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Circular Bioeconomy in the Amazon Rainforest: Evaluation of Açaí Seed Ash as a Regional Solution for Partial Cement Replacement

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Abstract: Açaí seed ash (ASA) is a waste product from processing the açaí fruit and burning the seeds for cogeneration purposes. The present study evaluated the use of ASA from the Brazilian Amazon as partial Portland cement replacement in self-leveling mortars (SLM) for social-interest buildings. The fresh and hardened state properties of mortars were accessed with 5% and 10% ASA content, and a life cycle assessment was performed to evaluate the greenhouse gas (GHG) emissions. The maximum transport distance to enable ASA as a building material was determined by a sensitivity analysis, and specific carbon-efficiency indicators for SLM were proposed and validated. The results showed that using up to 10% ASA as cement replacement was technically and environmentally feasible since the mechanical performance was maintained and GHG emissions decreased up to 8%. The sensitivity analysis revealed that transport efficiency is crucial for ASA applications far from its production area; therefore, it should be evaluated as a regional building material. The work brings an important contribution to regional sustainable development by assessing the characteristics of a residual material and proposing the reuse of waste, reducing GHG emissions from the cement industry, and stimulating the circular bioeconomy in the Brazilian Amazon region.

Keywords: life cycle assessment; GHG emissions; carbon-efficiency indicator; self-leveling mortar; local solution; transport efficiency; Brazil

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Citation: Rocha, J.H.A.; de Siqueira, A.A.; de Oliveira, M.A.B.; Castro, L.d.S.; Caldas, L.R.; Monteiro, N.B.R.; Toledo Filho, R.D. Circular Bioeconomy in the Amazon Rainforest: Evaluation of Açaí Seed Ash as a Regional Solution for Partial Cement Replacement. *Sustainability* **2022**, *14*, 14436. https://doi.org/10.3390/su142114436

Academic Editor: Antonis A. Zorpas

Received: 3 October 2022
Accepted: 1 November 2022
Published: 3 November 2022

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1. Introduction

Açaí is a fruit from açaizeiro (*Euterpe oleracea*), a native species of the Brazilian Amazon rainforest [1]. In recent years, the commercialization of açaí has increased due to its use in novel manufactured products, not only in the food sector but also in the cosmetic and pharmaceutical sectors. Among the best-known products are frozen açaí, açaí juices, açaí energy drinks, hair moisturizers and shampoos, skin moisturizers, supplements and vitamins, among others. The wide variety of applications has increased the interest in açaí fruit. In fact, Brazilian açaí production jumped from 216,000 tons in 2015 to 1.48 million tons in 2020, an increase of almost seven times in just five years [2,3]. It is noteworthy that about 99% of national açaí production is concentrated in the North Region of Brazil, where the Brazilian Amazon is located, and 94% of the total output comes from the state of Pará [2]. In this context, açaí may be considered a local product of great social and economic importance for the development of the North Region.

However, the yield of açaí after processing is relatively low. Indeed, the pulp and peel, which are the eatable parts, represent only 17% of the fruit, the other 83% is the seed, a waste rich in carbon [1,4]. The seed becomes an environmental liability since it is not able to be disposed of suitably. In addition, the increase in açaí consumption leads to an increase in rejected seeds. As previously stated, in 2020, Brazilian açaí production was about 1.48 million tons [2], corresponding to a potential generation of 1.23 million tons of seeds if the total consumption of national production is considered. These seeds have a low specific gravity (1.49 g/cm^3) and bulk density (0.64 g/cm^3) [5]; therefore, the potential amount of seeds represents a high volume of waste. Because of the large volume, the disposal of seeds in landfills might become unfeasible due to the cost of transportation and the space required to place the material. Since açaí production is concentrated in the North Region, the inappropriate disposal of these seeds can significantly impact the local environment, causing the siltation of rivers and the clogging of drainage networks in cities, for example. In this sense, alternative measures to minimize these problems are urgent.

