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Review

Is Sustainability Really Sustainable? A Critical Review

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Abstract

In recent years, the research and development of sustainable materials have seen a growing interest. The driving force behind this is environmental policies that aim towards a transition to a circular economy. There are numerous investigations into the potential use of waste and/or by-products in building materials and components. Using such materials, called "secondary raw materials", is to be favored due to their low environmental impact. Although research is numerous, most studies are limited to a purely performance assessment. There are still a few studies that also address environmental (or sometimes economic) aspects. Lacking such considerations, is it possible to say that the industrial product of research is truly sustainable? Is it enough to use secondary raw materials to define a product with a low environmental impact? By critically reviewing publications on this topic, this paper aims to highlight possible new developments for future research. Including environmental assessments among the criteria for evaluating the impact of research would provide a vision that is not limited only to the performance profile but can capture aspects that are currently underestimated. Overcoming this limitation would make it possible to obtain products capable of responding to the demands of sustainability regulations, avoiding the strategy of greenwashing.

Keywords: sustainable materials; environmental impact; by-product; secondary raw materials

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1. Introduction

It is now widely recognized that the current production system is decidedly unsustainable. In particular, the construction sector is one of the most polluting industries. A report compiled by the Global Alliance for Building and Construction, presented at COP25 in Madrid [1], revealed that the construction sector is responsible for

- 38% of the amount of global carbon dioxide dispersed into the air;
- 35% of global energy consumption;
- 50% of raw materials extracted;
- 1/3 of global consumption of drinking water.

In addition, it produces a huge amount of waste of various kinds every year, the treatment and disposal of which generates, among other effects, a considerable waste of energy that is expected to increase by 70% by 2050 [2].

It is possible to mitigate the effects and risks of global warming by improving the energy efficiency of existing buildings and promoting and incentivizing the use of low-environmental-impact, natural, and recyclable materials.

Numerous studies [3,4] state that the operational phase of buildings is responsible for a significant percentage of life cycle environmental impacts, such as the use of energy

for maintaining indoor comfort or water consumption, which in traditional buildings can account for 60% to 90% of the Cumulative Energy Demand. The remaining consumption or emissions, excluding the end-of-life scenario of the building, are linked to indirect energy use, i.e., the energy associated with the production of the materials used in construction [5].

Alongside energy-saving regulations [6–8], there is a growing number of directives promoting a change in current production systems, with an aim toward sustainable development. In order to implement this change, economic, social, and environmental aspects must be taken into account [9,10].

One of the strategies followed in recent years has been the use of low environmental impact materials and the promotion of waste recycling. The use of processing waste is preferred, as it requires low energy input during the production and processing phases, with a consequent reduction in consumption and related polluting emissions. The use of by-products from other production chains can also be useful in achieving sustainability goals. Furthermore, exploiting these materials would have two advantages: transforming waste material into a resource, with a consequent reduction in the amount of waste to be disposed of, and reducing the quantity of raw materials extracted [11].

This paper analyses the state of the art regarding the use of by-products in the construction sector. A review of the scientific literature shows that most research on by-products and their possible use focuses only on performance assessments. Mechanical and physical characteristics are studied, but aspects related to environmental assessments of the entire life cycle of these products are rarely explored in depth, even though they are crucial for demonstrating the real sustainability of the material under consideration. Evaluating only physical or mechanical performance, even if it leads to improvements, is not sufficient to define the sustainability of a product. To do so, it is necessary to assess the environmental impact of the product, focusing on each stage of its production. Including environmental assessments among the criteria for evaluating the impact of research would provide a vision that is not limited only to the performance profile but can capture aspects that are currently underestimated. Overcoming this limitation would make it possible to obtain products capable of responding to the demands of sustainability regulations, avoiding the strategy of greenwashing.

2. Materials and Methods

This research is based on a critical review [12] of scientific literature on the use of by-products from various production chains in the construction industry.

After identifying the relevant legislation, we analyzed publications and research evaluating the benefits of using different types of by-products in the manufacture of construction products (Figure 1).

This scientometric analysis was conducted for subsequent refinements, modifying the keywords for the selection of results in order to obtain meaningful results. We started with a generic search using the keyword “by-product”. This was then combined with the keyword “Sustainability” and with the keyword “Life Cycle Assessment”. Finally, the string “by-product AND Sustainability AND Life Cycle Assessment” was used. From the databases obtained, a further survey of the results was carried out, selecting only articles dealing with topics related to the construction sector. The aim was to assess how many studies also focused on environmental issues, in addition to performance, and how many carried out an environmental assessment of the product.

Subsequently, the critical issues that emerged from the analysis were identified. These served as a starting point for suggesting implementations in the search for new products with low environmental impact.

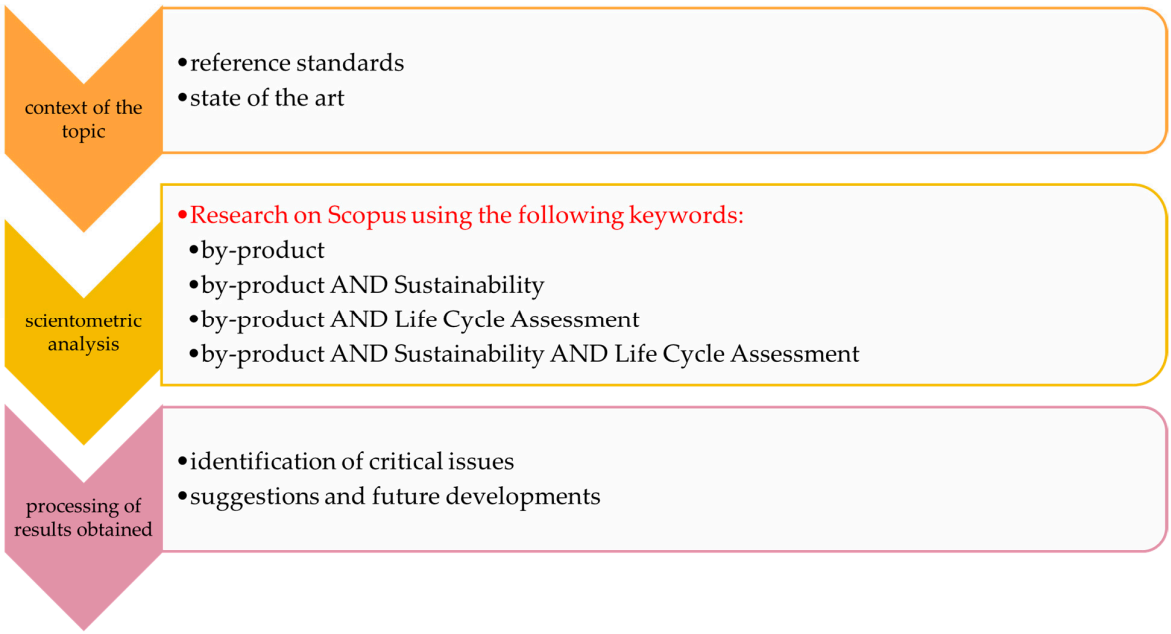

Figure 1. Methodology.

