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Review

An Update on the Waste Management of the Amazonian Açaí Berry for the Civil Engineering Sector

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Abstract: The rising demand for açaí berries in Amazonian Brazil and French Guiana generates a significant amount of waste, namely the fruit's stone, which accounts for 80% of the dry fruit's mass. Recently, various studies have explored the potential valorization of açaí waste in the civil engineering sector, including the functionalization of the fibers surrounding the stone and the multiphysics testing of composite materials based on açaí fibers and/or stones, treated or untreated. This literature review aims to provide an overview of the technology readiness levels (TRLs) of the existing techniques capable of reducing the environmental impact of both the cultivation and management of naturally occurring açaí. While the research to date is promising, it remains at the prototype stage, and the mass ratio of waste in composites, regardless of their type, limits addressing the underlying ecological problem of açaí waste processing. Further experimental investigations are required to improve the functionalization processes, enabling the use of higher proportions of fibers and/or stones in cementitious composites and their large-scale production.

Keywords: açaí; waste management; valorization; civil engineering



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1. Introduction

The açaí berry is an endemic fruit of the Amazon rainforest, harvested from the *Euterpe oleracea* palm tree. It is considered the “black gold” of the Amazon due to its significant economic impact (production value in 2021: BRL 5.3 billion, according to the IBGE) [1], with consumption growing substantially in Brazil since the 1990s. According to Nobre [2], the annual production of açaí pulp makes a substantial contribution to the economy of Amazonian Brazil, second only to beef and tropical timber. Açaí is primarily consumed in the form of pulp and juice (see Figure 1), and its popularity is attributed to its strong antioxidant and nutritional properties, which have been widely reported [3,4]. The fruit is abundantly found in Pará and Amapá in northern Brazil, as well as in neighboring French Guiana, where it is known as wassaí, and in the lower Oyapock river basin, on the border between Brazil and French Guiana. The fruit is spherical in shape, has a diameter ranging from 12 to 16 mm (see Figure 1), and weighs between 1.5 and 3 g.

The pericarp, which constitutes the açaí pulp, is quite thin, typically measuring between 1 and 5 mm [5]. During the process of extracting the pulp, waste products, such as seeds and surrounding fibers, are generated. The dimensions of these fibers are approximately 21.2 ± 7.5 mm in length and 0.12 ± 0.03 mm in diameter [6]. The literature

reports different values for the morphology of these fibers. For instance, treated fibers were found to have a length of $1288 \pm 516 \mu\text{m}$ and a diameter of $32.7 \pm 9.0 \mu\text{m}$ [7], while untreated fibers were found to have a diameter of $164.19 \pm 52.07 \mu\text{m}$ [8]. The percentage of seed mass varies between 74.6 and 80.9%, while the percentage of fiber surrounding the seed is approximately 5.3%, depending on whether the fruit is fresh or dry [9]. Figure 2 presents the morphology of the açai seed.

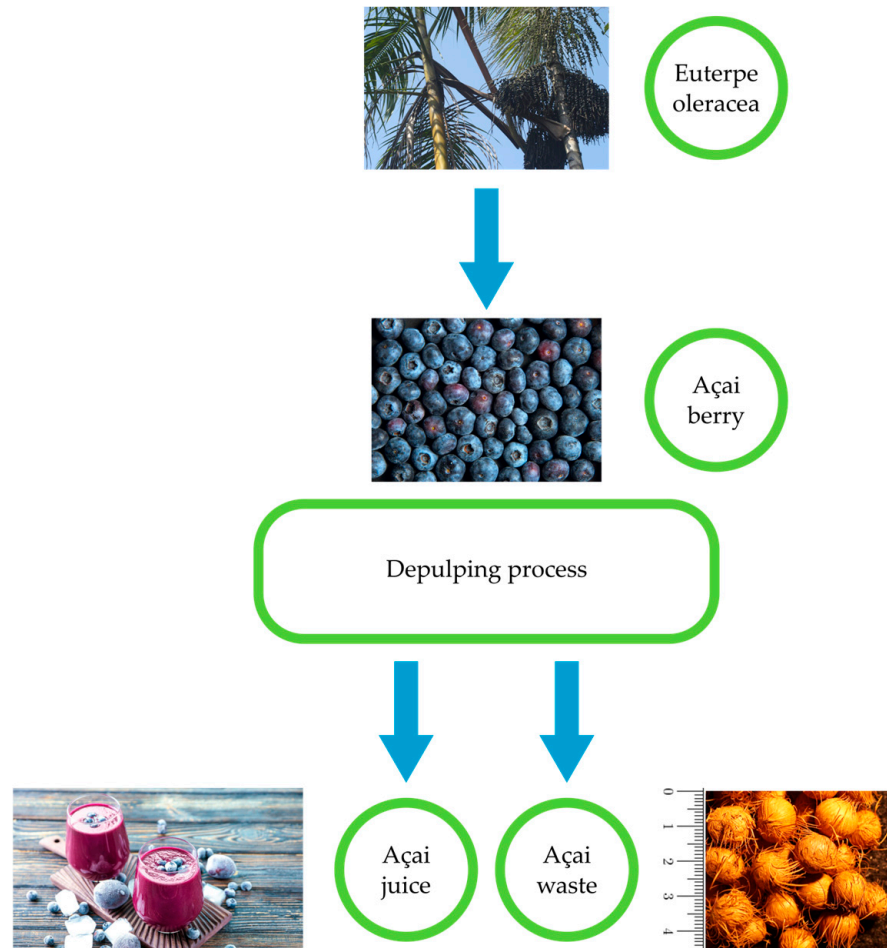


Figure 1. Post-harvest process in açai berries consumption.