Recently, some industrial units in Pará state started using seeds to produce bioenergy. In fact, burning seeds as biomass is an interesting alternative, as their gross calorific value is about 19.16 MJ/kg [6]. Besides providing a proper use for a waste material, using seeds as biomass has the benefit of power generation with sustainable resources. In this context, the seeds may contribute to a circular bioeconomy in the Brazilian Amazon region, producing clean energy for local industries. However, burning seeds generates one last waste that requires attention: the Açaí seed ash (ASA) [7]. The ash content of açaí seeds is about 1.1% [6], which could result in an annual generation of about 14,000 tons of ASA in Brazil, according to açaí national production data [2]. Considering that almost all the açaí production is concentrated in a single state in the country, and also considering the strong growth trend in açaí production, the amount of ASA might become an issue in a few years. Therefore, research on ASA characteristics is essential to find an appropriate use for this material and favor the sustainable development of the Amazon region.

Remarkably, the civil construction industry is well known for its ability to incorporate byproducts from other industrial sectors, such as ground, granulated blast furnace slag (GGBFS) from the steel industry, which is widely used in the cement industry. Moreover, partial cement replacement by biomass ashes is a strategy primarily used worldwide, with numerous studies about rice husk ash (RHA) [8–11], sugarcane bagasse ash (SCBA) [12–15], bamboo leaf ash [16,17], elephant grass ash [18,19], and many others. Cement replacement by supplementary cementitious materials (SCM), such as those mentioned above, is the most adopted technique worldwide to minimize the impact of the cement industry. Indeed, the cement industry is responsible for about 5% to 8% of global anthropogenic CO_2 emissions from clinker production, the main constituent of Portland cement [20], and for each ton of clinker produced, about 842 kg of CO_2 are released into the atmosphere [21]. Thus, the search for alternatives that reduce the environmental impacts of this sector is fundamental, where regional materials can be an important resource since transportation impacts are minimal. Therefore, ASA is a potential material for cement industry decarbonization in the North Region of Brazil, but it still requires more knowledge about its properties to make its use in cement-based materials feasible.

The Amazon rainforest occupies most of the territory of the North Region of Brazil, consequently, it directly impacts the social and economic development of this region. Pará is one of the states of the North and, as previously discussed, it is the primary producer of açaí in Brazil. Indeed, Pará is one of the largest states in the country, both by area and population, but it is also one of the states with the lowest monthly income *per capita* [22]. One of the main problems that the population faces is housing. Currently, Pará is among the five Brazilian states with the largest housing deficit, concerning the total number of cities [23]. In this case, different engineering solutions have been encouraged in order to make better use of resources. For example, self-leveling mortars (SLM) are widely employed in popular residential flooring, and the use of additions to reduce cement consumption is widespread. The main characteristic of SLM that encourages its use is its high flowability, which leads

to productivity gains [24]. Therefore, this technique can be a relevant alternative to help overcome the housing deficit situation in Pará by promoting the construction of social interest residential buildings in a more efficient way.

Considering a circular bioeconomy approach and the importance of açaí to the the state of Pará, ASA could be a novel material of lower associated cost for the development of the local construction industry, since it is a waste product and requires a suitable application. This strategy contributes to reducing environmental impacts from the optimization of resources by transforming waste into a byproduct and, mainly, by minimizing the use of natural resources [25,26]. However, evaluating the feasibility of these wastes is necessary since the local availability or the high transportation costs of these materials can be limiting factors to their application [27,28]. A methodology that allows this analysis is the life cycle assessment (LCA), which enables the evaluation of a given product's environmental impacts, systemically and reliably [29]. Several studies have used the LCA methodology in the construction sector to estimate the environmental performance of materials, especially in relation to mitigating greenhouse gas (GHG) emissions [27–31].