3. State of the Art

To mitigate the effects of climate change, research and development must be implemented in green materials and processes capable of combining innovation with the concepts promoted by the circular economy [13,14] and environmental policies [15]. The economic system, subject to innovative pressures, is evolving towards a circular approach that is not limited to energy efficiency alone but intervenes in a more systemic manner right from the design stage in order to reduce the use of resources and minimize waste production. It is therefore highly necessary to develop materials that are more environmentally friendly but, at the same time, capable of improving building performance.

The green economy, whose initial impetus came from the spread of renewable energy sources and energy efficiency, has also grown in recent years in the sectors of eco-friendly technologies and recycled materials. The reasons for this lie in the spread of stricter sustainability rules but also in greater awareness on the part of both users and producers.

In this transformation process, companies that produce materials and components for the building industry play a decisive role by innovating their range of construction products. The demand for these products, which combine low environmental impact and high performance, also comes from the building products market. This is an important sign of a paradigm shift: Companies are promoting change rather than just passively accepting it.

Giorgi [16] identifies three levels of circular economy applied to the construction sector: the macro level, concerning the scale of cities and urban agglomerations; the meso level, concerning the scale of buildings; and the micro level, focusing on the size of materials.

The micro level is mainly related to the scale of products and, in particular, to the management of resources and waste during production processes. Currently, research in this area is focusing on the composition of certain construction products, with an aim to replace virgin components, consisting of raw materials, with recycled components, such as secondary raw materials, scrap, or waste, including from other sectors.

By-products can be defined as "a substance or object resulting from a production process whose primary purpose is not the production of that article" [17].

Any substance generated by a production process that is not considered waste and could have a second life because it is not harmful to health or the environment is therefore classified as a by-product.

Italian legislation includes several decrees on this subject. Among the most important are the following:

- Decree No. 264 of 13 October 2016: regulation laying down indicative criteria to facilitate the demonstration of the requirements for the classification of production residues as by-products and not as waste, in which Article 2 provides definitions of product, production residue, and by-product [18]. In particular, a product is any material or substance that is deliberately obtained as part of a production process or as a result of a technical choice; production residue is any material or substance that is not deliberately produced in a production process and may or may not be waste; a by-product is a production residue that is not waste.
- Legislative Decree No. 152 of 2006, Article 184-bis, paragraph 1, specifies the requirements that a production process residue must meet in order to be considered a by-product rather than waste: "(a) 'the substance or object originates from a production process, of which it is an integral part and whose primary purpose is not the production of that substance or object'; (b) 'it is certain that the substance or object will be used in the same or a subsequent production or utilization process by the producer or a third party'; (c) 'the substance or object can be used directly without any further processing beyond normal industrial practice'; (d) 'the further use is legal, i.e., the substance or object meets, for the specific use, all relevant requirements relating to products and the protection of health and the environment and will not lead to overall adverse effects on the environment or human health' [19]".

The Decree does not contain either a list of materials that can undoubtedly be classified as by-products or a list of treatments permitted on them, as the assessment of compliance with the criteria indicated must in any case be left to a case-by-case analysis, as also specified in Article 1, paragraph 2, of Decree No. 264 of 13 October 2016.

There is extensive research into the potential use of carbon-neutral waste and/or by-products in construction materials and components. The use of secondary raw materials is to be preferred due to their low environmental impact. One possible use for by-products of various kinds and from various production chains is in the formulation of premixes.

A search in the Scopus database using the keyword "by-product" yields 5566 results, limiting the search to the field of engineering. Of these, only the first 250 results were analyzed in order of relevance. The number 250 was chosen in order to have a sample comparable to the results obtained from subsequent searches using the keywords sustainability and life cycle analysis. These 250 were further refined by reading, selecting only those relevant to the construction sector. Specifically, only 31 refer to the construction sector (Figure 2).

They were then classified and summarized in Figure 3 based on the origin of the by-products used in the categories "Agriculture," "Industry," and "Waste."

It is worth noting that most of the results focus on the use of industrial waste. The reason for this phenomenon could lie in the large volumes of waste produced by companies and their consistency due to production that is not affected by seasonality, as is the case with agriculture. Table 1 provides a summary of the studies reported in this section, which will be discussed in detail in the following sub-sections.