Figure 2. Açai seed morphology.

The Brazilian Institute of Geography and Statistics (IBGE) has estimated that in 2021, approximately 1.49 million tons of açai were produced in Brazil, accounting for 85% of solid waste [1]. With the açai berry market projected to grow annually by 12.6% during the forecast period, 2022–2027 [10], waste volumes are expected to increase proportionally. However, it should be noted that these estimates do not account for quantities consumed on-site, so the actual volume of waste generated may be much higher than reported. In French Guiana, there is a lack of production data and economic impact analysis on this sector, which can be used for both domestic and commercial purposes. Nevertheless, French Guiana is making efforts to industrialize this sector, with the funding and opening of its first wassai processing unit (Yana Wassai®) in 2021 near Cayenne. Industrial processing and artisanal production of açai pulp generate significant waste volumes, of which only a small fraction is utilized [11]. Considering the annual production of açai and the proportion of the seed to the whole fruit, it is estimated that more than 1,000,000 metric tons of seeds are deposited in the Amazon region every year [12]. Açai residues, which are usually not fully depulped, are either collected in controlled landfills or left in large, unregulated deposits in the public spaces of urban areas, causing environmental damage and polluting land and water [13]. The main reason for this is that only a few Brazilian producers bear the cost of transporting waste to appropriate locations [14]. Most producers are unaware of municipal waste management plans and the opportunities for reusing these residues [15]. Therefore, it is imperative to establish an efficient value chain for açai waste to address socio-environmental concerns [16]. However, to date, there are no published statistics or institutional reports on the percentage of açai waste converted into value-added products or processes. It should also be mentioned that the recognition of açai as a superfood in the 2000s is threatening the rainforest's biodiversity due to single-crop açai fields [17].

The reuse of açai seeds is an organic approach for valorizing biomass and encouraging the public policies of circular economy, which reduces the human impact on the production chain processes. Yet, overall, the bioconversion of this waste has remained marginal. Five potential value chains for treating açai waste have been identified, namely Amazon açai seed crafts, soil fertilizer, energy production, the healthcare market, and civil engineering, as shown in Figure 3.

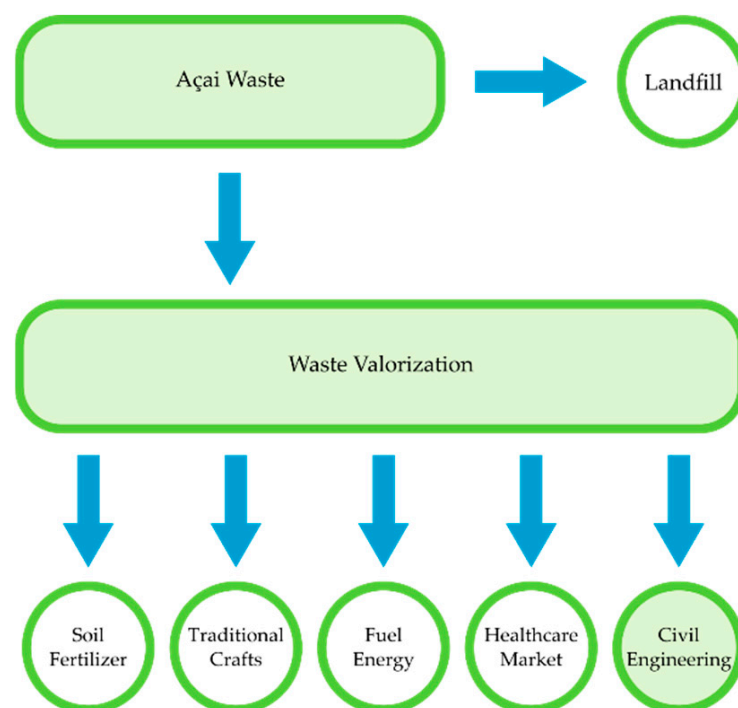


Figure 3. Main valorization schemes of açai wastes.

This analysis focuses on the literature studies reporting the utilization of açai waste, particularly in civil engineering in its broadest sense, encompassing the construction and public works sectors and associated equipment. Many initiatives focusing on waste valorization in the construction sector have been investigated [18]. In Brazil, this industrial sector accounts for approximately 75% of all extracted resources, and in France, it represents over 40% of final energy demand [19]. The valorization of açai waste in civil engineering can address two distinct, yet interrelated, concerns of the Brazilian and French government policies regarding eco-efficiency based on the circular economy concept. This will comply with Brazilian Law No. 12305, 2010, which established the National Policy on Solid Waste (PNRS), a policy that has hardly been applied to waste reduction through valorization to date [20]. Additionally, it will also satisfy the requirements of the French Ministry of Ecological Transition’s environmental regulation RE2020 concerning valorization of bio-sourced materials in civil engineering, either as raw or waste materials, which could be applied in French Guiana [21]. Hence, this review aims to comprehend the research regarding the use of açai waste in sustainable civil engineering, similar to other agro-materials [22–24]. Special attention is paid to the technology readiness level (TRL) of research in the literature, representing the maturity scale of research projects, from the initial stage related to basic principles observed and reported to the final stage of production implementation [25].