In this context, this study aimed to evaluate the performance of ASA as a partial replacement for Portland cement in the production of SLM for social interest residential buildings in the Brazilian Amazon region, since ASA is a waste product from biomass energy generation. In addition, one of the leading scientific contributions of this work is the proposition of a methodology for evaluating the GHG emissions in conjunction with the properties in fresh and hardened state of SLM. The study is innovative because, in addition to assessing the performance of ASA as partial cement replacement, it proposes an LCA study using specific indicators for self-leveling mortars according to their typical flow characteristics. The scope of the study considered, mainly, the state of Pará for the application of ASA, because it is the main producer of açaí in Brazil. In addition, a sensitivity analysis was performed to evaluate the maximum possible transportation distance for the use of ASA as a building material to be feasible. The methodology used can be adapted for studying other mortars with similar applications and different types of ash. Furthermore, the work brings a relevant contribution by promoting a residual material from the Amazon rainforest, the primary tropical forest and fundamental for world climate control, reducing waste generation, and stimulating a circular bioeconomy for sustainable development of this region.

2. Background

There are still few studies on the properties of ASA, which makes this work relevant in the context of sustainable materials for civil construction. Among the existing studies, Cordeiro et al. [7] showed that the residual ASA presents satisfactory physical characteristics for use as an admixture in construction. However, the residual ash did not show reactivity, probably due to the conditions of uncontrolled burning of the seed, and its chemical composition was not suitable for application as pozzolanic materials. Even so, the material acted as a filler in the cement matrix and showed good mechanical performance when applied to the concrete.

Do Nascimento et al. [32] also applied ASA in concrete, and they observed that the addition of ash brought benefits to the durability of the compound, making it less inclined to carbonation due to the filler effect of ASA. Marins et al. [4] studied the incorporation of ASA in structural ceramics and concluded that up to 15% of ash improved the physical and mechanical properties of the material. Based on the studies performed, it is clear that ASA has excellent potential for application in the construction industry. Still, ASA requires further studies about its impact on different building materials, as well as related to its environmental performance.

There are some fundamental aspects to evaluate the sustainable construction approach, such as energy consumption, resources used, waste generation, maintenance, and end-of-life. Therefore, assessing environmental impacts generated throughout the life cycle of buildings is a subject of increasing interest and research [33,34]. LCA is a methodology

that allows estimation of potential environmental impacts through different categories, such as global warming potential (GWP), ozone depletion (ODP), abiotic depletion (ADP), acidification (AP), eutrophication (EP), photochemical ozone creation (POCP), and others (BS EN 15978, 2011). Unlike traditional methods, LCA considers all phases of construction, from raw material extraction to the end-of-life of products [35,36].

Several studies are reported in the literature where environmental impacts are assessed with LCA of mortars with alternative materials [33,37–40]. Mortars with recycled aggregates, for example, can create the false impression of being environmentally beneficial when, in fact, they can increase the GWP due to the higher cement content required to achieve the same strength as conventional mortars [41]. Brás and Faria [42] showed that the composition of mortars also influences the environmental performance of structures in the long term, so cement-based mortars present a better performance than those based on hydrated lime. In addition, many studies confirmed the benefit of decreasing the environmental impacts of mortars with the incorporation of different waste materials, such as industrial wastes [43], recycled limestone [44], steel slag, and metakaolin [45]. In addition, Pineda et al. [46] found that grouting mortars with the addition of pozzolans (natural or artificial) provide lower GWP values than conventional ones.

Concerning biomasses, Teixeira et al. [47] studied the effect of biomass fly ash (BFA) on the durability and sustainability of mortars. The authors demonstrated that using small amounts of BFA provides similar properties to those of an ordinary mortar but with better environmental performance in GWP, ODP, AP, EP, POCP, and ADP categories. In another study, Da Costa et al. [48] evaluated the environmental impacts of incorporating wood biomass ash into building materials. The authors reported that these ashes reduced the extraction and processing of natural raw materials, transportation, and energy consumption. In the case of cement-based mortar production, wood fly ash avoided the emission of about 850 to 857 kg CO_2 eq/ton of ash. Moreover, all the scenarios evaluated (cement-based and adhesive mortars, concrete blocks, and bituminous asphalt) showed significantly better environmental performance than the disposal of ash in landfills.