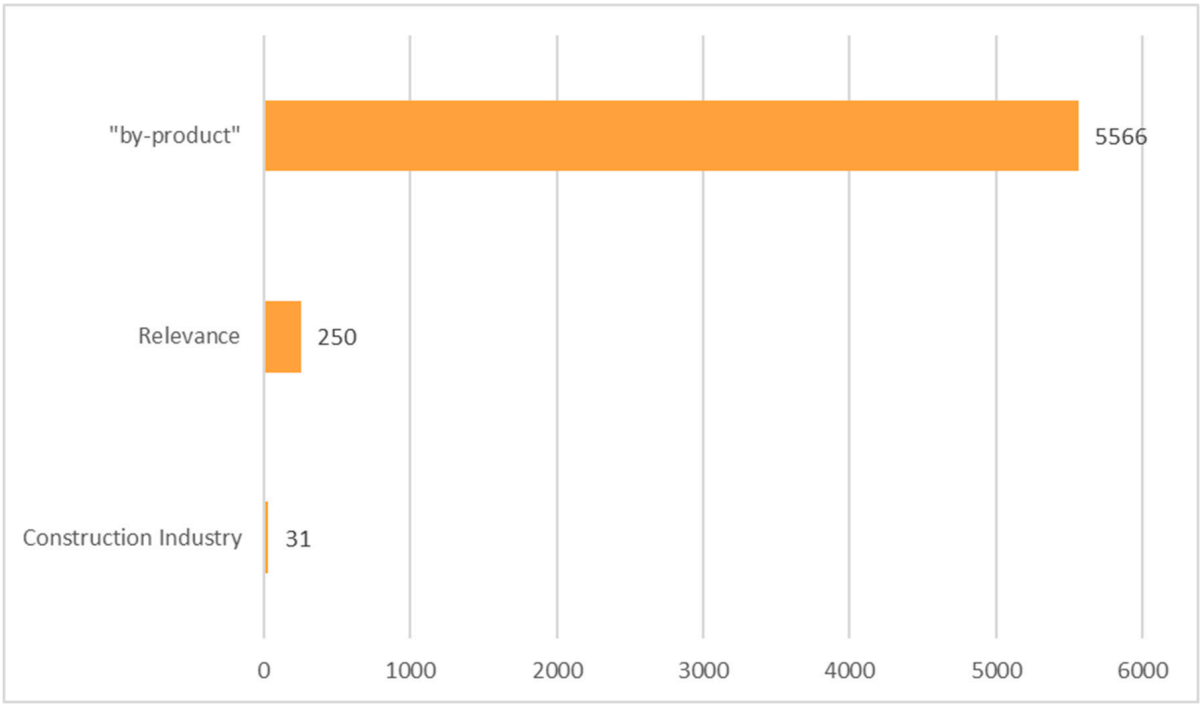

Figure 2. Schematic representation of the results obtained.

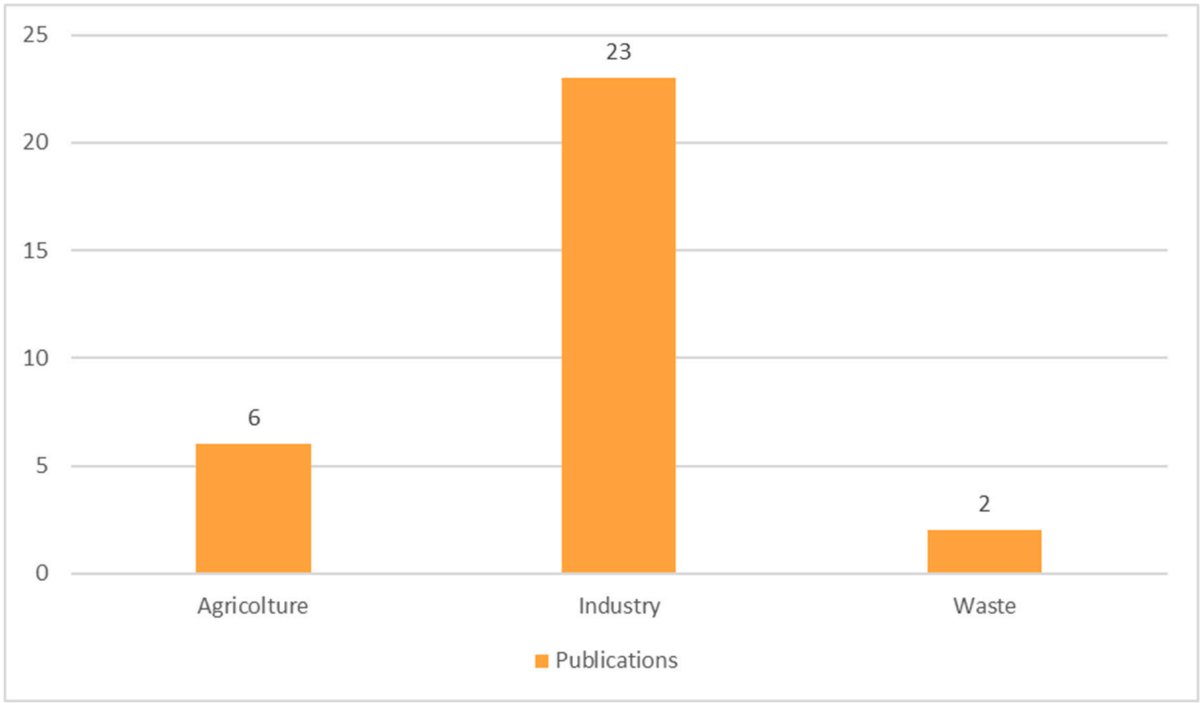

Figure 3. Classification of publications.

Table 1. Summary sheet of the studies reported in the "state of the art" session.

Authors	By-Product	Objective	Product	Results
Saeli et al. [20]	Spent coffee grounds	Demonstrate a possible alternative reuse of ground coffee waste in new eco-friendly building materials for thermal plaster applications in construction	Biocomposite mortars	Decrease in apparent density, decrease in mechanical properties, and decrease in thermal conductivity
Pintea et al. [21]	Casein, eggs, and rice gelatin	Evaluate the influence of organic polymers on the workability of fresh mortars	Mortar	Increased workability
Vitale et al. [22,23]	Citrus fruit paste	Evaluate the use of agricultural by-products for the production of thermal insulation products for building envelopes	Insulating panels	Good thermal insulation
Liuzzi et al. [24]	Leaves and twigs from pruning olive trees	Using agricultural waste materials in a mixture of clay and sand to obtain a bio-based plaster to study its hygrothermal behavior	Clay plasters	Linear reduction in density and an increase in porosity, reduction in thermal conductivity, and good capacity to exchange moisture with the surrounding environment
Schackow et al. [25]	Fired clay brick waste	Study of the effect on the durability of mortars with partial replacement (10, 25, and 40% by weight) of Portland cement with CBW	Mortar	Improved strength and density
Kumar et al. [26]	Marble processing waste	Examine the experimental results of self-compacting concrete (SCC) with marble waste as a partial replacement for fine aggregates and polypropylene fibers as an additive material	Self-compacting concrete	Increased resistance to bending and compression
Vaclavik et al. [27]	Ladle slag	Determine the optimal proportion of treated ladle slag additive and evaluate the environmental properties of the resulting cement composites	Concrete	Better workability of fresh cement paste, extended setting times, and increased water absorption of cement composites

Table 1. *Cont.*

Authors	By-Product	Objective	Product	Results
Bayat et al. [28]	Blast furnace slag and natural zeolite	Verify the possibility of using industrial and natural supplementary cementitious materials (SCM) in self-compacting concrete	Self-compacting concrete	Better water impermeability, electrical resistivity, and resistance to chloride migration
Vembu et al. [29]	Magnesite mine waste	Evaluate the suitability of using magnesite mining waste in self-compacting concrete (SCC) as a substitute for binders and aggregates, assessing fresh and hardened properties	Self-compacting concrete	Increased compressive strength
Da Silva et al. [30]	Two types of PET aggregates, PP and PF aggregates (which stand for plastic pellets and plastic flakes)	Study the effects of incorporating plastic waste into mortars	Mortar	Decrease in elasticity modulus, increase in impact resistance, and gain in water vapor permeability, preventing moisture condensation
Pedreño-Rojas et al. [31]	Biomass waste ash	Exploring the potential of using biomass ash waste as a secondary raw material for building composites	Gypsum-based composites (slabs)	Improvement of the building's energy efficiency

