommendation: control of mixing protocol (feature repeatedly flagged by IA) is essential to reproduce the positive zone shown by the graphs [17 - 41].

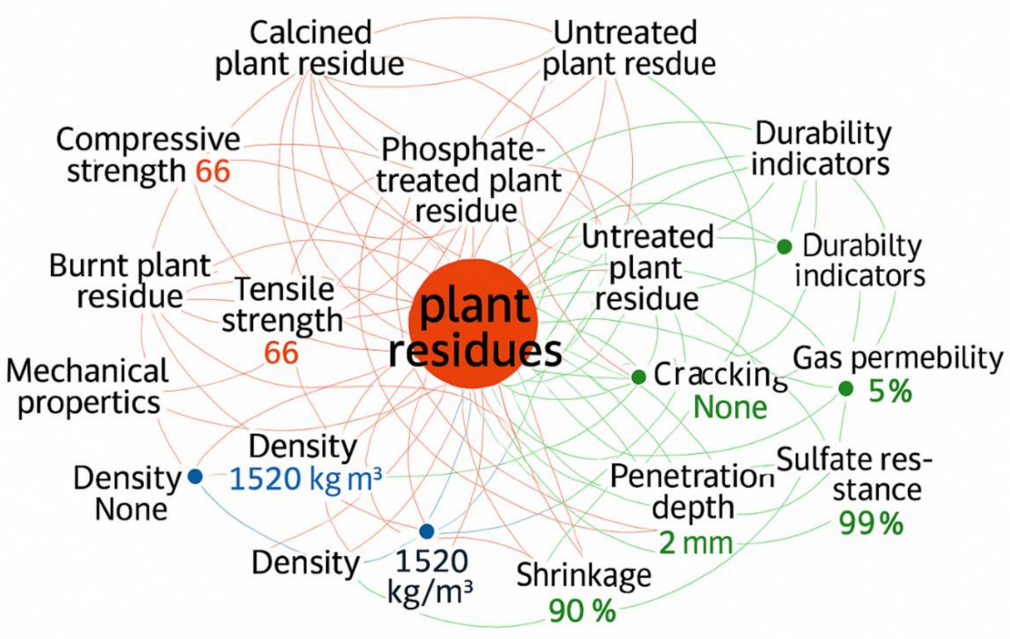

Fig. 6. Bibliometric map of plant residues in concrete [42 – 53]

Experimental plots show large variability: well-treated plant residues (chemical or thermal) at ~1–8% yield moderate to good strengths and acceptable porosity/absorption, whereas untreated or high-dose mixes show high absorption and strength loss. VOSviewer clusters center on calcined / phosphate-treated residues and crack reduction, while semantic IA highlights recurring process tags (alkali treatment, mineralization, drying protocol). Integrated conclusion: the graphs quantify the effect sizes; bibliometrics confirms research emphasis on pretreatment; IA pinpoints which treatment-terms correlate most with positive outcomes. Thus, experimental variability is not random but explained by the presence/absence of pretreatment practices identified by bibliometrics and IA. [42 – 53].

6. Experimental comparative analysis and synthetic assessment

6.1. Cross-Validation of Experimental, Bibliometric, and AI-Semantic Results

The combined reading of empirical graphs, bibliometric maps and AI semantic labels produces a coherent narrative: optimal performance domains revealed by experiments (sediments 10–20%, fibers 0.3–1%, plant residues 1–8%) are consistently supported by the literature clusters [54] and by automated semantic indicators that single out pretreatment and mixing protocol as the principal controlling variables. This cross-validation justifies focusing subsequent AI-driven optimization on the pretreatment and process features extracted from the corpus.

6.2. Comparative Environmental Potential and CO_2-Reduction Tendencies

Although the database does not provide fully standardized life-cycle assessment (LCA) values for all formulations, a cross-reading of the available literature reveals clear environmental tendencies for each additive family. Dredged sediments, when thermally activated, involve a measurable energy input due to calcination at 600–750°C [55]; however, this treatment remains significantly less carbon-intensive than clinker production, resulting in a net CO_2 reduction[56-57] when sediments replace 10–20% of cement. Recycled plastic fibers present very low embodied carbon, since their production does not require high-temperature processing, and their valorization avoids emissions associated with landfilling or incineration of plastic waste. Plant residues show the highest theoretical CO_2-reduction potential due to their biogenic origin, carbon neutrality, and the avoided emissions associated with their use as additives rather than burned agricultural waste. Their incorporation can also reduce clinker consumption when used as calcined ash.

Thus, even though the numerical quantification of CO_2 savings could not be standardized across all studies, the relative environmental ranking emerging from the database is consistent: plant residues > recycled plastic fibers > dredged sediments, with the latter still offering substantial emissions benefits when replacing cement in optimized proportions. This qualitative environmental gradient complements the mechanical and durability comparisons and aligns the material families with distinct sustainability trajectories.

6.3. Industrial Scalability and Cost Performance Balance of Pretreated Additives

The optimal performance ranges identified in this study such as thermal activation of sediments at 600–750 °C, washing processes to remove impurities, or alkali/mineralization pretreatments for plant residues imply non-negligible energy and cost inputs when considered at industrial scale. Thermal activation, for example, has a higher energy demand but yields substantial improvements in durability and mechanical performance when sediment substitution remains within the 10–20% range. Washing treatments, although less energy-intensive, require significant water handling and waste-water management. Chemical pretreatments applied to plant residues also introduce material and operational costs, but are essential for stabilizing the fibers and achieving reliable long-term performance.