Among the studies found in the literature, the evaluation of the environmental performance of ASA in mortar or concrete was not verified, showing a knowledge gap to be filled. Using biomass ash as a partial replacement for Portland cement presents a lucrative long-term prospect and accentuated potential in the roadmap for reducing GHG emissions [49–51], as they contribute to reducing energy and raw material consumption by the cement industry and landfill disposal.

3. Materials and Methods

3.1. Materials Used in Mortar Production

ASA was collected from an industrial ceramic unit in São Miguel do Guamá, Pará State, Brazil. The ash was obtained by the uncontrolled burning of seeds. After separating from the pulp, the açaí seeds were stored in a silo and directed to the oven to be used as biomass in industrial units. The residual ash, generated after burning the seeds, was collected and manually sieved (#200 mesh) to be used as cement replacement. No additional procedures were performed once it was intended to evaluate the use of ASA as a residue. In addition, Brazilian blended Portland cement containing blast furnace slag (type CP II-E-32) was used in this study. This cement was chosen because of its easy acquisition in the metropolitan region of Belém, the capital of the state of Pará, Brazil. It is worth remembering that this study aimed to stimulate the circular bioeconomy and, to do so, locally available materials were used.

Both cement and ASA were typically characterized. First, oxide compositions were obtained by X-ray fluorescence spectrometry, using Shimadzu EDX-720 equipment (Kyoto, Japan). Particle size distribution was determined by laser diffraction, using Malvern Mastersizer 2000 equipment (Malvern, UK) and dispersion in absolute ethanol. In addition, the density of both materials was established using helium gas pycnometry (Micromeritics Accupyc equipment – Atlanta, GA, USA). Finally, the specific surface area (SSA) was

determined using Blaine fineness [52]. The chemical composition and physical properties of ASA and cement are presented in Tables 1 and 2, respectively. Furthermore, the pozzolanic activity of ASA was measured according to the modified Chapelle method [53], which consists in determining the reactivity of the material by fixation of calcium hydroxide from a solution with 2.0 g of CaO, 1.0 g of sample, and 250.0 g of water after 16 h at 90 °C.

Table 1. Chemical composition of ASA and cement (%).

Oxide	ASA	CP II-E-32
CaO	17.8	65.5
SiO_2	10.3	12.6
Al_2O_3	3.7	4.4
Fe_2O_3	2.2	4.7
K_2O	28.8	0.5
P_2O_5	8.8	-
SO_3	5	3.1
Cl	3.1	-
MnO	1.3	0.2
TiO_2	0.7	0.4
Loss on Ignition (LOI)	18.3	8.6

Table 2. Physical properties of ASA and cement (%).

Parameter	ASA	CP II-E-32
D_{10} (μm)	3.65	2.62
D_{50} (μm)	17.47	14.49
D_{90} (μm)	53.18	45.53
Specific gravity (g/cm^3)	2.49	3.06
Specific surface area (cm^2/g)	5080.24	3975.15

The sum of the chemical components SiO_2+Al_2O_3+Fe_2O_3 was less than 70% (Table 1), indicating that ASA does not attend to the requirements of a pozzolanic material according to ASTM C618 [54]. In addition, the result of the modified Chapelle method was 88.7 mg $Ca(OH)_2$/g of ASA, a value below the minimum (436 mg $Ca(OH)_2$/g pozzolan) to be classified as a pozzolanic material [55]. In addition, the SSA of ASA was higher than that of cement and the particle size (D_{10}, D_{50}, D_{90}) of both cement and ASA was close (Table 2 and Figure 1), suggesting that ASA should be evaluated as a filler admixture, as previously indicated by Cordeiro et al. [7].