2. Materials and Methods

Following guidelines for scoping reviews and the Preferred Reporting of Items for Systematic Reviews and Meta-Analyses (PRISMA) procedures [26], we devised a search strategy to identify articles pertaining to açai waste management issues in civil engineering. The literature search was conducted using the keywords and Boolean operators “açai OR açai seeds AND fiber AND waste AND construction OR building OR public works AND valorization” on reference bibliographic databases such as Scielo, Scopus, and Web of Science. Articles published in languages other than English and Portuguese were excluded, and no temporal restrictions were applied. The search returned 203 papers published up to May 2024. In the second step, we screened the literature based on a set of inclusion and exclusion criteria to identify the papers to be examined in detail. Out of the 203 papers, 8 were found to be duplicates, and another 156 articles were excluded, as they were not directly related to the purpose of this review. Additionally, 5 master’s theses from Brazilian students were excluded. In total, 26 studies, including 3 reviews [27–29], were finalized for inclusion in this study. Regarding the research articles, 17 were written in English, and 6 were in Portuguese. Although several articles refer to ongoing experimental studies, only the published results were analyzed for this review, and preliminary results were not considered. The overall research strategy is depicted in Figure 4, and the corresponding PRISMA flowchart is shown in Figure 5.

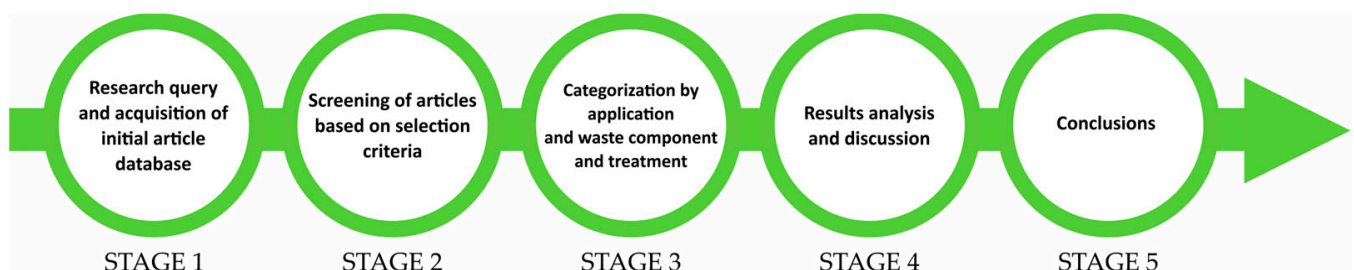


Figure 4. Global research strategy.

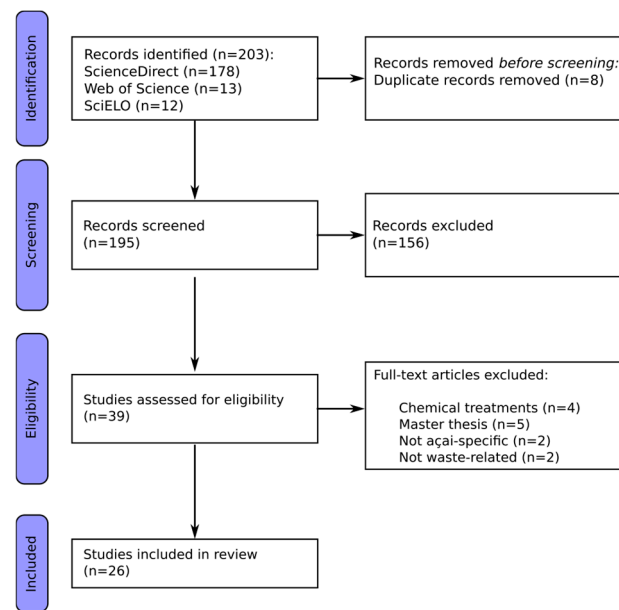


Figure 5. PRISMA flow chart; adapted from [26].

3. Results and Discussion

The included articles are listed in Table 1 and categorized by their primary outcome application. The first observation is that all of the studies originate from Brazil, with no literature mentioning French Guiana. The second observation is that the concern for valorizing açai berry waste in the civil engineering sector is relatively recent, as the oldest study in our review dates back to 2012, while most studies were published in 2018 or later. The breakdown of documents by year is summarized in Figure 6.

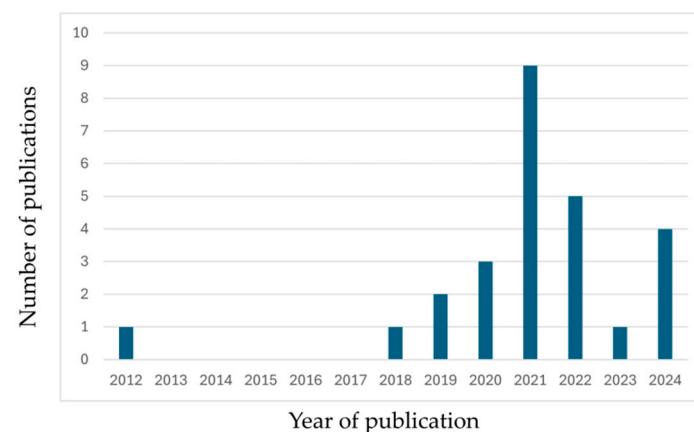


Figure 6. Breakdown of documents by year.