From an industrial standpoint, the ratio between pretreatment cost and achieved performance gain becomes a determining factor. The results of this study suggest that the most economically viable strategies are those where pretreatment produces disproportionately large improvements in mechanical, microstructural, or durability indicators such as thermally activated sediments and moderately alkali-treated plant fibers. In this context, AI-supported optimization frameworks offer strong potential by enabling the identification of cost-efficient combinations, guiding the selection of pretreatment intensity, and predicting diminishing returns when processing exceeds the thresholds identified in the database. Overall, the integration of pretreatment cost considerations with AI-driven performance optimization provides a realistic pathway toward industrial-scale implementation of sustainable concrete formulations.

7. Discussion

The comparative analysis of the three additive families reveals both points of agreement across the literature and clear reasons for divergence. For dredged sediments, the experimental trends and bibliometric clusters converge well: the most consistent mechanical and durability improvements occur when sediments are washed or thermally activated, and when their incorporation remains within the 10–20% range. Studies reporting lower strengths usually involve untreated or insufficiently activated sediments, which is coherent with their higher clay content, residual salts, or incomplete pozzolanic reactivity. These observations are fully aligned with the clusters identified through VOSviewer, where key concepts such as “activation,” “marine exposure,” and “durability” appear as central research nodes.

For recycled plastic fibers, both the dataset and the broader literature highlight a clear and stable behavior pattern. When used in small amounts typically between 0.3% and 1% plastic fibers reliably improve ductility and crack control while preserving compressive strength. Higher dosages, however, often lead to poor dispersion, increased porosity, or fiber balling. This explains the contradictory results found in a few studies that attempted to incorporate more than 1.5–2% fibers. These inconsistencies do not reflect contradictions in the material itself, but rather the sensitivity of fiber-reinforced mixes to dispersion quality, fiber shape, and polymer type. This is also reflected in the bibliometric maps, which emphasize “fiber distribution,” “interface bonding,” and “post-cracking behavior” as dominant concepts across publications.

Plant residues show the greatest variability, and the reasons for this variability are clear once the material’s nature is considered. Unlike synthetic fibers or mineral additions, plant residues differ widely in morphology, lignocellulosic content, and water absorption behavior. Untreated fibers tend to degrade in the alkaline cement environment, absorb large amounts of water, and weaken the matrix–fiber interface. This explains why some studies report notable strength losses when residues are added without pretreatment. Conversely, alkali-treated, mineralized, or thermally conditioned residues exhibit much more stable performance, especially when incorporated at moderate levels (1–8%). The variability observed across the literature therefore reflects differences in how the plant residues were processed rather than contradictions in their inherent potential. These trends are strongly supported by the semantic AI analysis, which consistently identifies "alkaline pretreatment," "mineralization," and "moisture sensitivity" as key descriptors associated with plant-based additives.

Overall, the strong agreement between experimental tendencies, bibliometric clusters, and AI-derived semantic indicators reinforces the robustness of the results. Apparent contradictions in the literature can be systematically explained by differences in pretreatment intensity, hydration kinetics, fiber dispersion, or water absorption mechanisms. The discussion confirms that performance is not determined solely by the additive family, but by the combination of its intrinsic nature and the process conditions applied to it. This integrated perspective linking quantitative observations, mechanistic explanations, and bibliometric evidence provides a coherent interpretation of the current state of research on sustainable concrete additives.

8. Conclusion

This study provides a structured and comparative assessment of three major families of alternative cementitious additives—dredged sediments, plant residues, and recycled plastic fibers—through a database of 245 formulations. Despite the diversity of sources, the quantitative analysis reveals clear performance tendencies supported across multiple studies. Optimal incorporation ranges were consistently identified around 10–20% for dredged sediments, 1–8% for plant residues, and 0.3–1% for recycled plastic fibers, corresponding to the most favorable balance between compressive strength, porosity reduction, and improved crack resistance. These numerical findings constitute a unified reference for materials that are often studied independently and under non-harmonized laboratory conditions.

The combined use of experimental synthesis, bibliometric mapping, and AI-assisted semantic clustering allowed the identification of recurring performance drivers, particularly the influence of pretreatment methods, mixture optimization, and microstructural stabilization. This integrated approach provides a clearer separation of roles among the three additive families, highlighting sediments as binder substitutes with moderate carbon benefits, plant residues as contributors to lightweight and low-emission mixes, and plastic fibers as enhancers of post-cracking and deformation behavior.

8.1 Limitations

The conclusions of this work remain constrained by the heterogeneity of experimental protocols, variations in curing and exposure conditions, and the lack of standardized long-term durability indicators, especially for marine and sulfate environments. In addition, incomplete life-cycle assessment (LCA) datasets limit the accuracy of CO_2-reduction estimations. As the analysis is based entirely on published data, extreme or atypical results could not be independently verified.

Future directions. Progress in this field will require harmonized testing procedures, unified durability metrics, and comprehensive LCA reporting across studies. The development of hybrid AI frameworks capable of linking semantic descriptors, mixture parameters, and durability outcomes presents a promising path for predictive and optimization-oriented mix-design. Strengthening these aspects will support the emergence of reliable, scalable, and low-carbon cementitious materials suitable for next-generation structural and environmental challenges.

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