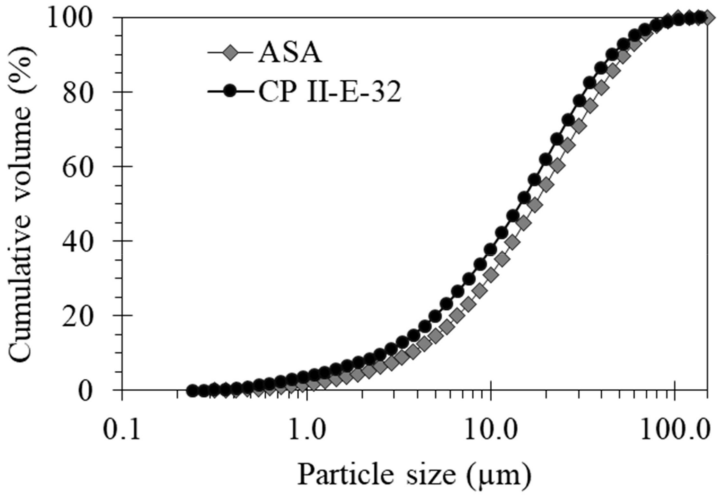


Figure 1. Particle size distribution of ASA and cement (CP II-E-32).

As fine aggregate, pit sand from the city of Castanhal, Pará State, Brazil, with a fineness module of 2.06 [56], was used. The specific gravity (2.64 g/cm^3) and unit mass (1.48 g/cm^3) were obtained, respectively, according to NBR NM 52 [57] and NBR NM 45 [58] Brazilian standards. Water from Belém city public supply was used. In addition, a high-performance superplasticizer (MC-Powerflow 1180) was used to adjust the workability of all mortars according to the requirements for SLM.

3.2. Production and Characterization of Self-Leveling Mortars

3.2.1. Dosage and Characterization of Self-Leveling Mortars in Fresh State

The SLM were produced by adapting the procedure for mix design of EFNARC [59], considering the methodology for superplasticizer dosage in mortar. A constant water–cement ratio of 0.50 and cement–sand ratio of 1:2 was defined. The cement replacement content by ASA was 0%, 5%, and 10%. Superplasticizer content was obtained by determining the dosage curve of each SLM. To do so, slump flow and flow time were evaluated with flow cone and V-funnel tests, respectively, according to EFNARC [59] and ASTM C1708 [60] standards. The materials consumption for each SLM is presented in Table 3, where REF is the reference mortar (0% ASA), and the mortars with ASA were denominated *x*ASA-*y*, where *x* corresponds to cement replacement level, and *y* is the superplasticizer content.

Table 3. Materials consumption for each SLM (%).

Nomenclature	Cement	ASA		Sand	Water	Superplasticizer	
	(kg/m^3)	(%)	(kg/m^3)	(kg/m^3)	(kg/m^3)	(%)	(kg/m^3)
REF	617.3	-	-	1234.6	308.6	0.65%	4.01
5ASA-0.55	586.4	5%	30.86	1234.6	293.2	0.55%	3.40
5ASA-0.65	586.4	5%	30.86	1234.6	293.2	0.65%	4.01
10ASA-0.80	555.6	10%	61.73	1234.6	277.8	0.80%	4.94
10ASA-0.85	555.6	10%	61.73	1234.6	277.8	0.85%	5.25
10ASA-0.95	555.6	10%	61.73	1234.6	277.8	0.95%	5.86

3.2.2. Control and Characterization of Self-Leveling Mortars in Hardened State

The reference mortar was designed for a compressive strength of 20 MPa, and the influence of cement replacement by ASA was evaluated. After determining superplasticizer content, mixing, molding, and curing were performed according to Brazilian standards to assess mortars' mechanical performance at 28 days using compressive strength [61] and flexural strength tests [62]. To that end, five cylindrical (50 mm diameter and 100 mm high) and five prismatic (40 mm × 40 mm × 160 mm) specimens were used, respectively. Data were compared using a one-way analysis of variance (ANOVA) with Tukey's multiple-range test ($p \leq 0.05$).

3.3. Life Cycle Assessment (LCA)

LCA is divided into four phases, according to ISO 14040 [35] and ISO 14044 [36]: (a) definition of goal and scope; (b) life cycle inventory (LCI) analysis; (c) life cycle impact assessment (LCIA), and (d) interpretation, which will be described below.