3.1. Agricultural Sector

When analyzing the agri-food supply chain, one of the most studied wastes is coffee powder, with applications ranging from its use in premixes to the construction of entire buildings. The study conducted by Saeli et al. [20] focused on the use of coffee waste, with percentages of up to 17.5%, to evaluate the engineering performance of the biocomposite mortars produced. The results show that a small amount of coffee waste can determine

- A decrease of up to 15.4% in apparent density (making the products comparable to a lightweight structural aggregate or lightweight plaster mortar);
- A sharp drop in mechanical performance (while still maintaining acceptable values for the plastering application considered) and in thermal conductivity (up to 47%).

The study was not limited to investigating physical performance alone but was implemented with a multi-criteria analysis, also considering aspects related to environmental and economic impact, with the result that the mix with the best results is that containing 10% waste.

Moving up the building ladder, the start-up Woodpecker, based in Bogota, Colombia, uses coffee husks to produce lightweight prefabricated buildings for residential and educational use. By combining coffee husks with recycled plastic, it is possible to create a more durable and environmentally friendly material [32]. This special composite wood-plastic material has some very interesting performance characteristics: It is self-extinguishing, pest-resistant, and moisture-resistant, making it a safe alternative for low-income housing. The system consists of standardized plastic parts that snap into a steel frame for easy installation.

The use of waste from coffee plantations not only reduces landfill but also allows for rapid construction that can be carried out by non-professional laborers.

Numerous studies have investigated the use of casein in premix formulations. Among these, an interesting study was conducted by Pintea et al. [21] on the influence of natural organic polymers on the workability of fresh mortar. In this study, the natural organic polymers used were casein, eggs, and rice, used in the form of gelatin. The addition of the three polymers resulted in an increase in workability of at least 30–45 min. Specifically, the addition of casein to plaster mortar increases workability by up to over an hour.

The use of casein has not been limited to experimental applications but has also entered the commercial market. Notable examples include the Harobau company, based in Laghetti, near Bolzano, Italy, which produces a 100% natural plaster with high dehumidifying, breathable, and waterproofing properties [33,34]. It is not the only company that has invested in the use of casein in its products. The start-up Milk Brick recovers waste milk from the dairy industry and large-scale distribution, transforming it into a new secondary raw material for use in the production of zero water impact concrete products for the construction industry [35].

Continuing the investigation, we find applications centered on citrus processing waste. Its use ranges from interior design [36] to paper [37], cosmetics [38], and leather [39]. The project developed by Vitale et al. [22,23] involved the creation of self-supporting panels obtained from the processing of orange processing waste, known as pastazzo. This mixture, composed of the outer part of the peel, the white inner part, and the seeds and pulp residues left over after the citrus fruit has been squeezed, has excellent properties that are necessary for the panel. Due to its intrinsic characteristics, the product is able to "self-bond" without the addition of chemical additives, which are often polluting or hazardous to health. In addition, the panel has excellent thermal insulation properties, in line with building products currently on the market and, in some cases, being even better. Its good properties allow it to be used in construction as a thermal and acoustic insulation panel for the external walls of buildings. Aesthetically, the panel is similar to cork, making it suitable for use as wall cladding or ceiling panels, as well as in the furniture and design sectors. The project is a concrete example of the circular economy, using a resource that is widely available in Sicily (Italy).

Remaining on the subject of waste from the agri-food chain, the study by Liuzzi et al. [24] analyzes the properties of clay plasters in which leaves and twigs from olive tree pruning have been incorporated. Soil samples with different percentages of olive fibers were prepared and tested to investigate their hygrothermal behavior. The results show that the addition of olive fibers to the soil matrix led to a linear reduction in density and an increase in porosity. This leads to a reduction in thermal conductivity and therefore a more insulating behavior of the material. The experimental tests also made it possible to characterize the hygrometric properties of the materials, which are in agreement with those of other bio-based plasters of similar density. The addition of olive fibers does not produce significant differences in the absorption curves up to 80% relative humidity. Increasing this value beyond 80%, the absorbed moisture content increased, especially for samples with a higher fiber content (C08, C012). The results in terms of ideal moisture absorption value show that all mixtures allow for a plaster with good moisture exchange capacity with the surrounding environment, ensuring good indoor air quality and greater comfort for occupants.

3.2. Industrial Sector

Moving on to the industrial sector, there are even more examples. The study conducted by Schackow et al. [25] analyzes the influence of adding fired clay brick waste to mortars on

their durability. The idea came from the similarity between the characteristics of metakaolin, whose properties are already well known, and powdered fired clay brick waste (CBW). The powder was added as a partial replacement for Portland cement at percentages of 10, 25, and 40%. Hardened mortars containing CBW showed improved strength and density as a result of pore filling. Mortar without CBW, which was more porous, showed greater diffusion and greater resistance to sulfates and chloride absorption capacity. The optimal performance was found for mortar with 40% by weight CBW, whose compressive strength can be up to 130% higher than that of mortar without CBW. The properties studied suggest that a moderate addition of CBW (up to 10% by weight) is desirable to achieve comparable workability. Higher percentages require additional measures to control the workability of fresh mortars, achieving a level comparable to that of CBW-free mortar.

Other studies focus on the use of marble processing waste as a partial replacement for fine aggregates. This is the case of Kumar et al. [26], who examine its use, together with polypropylene fibers as an additive, in self-compacting concrete. Upon analyzing three mixtures, with a replacement of 20%, 30%, and 40% in natural fine aggregates and polypropylene fiber with a constant ratio of 0.4%, an increase in flexural and tensile strength was observed compared to the conventional mixture. Furthermore,

- Compressive strength increased with the replacement of 20% of marble waste and then decreased after several mixtures. Furthermore, compared to the control mixture, the compressive strength values of other portions of the mixture increased and became acceptable.
- Generally, fiber content increases the flexural and tensile strength of concrete. Compared to the control mixture, the test values of all other mixtures increased.
- Marble waste replaced up to 40% showed acceptable results for fresh concrete and also showed an increase in flexural and tensile strength. Therefore, replacing the fine aggregate with 40% marble waste together with the fiber additive is considered an optimal percentage.