The initial finding indicates that there is no literature review on the utilization of wassaï (French name of açai) waste in the construction industry of French Guiana, where interest in employing plant fibers or waste in the civil engineering sector has primarily focused on the manufacturing of rice-husk particleboard [30–33]. This is primarily because wassaï consumption is not yet prevalent in Guyanese culture. As a result, the Brazilian population in French Guiana is insufficient to produce an adequate amount of waste. However, when this dietary habit is extended to French culture, establishing açai pulp production units would be a feasible option in the context of eco-efficient waste recycling, as encouraged by the French Ministry of Ecological Transition.

From the compiled data in Table 1, it is evident that interest in the responsible management of recovered açai waste in Brazil's broader civil engineering sector is recent. The

earliest publication dates back to 2012, but most developments only appeared after 2018. Almost all studies pertain to building applications, such as particleboards, facade and wall coatings, sound-absorbing panels, flooring, or structural defect repairs. Only one publication [34] refers to a public works application (pavement). It should be noted that several articles have been rejected, as they include analyses that are not necessarily intended for the construction sector, even though this sector is mentioned as a possible application [31–35]. In details, the breakdown of waste elements considered in the literature is quite evenly distributed, as seen in Figure 7. It can be seen that 42% of the published studies investigate the use of fibers, while 33% and 25% address the incorporation of ash and whole stone, respectively. Table 2 provides additional details regarding the application and outcomes as reported by the authors.

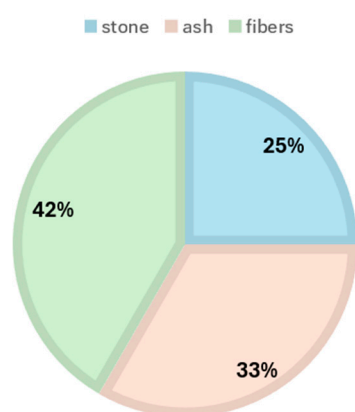


Figure 7. Breakdown of açai waste considered in the literature.

Table 1. Type of study, targeted sector, and application mentioned in the selected studies (excluding reviews).

Study	Year	Journal	Language	Type of Study	Targeted Civil Engineering Sector	Targeted Application	Technology Readiness Level
Characterization of açai waste for potential use in civil engineering (as mentioned by authors)							
[35]	2021	<i>Applied Sciences</i>	English	Experimental	Building	-	2
[36]	2019	<i>Revista Materia</i>	Portuguese	Experimental	Building	-	1
[37]	2021	<i>Engenharia de Produtos Naturais</i>	English	Experimental	Building	Particleboards	3
Preparation of cementitious composite							
[6]	2021	<i>Journal of Building Engineering</i>	English	Experimental	Building	Façade coating	2
[38]	2019	<i>Ambiente Construído</i>	Portuguese	Experimental	Building	-	4
Composite sample testing							
[39]	2012	<i>Advances in Acoustics and Vibration</i>	English	Experimental	Building	Sound-absorbing panels	4
[40]	2021	<i>Mix Sustentável</i>	English	Experimental	Building	Interior wall coating	4
[41]	2021	<i>Revista de Engenharia e Tecnologia</i>	Portuguese	Experimental	Building	-	4
[42]	2018	<i>Industrial Crops and Products</i>	English	Experimental	Building	Particleboards	4
[43]	2021	<i>Brazilian Journal of Development</i>	Portuguese	Experimental	Building	Non-structural lightweight concrete	4
[44]	2020	<i>Research, Society and Development</i>	Portuguese	Experimental	Building	Flooring, cladding	4

Table 1. Cont.

Study	Year	Journal	Language	Type of Study	Targeted Civil Engineering Sector	Targeted Application	Technology Readiness Level
[45]	2020	<i>Case Studies in Construction Materials</i>	English	Experimental	Building	-	4
[46]	2021	<i>AIMS Materials Science</i>	English	Experimental	Building	Reparation of structural defects with low load demand	4
[47]	2020	<i>Brazilian Journal of Development</i>	Portuguese	Experimental	Building	-	4
[34]	2021	<i>Desafios das Engenharias</i>	English	Experimental	Public works	Pavement	4
[48]	2021	<i>Agronomy Research</i>	English	Experimental	Building	Cladding and slabbing in rural buildings	4
[49]	2023	<i>Environmental Development</i>	English	Experimental	Building	Cement	4
[50]	2022	<i>Polymers and Polymer Composites</i>	English	Experimental	Building	Particleboards	4
[51]	2024	<i>Advances in Cement Research</i>	English	Experimental	Building	Fiberboards	4
[52]	2024	<i>Case Studies in Construction Materials</i>	English	Experimental	Building	Soil–cement bricks	4
[53]	2024	<i>Journal of Building Engineering</i>	English	Experimental	Building	Coating mortars	4
[54]	2022	<i>Sustainability</i>	English	Experimental	Building	Self-leveling mortars	4
[55]	2024	<i>Minerals, Metals and Materials Series</i>	English	Experimental	Building	Coating mortars	4

Table 2. Components of the seed, application, and outcomes of the selected studies (excluding reviews).

Study	Year	Components of the Seed	Application	Outcomes
[35]	2021	Fibers	Portland cement pastes	Reinforcement of cementitious matrix with ground fibers treated with NaOH and HCl in proportions of 5 to 10% relative to cement mass increases fiber functionalization; the composite cement with 5% fibers compares to plain cement pastes.
[36]	2019	Stone and fibers	Characterization	The density and moisture of ground açai stones and fibers make them good candidates for the elaboration of composite materials.
[39]	2012	Fibers	Panels	Panels made of açai fiber in combination with other natural fibers feature promising acoustic properties, even greater than conventional acoustic materials over certain frequency ranges.
[40]	2021	Ground stone	Composite matrix material	The obtained material has high density and may replace synthetic materials in composites.
[38]	2019	Stone ash	Concrete	Slight, but acceptable, decrease in axial compressive strength but an increase in water absorption of concrete with added açai stone ash.
[41]	2021	Stone ash	Coating mortar	Water absorption, shrinking, and durability remain acceptable for 0, 5, and 10% of stone ash proportion, but flexural strength is affected negatively.
[6]	2021	Fibers	Cement-based mortars	Açai fibers in additions of up to 3.0% relative to cement mass and properly treated with NaOH solution can be used as reinforcement mechanisms for mortar applications.
[42]	2018	Fibers	Characterization of açai fibers treated with NaOH	Açai fibers may be used as a raw material in the form of medium-density homogeneous particleboards.
[43]	2021	Stone	Non-structural lightweight concrete	Lightweight concrete with a 30/70% boiled açai stone/pebble ratio displays lighter specific mass and higher compressive strength compared to untreated stone and stone coated with stone ash.

Table 2. Cont.

Study	Year	Components of the Seed	Application	Outcomes
[44]	2020	Stone ash	Red ceramics	Açaí seed residues may be used up to 10% in mass proportion as a partial substitute in the red clay industry while retaining technological properties within the minimum standards.
[45]	2020	Fibers	Coating mortars	The durability of coating mortars containing NaOH-treated açaí fibers after wetting, drying, salt spray exposure, and thermal shock is enhanced, and the compressive strength of mortars containing 3.0% of açaí fibers is increased.
[37]	2021	Fibers	Medium-density particle boards	Açaí fibers treated with 0.5% NaOH solution are viable in the manufacturing of composites, and chemical composition is comparable with the usual values of the lignocellulosic vegetal fibers used in particleboards.
[46]	2021	Stone	Structural mortars	The compressive strength of mortars with 25% of sand mass replaced by açaí stones is decreased but remains above minimum values recommended, and the density is also decreased. However, its use should be limited to structural elements with low load demand.
[47]	2020	Stone ash	Concrete	A mass proportion of 5% of açaí stone ash results in higher carbonation resistance and enhanced workability.
[34]	2021	Fibers	Interlocked pavement concrete	Replacement proportions of 10, 1.5, and 1.0% of large and small aggregates by açaí fibers are not recommended for interlocking pavements in light and heavy vehicle traffic since they do not reach the recommended 35 MPa. However, they are suitable for sidewalks and pavements without heavy traffic.
[48]	2021	Fibers	Mortar applications in rural construction	Fibers added in the proportion of 2.5 and 5.0% relative to cement mass and treated with NaOH solution produce mortar suitable for rural construction in terms of compression strength.
[49]	2023	Stone ash	LC3 (Limestone Calcined Clay Cement)	The addition of 10% of açaí stone ash in a 45% Portland cement, 30% calcined clay, and 15% limestone mixture produces a composite that does not reach the minimum requirements in terms of compressive strength.
[54]	2022	Stone ash	Self-leveling mortar	Maintains mechanical performance (compression and bending) up to 10% Açaí seed ash in the composite while reducing GHG emissions by 8%.
[53]	2024	Calcined seeds, crushed seeds	Mortar applications	The replacement of 10% of sand by mass in mortar with calcined, ground, or paraffin-treated cores resulted in the reduction of compressive and tensile strength in all cases and negatively affected the properties of coating mortar (application not feasible).
[52]	2024	Stone ash	LC ³ (Limestone Calcined Clay Cement)	The replacement of 5, 10, 15, and 20% cement in LC ³ (representing 10% of the cementitious composite) improved soil stabilization in the composite, with no statistically significant reduction in compressive strength up to 20% ash by cement clinker mass.
[50]	2022	Stone	Polymeric composite	The coarse particle size (between 1.19 and 2.38 mm) and 10% polyurethane resin give the best results for non-structural applications such as indoor partition and ceiling applications.
[51]	2024	Fibers	Cement-bonded fiberboards	Based on the compression strength, raw açaí fibers were ranked as most suitable to produce cement-bonded fiberboards, compared to thermal- and chemical-treated fibers.
[55]	2024	Fibers	Mortars	Adding 0.5, 1.0, and 3% fiber (tannic acid-treated or untreated) by mass in relation to cement reduced the consistency index and mass density of the mortars while increasing the air content.