A particular type of by-product that has been the subject of numerous studies is ladle slag [40–42]. Research conducted by Vaclavik et al. [27] investigated its use as a substitute for cement in the manufacture of cement products. The aim of the research was to determine the optimum proportion of additive based on the treated ladle slag and to evaluate the environmental properties of the resulting cement composites. Treated ladle slag, as a mixture, was examined together with four types of cement (CEM I, CEM II, CEM III, and CEM V). The results of the research revealed that the incorporation of coarse slag improved the workability of fresh cement paste in all the formulations tested. Furthermore, the use of treated ladle slag as a mixture in the cement paste (replacing cement) extends the setting times of all the designed recipes and slightly increases the water absorption of the cement composites, especially in the case of fine slag.

Bayat et al. [28] investigated the use of blast furnace slag and natural zeolite for the production of self-compacting concrete. The aim was to verify the possibility of using industrial and natural supplementary cementitious materials in self-compacting concrete with low embedded carbon content. Binary and ternary mixtures of ground granulated blast furnace slag (GGBFS) and natural zeolite (NZ) were used at higher replacement intervals up to 50% by weight of Portland cement (PC). The use of GGBFS and NZ has a positive synergistic effect, resulting in improved water impermeability, electrical resistivity, and chloride migration resistance compared to binary mixtures of GGBFS + PC or NZ + PC.

3.3. Waste

A “green” self-compacting concrete was also the subject of attention by Vembu et al. [29], who focused on analyzing the effects of using magnesite mine waste instead

of cement (binary and ternary mixtures) and also as aggregates (fine and coarse) in self-compacting concrete (SCC). By evaluating the fresh properties and compressive strength, an increase in compressive strength was observed due to the irregular angular shape of the coarse mine waste aggregates, which creates internal friction and bonding between the aggregates. The density of SCC with binary and ternary mixed cement decreased slightly when mining waste was added. Conversely, the density increased slightly when mining waste was replaced with aggregates.

Plastics are used in the study by Da Silva et al. [30], which considers plastic waste to study the effects of its incorporation into mortars. The results of tests conducted on three mixtures with three replacement ratios, by volume, of natural aggregate (5%, 10%, and 15%) with plastic are reported. The waste examined was two types of PET aggregates, PP and PF aggregates (which stand for plastic pellets and plastic flakes). The results show that, although the incorporation of plastic aggregates led to poorer performance in some properties, such as bulk density and compressive and flexural strength, in others, the modified mortars showed significantly better performance than the control mortar (without plastic).

The improved performance highlighted concerns about the decrease in the elastic modulus and the increase in impact resistance, leading to a more deformable mortar with a greater capacity to absorb impact energy. In addition, the impact resistance test also showed a reduction in crack width as the replacement ratio increased.

The results obtained from the dimensional stability test show a decrease in shrinkage as the plastic ratio increases. Lower shrinkage results may allow for a reduction in cracks associated with dimensional variations.

In terms of water absorption, modified mortars perform worse than conventional mortars. The difference in the shape of PET aggregates causes variations in porosity and therefore an increase in capillary absorption, resulting in improved water vapor permeability and preventing moisture condensation inside buildings.

The results of the current study have been quite encouraging and have paved the way for the recycling of PET waste aggregates in mortars.

Finally, among the studies that use production waste, we can mention Pedreño-Rojas et al. [31], who explored the potential use of biomass ash waste generated by a thermoelectric power plant as a secondary raw material for building composites. The study examines the physical and mechanical properties of gypsum-based composites containing different proportions of biomass ash waste, comparing them with reference and regulatory documents. Based on preliminary test results, the best composite was the sample containing 25% waste. Gypsum boards were made from this sample, leading to an improvement in the building's energy efficiency (up to 5%).

4. Environmental Assessment

In recent years, the use of waste from production chains other than construction has been a recurring theme in scientific studies and research. This interest is driven by various regulations [43–45] which, in order to reduce the environmental impact of the construction sector, increasingly promote the use of circular production systems. Companies are increasingly interested in conducting environmental analyses of their products in order to qualify as "green" companies. The market for high environmental quality products and services is certainly a rapidly expanding market, especially in the last decade.

In order to inform users about the environmental characteristics of products, communication tools known as environmental certifications have been standardized. These are voluntary attestations that highlight compliance with certain environmental and ethical parameters. They can refer to both the product and the process, depending on whether

the object of the verification is a management system rather than a product or service. Compliance with certain regulations is assessed by an accredited external body that verifies the application of the standard.

These labels stem from companies' desire to improve their image or optimize their processes. They are established by ISO 14020 [46], which sets out the guiding principles for the development and use of environmental labels and declarations. They are divided into

- Type I environmental labels—ISO 14024: voluntary certifications based on a multi-criteria system that considers the entire product life cycle, subject to external authentication by an independent body. These include, for example, the European ECOLABEL ecological quality mark. They are regulated by UNI EN ISO 14024:2018 [47], which establishes the principles and procedures for the development of labeling programs.
- Type II environmental self-declarations—ISO 14021: labels bearing environmental self-declarations by manufacturers, importers, or distributors of products, without the involvement of an independent certification body (including: "Recyclable," "Compostable," etc.). The UNI EN ISO 14021:2016 standard [48] specifies the requirements, including declarations, symbols, and graphics relating to products. It also describes specific assessment, specific evaluation, and verification methods for the claims selected in this international standard.
- ISO Type III Environmental Product Declarations—ISO 14025: These contain statements based on established parameters and quantify the environmental impacts associated with the product's life cycle, calculated through an LCA assessment. They are independently verified and presented in a clear and comparable format. These include, for example, "Environmental Product Declarations." The UNI EN ISO 14025:2010 [49] standard establishes the principles and specifies the procedures for the development of Type III environmental declarations and corresponding programs. It also establishes the principles relating to the use of environmental information in addition to those provided by UNI EN ISO 14020.

Life cycle assessment (LCA) is a structured and internationally standardized method, defined by ISO 14040:2021 and ISO 14044:2021 [50,51], which allows the quantification of the potential impacts on the environment and human health associated with a good or service, starting from its resource consumption and emissions. In its traditional conception, it considers the entire life cycle of the system under analysis, from the acquisition of raw materials to end-of-life management, including the manufacturing, distribution, and use phases (an approach known as "cradle to grave"). It is often used as a decision-making tool to provide an effective and efficient contribution to the greater sustainability of goods and services.