3.1. Açaí Fibers

Nine studies focused on açaí fibers, which are mainly used in two different applications: cement pastes and particleboards. Four studies investigated the functionalization (i.e., enhancement of the bonding capabilities) and subsequent use of the fibers. The functionalization method most frequently reported is mercerization, also known as alkaline treatment. It involves immersing natural fibers in a sodium hydroxide (NaOH) solution to enhance their mechanical and interfacial properties. This process promotes the ionization of hydroxyl groups in the fibers, converting them into alkoxides. It is widely used due to its cost-effectiveness and relatively lower environmental impact compared to other chemical treatments. However, mercerization still produces a significant amount of waste, as the

NaOH solution, which dissociates into sodium (Na⁺) and hydroxyl (OH⁻) ions, can raise the pH of aquatic ecosystems and groundwater, harm wildlife, and cause soil pollution. While sodium is an essential nutrient, the hydroxyl ions are primarily responsible for the environmental risks associated with NaOH. For example, the work by de Azevedo et al. [6] mentioned the mercerization process, which aims to improve the fibers' adhesive capacity to the composite matrix and/or enhance their mechanical performance. Azevedo et al. [35] used ground açai fibers, treated with NaOH and HCl, in proportions of 5 to 10% relative to cement mass and found that the composite cement with 5% fibers is similar to plain cement pastes. Contrary to other studies, Marvila et al. [45] incorporated fibers treated with NaOH in proportions of 0 to 5% in coating mortars, subjected to wetting and drying, as well as thermal shocks and salt spray tests. They observed a 35% increase in the compressive strength of coating mortars incorporated with 3% fibers in mass. In another study, Natalli et al. [55] added the fibers treated with tannic acid to Portland cement, with mass ratios ranging from 0.5 to 5%. On comparing the consistency index and mass density of this cement to cements without fibers and without surface treatment, they found that both these values decreased upon addition of fibers.

De Lima Mesquita et al. [42] and Mesquita et al. [37] evaluated the same mercerization process on fibers for particleboard applications, while Bastos et al. [39] obtained promising acoustic results when açai fibers were combined with other natural fibers in particleboards. De Oliveira et al. [51] found that treating short açai fibers with NaOH or NaOH-H₂O₂ improves compatibility with cement, but lowers the bending strength of cement-bonded fiberboards.

While these studies are, undoubtedly, scientifically interesting, açai fibers only account for 3–5% of the total mass of waste. Thus, the question arises about how to address the environmental problem associated with managing large amounts of waste. Additionally, the effluents from the mercerization process are not eco-friendly, and separating the fibers from the stone requires energy during extraction as well as sorting, a cost that is inconsistent with the principles of circular economy and the government's recommendations for responsible and prudent energy management. Moreover, health hazards related to the handling of small fibers should not be neglected: it is advisable to wear Personal Protective Equipment (PPE), such as masks and gloves, and ensure proper ventilation to help mitigate health risks.

3.2. Açai Stones

Açai stones have been the subject of twelve studies, which have reported their use in various forms, such as whole, ground, burnt (stone ash), or boiled. The selected studies mention their characterization [36] as well as their incorporation in cements [49], mortars [46], concrete [43], or ceramics [44]. However, the overall performance of the resulting composites, regardless of the matrix nature, remains within the acceptable standards only for limited proportions of açai stones (approximately 10%). Moreover, treating or grinding the stones does not appear to bring significant benefits in terms of the matrix-to-stone ratio or the enhancement of the composite's mechanical properties. Notably, only one study by G.P. Monteiro et al. [46] focuses on the use of açai stones in structural mortars. Yet, the study concludes that the incorporation of açai stones is only feasible for structures with low load demand, given the significant decrease in compressive strength observed in the composite mortar. It can be reasonably concluded that it is possible to use açai stone waste as a partial substitute for pebble in lightweight, non-structural concrete.

Regarding the use of açai stones in burnt form, Tino Balestra et al. [49] report that the addition of 10% of açai stone ash in a cementitious matrix produces a composite that does not reach the minimum requirements in terms of compressive strength. Similar results are stated by Cordeiro et al. [38], who report a decrease in the axial compressive strength for mass ratios of açai stone ash above 5%, and da Silva Araujo et al. [41], who observe decreased flexural strength for cement mass replacement ratios between 0 and 10%. Rocha et al. [54] focus on self-leveling mortars and conclude that replacing up to 10% of

the cement content with açai ash maintains the mechanical performance of the composite. Monteiro et al. [53] report that regardless of the composition, the composite does not match the required minimum for feasibility in coating mortars.

In the field of Limestone-Calcined Clay Cement (LC^3), Tino Balestra et al. [49] report that incorporating 10% of açai stone ash results in a significant decrease in both tensile and compressive strengths. Contrary to other studies, Garcez et al. [52] reported an increase in the mechanical properties of soil–cement bricks with partial replacement of cement clinker with açai ash. However, the addition of metakaolin may significantly affect these results and compensate for the negative effects brought by açai ash, observed in other studies.

Regarding durability, Oliveira et al. [47] reported that adding 5% of stone ash in concrete enhances its workability and durability (resistance to carbonation).

Other types of applications are also addressed, such as ceramics. Ferreira et al. [44] showed that replacing up to 10% of the ceramics mass by açai seed ash allows maintaining the technological properties within the minimum standards. However, this application stands out from those already mentioned due to its specific manufacturing process.

Assessing the success rates of different stone/fiber treatments or the comparative effectiveness of different waste assessment methods is made very difficult by the broad range of formulations in the cementitious composites. Moreover, several studies do not include mechanical performance or lack a comparison with a reference sample containing no açai component. Figure 8 provides an overview of the maximal relative compressive strength variations obtained in studies investigating biocomposites containing açai stone (treated and untreated), açai stone ash, and/or açai fibers. The first result to emerge is that almost all studies report an optimal mechanical performance for a total percentage of waste below 10% in weight. As mentioned earlier, the value appears to be quite low in view of the very large amounts of açai waste to be processed in the Amazon region. Secondly, a high variability in mechanical performance is observed, ranging from -60% to $+55\%$ compared to the reference, waste-free material. Açai stone ash (ASA) clearly appears to be the most promising valorization of açai waste, with gains in compressive performance between -5 and $+55\%$.

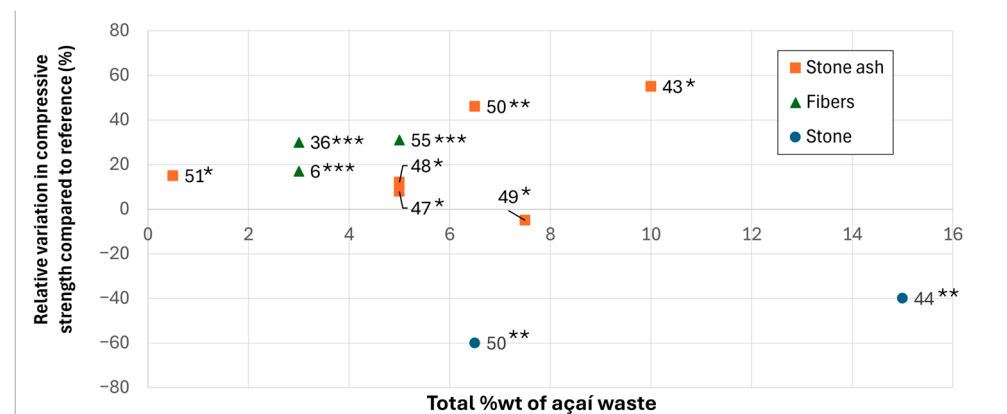


Figure 8. Relative variation in compressive strength vs. total weight percentage replaced by açai waste. Reference number is indicated at each point. (*), replacement of cement; (**), replacement of sand; and (***), addition relative to cement mass.

3.3. Comparison with Similar Types of Agricultural Wastes

This literature review focuses on the valorization of açai waste, but it is also worth considering the potential application of this approach to similar wastes, such as pineapple fibers, coconut fibers, or rice husk. It is important to note that the valorization of these wastes varies depending on their nature: for example, rice waste is often used in the form of ash incorporated into construction materials, while the fibers of pineapple, coconut, and açai are more commonly utilized in a natural state or treated with NaOH. We will therefore

compare the mechanical performance of materials incorporating pineapple, coconut, and açai fibers.

Regarding pineapple waste, the crowns are generally discarded in landfills, unlike the peels, which are used for animal feed or compost. The main challenge with incorporating pineapple crown fibers into concrete lies in removing impurities, which requires surface treatment, often with NaOH, to eliminate non-cellulosic compounds such as lignin. Faruk et al. [56] report that adding pineapple fibers increases tensile (+14.65%) and compressive strength (+15.61%). Yet, at higher fiber content, the fiber alignment becomes difficult, which can reduce the concrete's strength.

Coconut fiber, extracted from the husk, stands out for its advantageous properties: low cost, availability, high lignin content, and high elongation resistance. This robustness makes it ideal for various uses, such as ropes, carpets, and panels, although current applications offer limited added value. Therefore, further exploration of its potential in cement-based products, such as mortar, is essential.

Table 3 presents the results of the mechanical strength of mortars incorporating açai, coconut, and pineapple fibers. Mortars using NaOH-treated pineapple fibers (7.5% NaOH) show improved strength, reaching 5.22 MPa for wall and ceiling coatings and 8.81 MPa for structural repairs (with 2.5% treated fibers). Açai fibers provide a more modest increase, peaking at 4.23 MPa, making them more suitable for non-structural applications, such as facades. Lastly, coconut fiber performs exceptionally well in structural repairs, with a maximum strength of 29.97 MPa for only 0.1% fibers treated by boiling. It is worth noting that coconut fiber is the most effective at increasing the mechanical strength of mortars, particularly in structural repairs. Treated pineapple fiber also provides significant improvements, especially for wall coatings and repairs. Açai fiber, with its more modest performance, is better suited for non-structural applications.

Table 3. Compressive strength of mortar with partial replacement of cement with different types of agricultural waste fibers.