Life cycle assessment is an iterative process comprising four main stages [52]:

- Definition of the objective and scope;
- Inventory analysis (LCI, Life Cycle Inventory);
- Impact assessment (LCIA, Life Cycle Impact Assessment);
- Interpretation.

The European Commission introduced the concept of LCA into sustainability policies a long time ago, with COM 302 (2003) [53], specifying that it is the best available methodology for assessing the potential environmental impacts of products. The calculation method, described in technical standards EN 15804 (construction products) [54] and EN 15978 (buildings) [55], is the specific LCA methodology for the construction sector and is referred to in the document in the award criteria relating to "Methodologies for optimizing design solutions for sustainability."

5. Discussion

Several studies support the use of by-products in the formulation of premixes as a positive contribution to the environmental footprint of the finished product, reducing the environmental impact associated with the extraction phase. They reiterate the importance of using raw materials with low environmental impact, a characteristic that can be broken down into several factors: origin, location, and subsequent transport and processing.

To further refine this review and also take environmental parameters into account, the search of the Scopus database using the keyword "by-product," which had yielded 5566 results, was repeated and refined, limiting the search to the field of engineering, using the following strings in succession:

- "By-product AND Sustainability";
- "By-product AND Life Cycle Assessment".

The string "By-product AND Sustainability" yielded 208 studies, while the string "By-product AND Life Cycle Assessment" yielded just under 78. Further research was carried out, combining all three keywords ("By-product AND Sustainability AND Life Cycle Assessment"). This led to a significantly lower number of results, 37 in total (Figure 4).

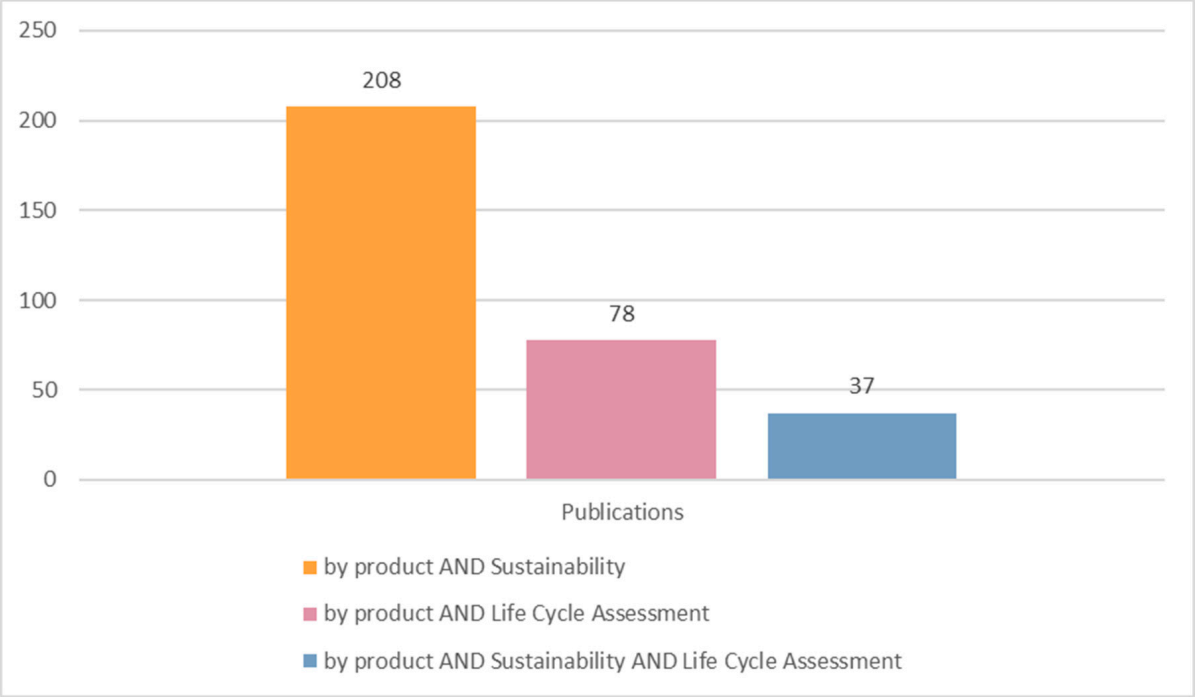

Figure 4. Classification of publications sorted by different strings.

All the results were refined by reading, selecting only studies relevant to the construction sector, arriving at 72 for the first search, 26 for the second, and only 6 for the third. They were then categorized and summarized in Figure 5 according to the origin of the by-products used in the categories "Agriculture," "Industry," and "Waste."

Analysis of the data obtained from the research carried out shows that studies on the use of by-products in the construction sector that focus on environmental performance assessment are very limited.

In particular, analysis of the database obtained shows that LCA is used in other engineering sectors but less so in the construction sector. According to Löfgren et al. [56], LCA is an important method in modern environmental management in industry. Understanding

which stages have the greatest impact is the starting point for improving the product and its production process.

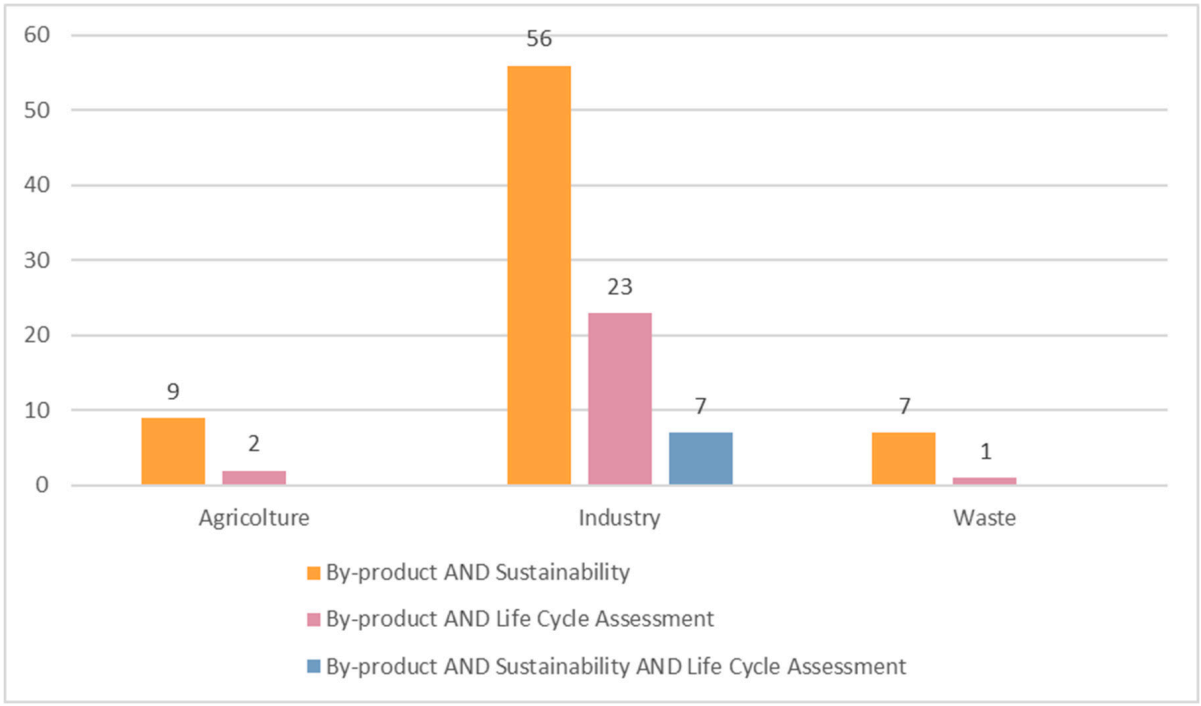

Figure 5. Histogram of refined results by keywords.

As can be seen, not all studies on building product formulations incorporating by-products are accompanied by a study on sustainability and environmental impact. In the absence of such assessments and related considerations, it is not possible to state with certainty that the environmental footprint of the product is reduced through the use of natural by-products. This is confirmed by the results of a study carried out by Carbonaro et al. [57,58], which, thanks to an LCA assessment, showed that a premixed plaster containing EPS had a lower environmental impact than other mixtures based on natural materials. This study analyzed the environmental effects of thermal plasters obtained using waste materials from local industrial and agricultural processes. The materials used were corn cobs, granular cork obtained from recycled bottle caps, and straw fiber. The mixtures analyzed were

- Cork_001: natural hydraulic lime (NHL), granular corn cobs, expanded perlite, zeolite, and additives;
- Bioart Cork: natural hydraulic lime (NHL), wheat straw granules, cork granules from bottle caps, and cellulose flakes;
- VGT_001: natural hydraulic lime (NHL), zeolite, expanded vermiculite, expanded perlite, and corn cob granules;
- VGT_014: natural hydraulic lime (NHL), Portland cement, sulfoaluminate cement, expanded perlite, corn cob granules, and wheat straw granules.

These were compared with two commercial plasters:

- Thermal plaster: natural hydraulic lime (NHL), Portland cement, EPS, and additives;
- Thermolime: natural hydraulic lime (NHL), Portland cement, expanded perlite, and additives;

used as benchmarks. At the same time, an experimental characterization of the thermal properties was carried out.

The LCA study is divided into three progressive phases: analysis of raw materials to support the formulation phase, comparison between prototypes and benchmarks, and assessment of embodied energy, also considering the effect of the installation phase. The system boundary, covering cradle-to-gate, includes all processes, from raw material extraction to transport, to production and packaging plant processes.

From the comparative study of raw materials, VGT_001 has a much higher impact than VGT_014 due to the presence of zeolite. The LCA analysis shows that the emissions related to thermal plaster with EPS, Thermolime, Bioart cork, and VGT_014 are almost comparable. The technological characteristics during application were also evaluated, comparing the quantities of each plaster required for the same surface area (1 m^2) and thickness (4 cm). This gives the "best" score to thermal plaster with a required quantity of 8.6 kg, about half that of the other plasters. An analysis of the raw material alone would have led to the exclusion of EPS from the mixture, as its optimal thermal properties and low density were not taken into account. Thanks to these characteristics, in relation to the energy incorporated, it is precisely the thermal plaster that has the lowest impact. It can be deduced that a product which, taken individually, does not have a good ecological footprint, can still achieve good environmental performance when combined with other products.

When using by-products from other supply chains, it is important to understand whether they need to be processed before they can be used in another sector. The study conducted by Pedreño-Rojas et al. [59] addressed the influence of the heating process on the reuse of gypsum waste in plasters. Gypsum, thanks to its chemical composition, which maintains its characteristics even after treatment, can be considered a completely and eternally recyclable material. Until now, most plants using gypsum waste have subjected the material to a preventive heating process, resulting in significant energy consumption and a reduction in the environmental benefits of recycling. In the first phase of the study, two different types of gypsum waste were analyzed: gypsum waste from industrial plasterboard production (GPW, gypsum waste from industrial plasterboard production) and gypsum obtained from flue gas desulfurization (FGD, Flue Gas Desulfurization Gypsum) in a central heating plant. Tests were carried out on samples containing both types of gypsum waste, heated and unheated. Since the mechanical performance of FGD-based plasters was not satisfactory, it was decided to conduct the environmental analysis only on plasters containing plasterboard waste. The categories evaluated were embodied energy and global warming potential, following the methodology described by García Martinez [60]. The data used were obtained from the Ecoinvent 3 and ITEC databases for the year 2018. The functional unit considered was the amount of raw material needed to produce 1 cubic meter of each plaster. The system boundaries included three phases: the production phase, the transport phase, and finally, the disposal phase. On the other hand, the demolition and disposal phases were neglected. The data analysis showed that the highest energy consumption corresponds to the production phase, but the transport phase also had a significant influence on the analysis. The lowest impacts were obtained for GPW100WH plaster (wt. 100% GPW Without Heating), where a 77% reduction was found compared to the reference material. In general, the energy consumption related to the production phase decreases as the content of GPW added to the mixture increases. Finally, when comparing the different heating processes, the greatest environmental impact was attributed to plaster heated for 24 h at 100 °C. Regarding global warming potential, the results show the same trend: The lowest impacts were recorded for GPW100WH plaster, with a reduction of 83% compared to the reference material. Consumption during production decreases as the amount of GPW added to the mixture increases. Again, the greatest environmental impact is that of plaster heated for 24 h at 100 °C. The LCA analysis therefore shows that

adding GPW to the mixtures reduced the environmental impact of the product, with the best results obtained for plasters containing 100% GPW without any heating process.