Fiber	Study	Fiber Condition	Fiber Amount (% wt.)	Compressive Strength (MPa)
Açai	[6]	Natural	3	4.02
		Treated with NaOH	3	4.23
Coconut	[57]	Immersion in boiling water	0.1	29.97
Pineapple	[58]	Natural	5	4.44
		Treated with NaOH	7.5	5.22

It may also be interesting to analyze the selected studies in view of their potential for a large-scale use. In this regard, the technology readiness level (TRL) scale provides information on the “proximity to market” of a technology. The TRL scale was first developed by NASA in the 1970s, and its main purpose is to assist in making decisions concerning the development and transitioning of technology. It should be viewed as one of several tools that are needed to manage the progress of research and development activity within an organization [59]. Figure 9 presents the TRLs scaled from 1 to 9, which are used to gauge the scientific maturity of research in the açai waste management literature. These levels indicate whether only basic principles of açai waste management have been established or whether they have already been tested on pilot building installations, for example.

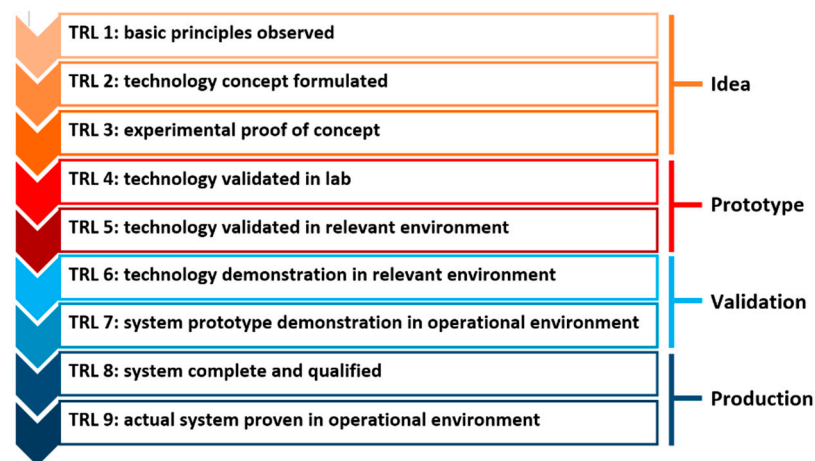


Figure 9. Definition of technology readiness level (TRL).

It has been determined that all published studies, due to their recent nature, can be classified with TRLs equal to or below 4 (technology validated in the laboratory), which corresponds to prototypical stages. Thus far, potential applications of the açai waste have been limited to non-structural uses, including particle boards (for decoration and sound absorption), paving under reduced loads, and repairing defects in elements subjected to low levels of mechanical stress.

The analysis presented in this study is based on a scoping review of the Brazilian and international scientific literature. It is important to acknowledge that there may be limitations to this approach, as local initiatives in Brazil may have been implemented but not published in the scientific literature. In view of the experimental results in terms of workability of the cementitious biocomposites and their mechanical performance, the economic feasibility of using açai waste in civil engineering may be questioned. It relies on several factors, including the cost of collection, processing, and integration into construction materials. Açai waste, especially seeds and fibers, can be utilized in cementitious composites or eco-panels. However, the high cost of functionalization, especially using chemical treatments like mercerization, remains a barrier to scaling this technology to an industrial level. Furthermore, incorporating açai waste into construction requires addressing environmental impacts and regulatory standards. A key challenge lies in optimizing the processing costs to make it competitive with traditional materials. Although laboratory tests show promising results, the cost of scaling these processes—particularly for extracting bioactive compounds and integrating the waste into concrete or panels—poses a financial challenge. These materials can, however, reduce the consumption of natural resources and contribute to sustainable building practices.

In summary, while açai waste has potential in civil engineering, further research and cost reduction strategies are needed to make its application economically viable on a large scale.

4. Conclusions

In view of the outcomes mentioned in the included studies, it first appears that the priorities of academic researchers and their industrial counterparts, who can apply the research in practice, are poorly aligned. Since no clear guidelines are defined, the path to a large-scale, sustainable implementation of açai waste in the construction sector requires further technological advancements. Bridging this gap will involve not only refining processing techniques but also fostering closer collaboration between academic institutions, industry stakeholders, and policymakers.

Secondly, the present review may be limited by research exclusively carried out in Brazil. Açai also grows in French Guiana, Peru, and Colombia. However, the production levels in these countries are way below those in Brazil: the resulting volumes of waste do

not reach a concerning threshold, and to the best of the authors' knowledge, have not led to research works to date.

Finally, the present review aims to provide a comprehensive overview of açai waste valorization in the civil engineering sector, encompassing both the building and public works domains. Although studies conclude that açai fibers and stones hold potential for use in cementitious composites or eco-panels, current processes remain limited to laboratory prototypes and are not feasible for industrialization at present. Moreover, the technology for functionalizing fibers and stones, whether chemical (e.g., mercerization) or physical, is insufficient to address the environmental challenge posed by millions of tons of waste generated each year. The very wide range of applications and compositions makes it difficult to define a critical threshold for the incorporation of açai residues and therefore the real potential of this value-added route.

Despite recent concerns related to responsible açai waste management, promising results in this preliminary stage call for further investigation. Efforts should focus on conceptualizing a different approach or implementing higher mass ratios to formulate composites with greater mechanical strength, aimed at the broader civil engineering sector. In the frame of concrete or mortar applications and with the construction standards in mind, even low ratios of residues may contribute to a reduction in the amount of açai waste as well as greenhouse gas emissions. Regarding building applications, future research should aim to achieve thermal and acoustic performance matching current standards in sustainable development in the Amazonian area, covering Brazil and French Guiana.

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