Finally, the study conducted by Melià et al. [61] demonstrated how the location and subsequent transport of raw materials influence the final impact of the product. Two different types of earth plaster were compared: a base plaster and a finishing plaster. In particular, two different colors were analyzed from among those available, yellow and ocher. This difference was fundamental in assessing the influence of transport: The ocher clay comes from local suppliers (based in Piedmont and northern Italy), while the yellow clay is imported from Germany. The gravel, clay, and straw used to produce the base plaster come from the same province where the manufacturing company is located (approximately 60, 14, and 24 km for the three components, respectively); the sand used for the finishing plasters comes from central Italy (approximately 550 km), while the ochre clay comes from northern Italy (approximately 250 km) and the yellow clay from Germany (approximately 530 km). The study shows that transport accounts for 67% of the energy required to produce ochre-colored finishing plaster, while in the case of yellow finishing plaster, it reaches 74%.

This shows that distance is an important factor to consider, as long distances between suppliers of by-products and the companies that will use them cancel out the beneficial effect of using secondary raw materials.

6. Conclusions

This study examined the scientific literature on the use of products in line with the principles of sustainability and the circular economy. In particular, attention was focused on the use of by-products from different production chains in the construction sector and on the assessment of their environmental impact. A search of the Scopus database using the keyword “by-product” and limiting the search to the engineering sector identified more than 5000 studies. The search was then refined by adding the keyword “sustainability” to “by-product”, yielding approximately 210 results, and finally by using the string “by-product AND life cycle assessment”, which identified just under 80 publications. It is clear that the number of studies analyzing environmental aspects is very limited, despite widespread research in the field. In order to estimate the real degree of sustainability of a building product that also incorporates by-products or secondary raw materials among its components, it is therefore desirable to also focus on environmental assessments.

As shown in Figure 6, the ideal development of a new product should be based on the evaluation of the by-product to be incorporated and the characterization of the product in terms of performance. These two evaluations will converge and constitute the overall evaluation of the product. Only if both evaluations meet the necessary requirements can the research be considered complete. Otherwise, it will be necessary to repeat one of the two initial steps: change the by-product or modify the formulations adopted. The same evaluation system should also be adopted by certification bodies, thus extending certification to the entire process.

A building product, even if developed through innovative research and with attention to environmental needs, can only be defined as truly eco-sustainable if we do not stop at quantifying the benefits that can be obtained from its use during the operational phase, which almost always concerns the evaluation of physical and/or mechanical performance. A more comprehensive assessment is needed, covering its entire life cycle. Evaluating only physical or mechanical performance, even if it leads to improvements, is not sufficient to define the sustainability of a product. To do so, it is necessary to assess the environmental impact of the product, focusing on each stage of its production. Considering the different stages, from the procurement of raw materials to the disposal of manufactured products, would lead to a methodological approach capable of providing real data on

the eco-compatibility of the product. As seen from the examples given in this paper, it is not enough to replace any raw material with a by-product or secondary raw material in order to be certain of environmental benefits. It is important to consider aspects that are sometimes considered secondary, such as transport and/or any processing required before its possible use. The impact of these stages can undermine the benefits of using a by-product or secondary raw material, even if it comes from other production sectors. From this point of view, for example, promoting the use of locally available resources is certainly one of the measures that can be taken to reduce transport-related emissions.

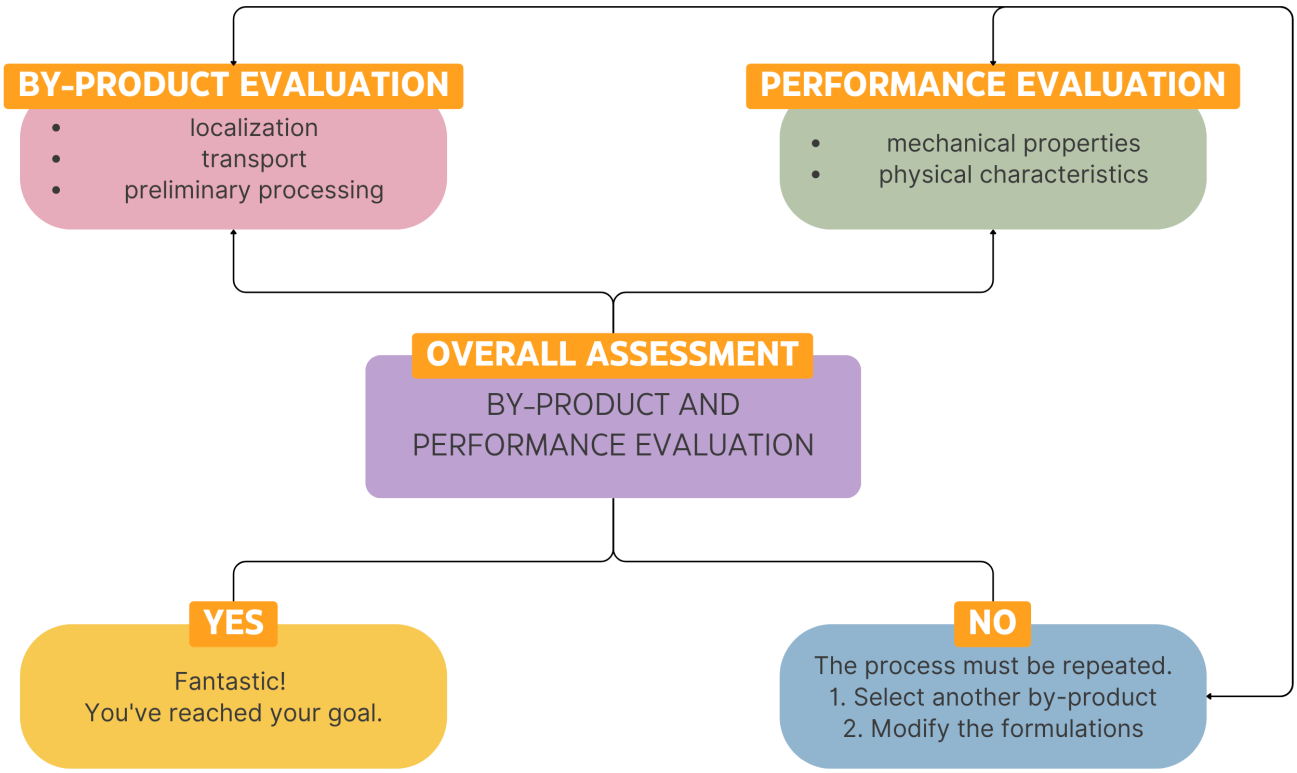

Figure 6. Diagram of the proposed methodology.

Only through an assessment covering the entire life cycle of an alternative building material to those commonly used (which, for example, incorporates by-products or secondary raw materials) will it be possible to obtain a comprehensive view of the impacts generated by the entire system, obtain an effective assessment of its sustainability, and limit the strategy of greenwashing.

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