3.3.1. Definition of Goal, Scope, and Functional Unit

The product of this study is the self-leveling mortar, considering three mixtures: 0% ASA (reference), 5% ASA, and 10% ASA, as established before. The goal of the LCA study was to evaluate and compare the GHG emissions through the global warming potential (GWP) of the different mortars with ASA, considering raw material extraction, transportation, and mortar production.

The scope of the LCA study was defined as cradle-to-gate, according to EN 15978 [63], which includes raw material supply, transportation, production, and associated processes. In summary, this study included only the materials and processes associated with cement-

based mortar production, excluding the construction (A4-5), use (B1-7), and end-of-life (C1-4) phases. As pointed out by several investigations, the uncertainties of the real use of building materials, actual energy consumption, repairs, maintenance, and other variables, make it very difficult to collect data from these last phases [64–66]. Therefore, cradle-to-gate is the most used scope in LCA studies of building materials. Figure 2 shows the scope and boundaries of the LCA for this study, where A1 denotes the acquisition of raw materials, A2 is the transportation of raw materials, and A3 represents mortar production. It is worth mentioning that two different raw material transportation scenarios were evaluated (A2), considering the transport efficiency. In addition, no previous impact was considered for ASA in phase A1 since it is a waste material, and no process or pretreatment was conducted on the ash.

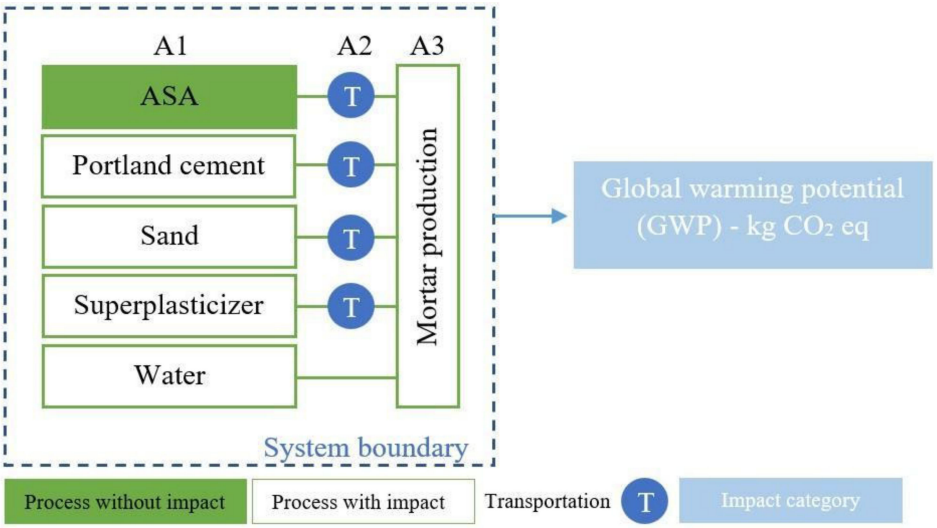


Figure 2. System boundaries for the LCA study of SLM.

In this study, only GWP impact was assessed, since this category is the most affected by the production of cement-based materials [43,45–47], especially mortars [33]. Additionally, the choice of this category was based on EN 15804 [67], which indicates that GWP is one of the most relevant categories for construction products.

The functional unit (FU) was defined as 1 m^3 of mortar. In addition, four indicators were proposed based on the properties of SLM: compressive strength, flexural strength, slump flow, and flow time. The requirements for these indicators were assumed following the national and international legislation and regulations of buildings and construction [59–62]. It is noteworthy that, although there are different mortar mixtures, which implies different mechanical properties, for the LCA study, they were considered to have the same service life, as stated by Caldas et al. [68] and Paiva et al. [69]. The adoption of this FU is supported by previous works, where a volumetric FU was used for mortars and cement-based materials [41,70,71].

3.3.2. Life Cycle Inventory

For the life cycle inventory (LCI), the data were collected from Ecoinvent v.3.6. Table 4 presents the summary of the LCI used for this study. The detailed inventory version can be found in Table S1 (Supplementary File), with the inputs and outputs calculated in this study. In addition, the cut-off model was adopted for the data sets. The production stage (A1–A3) considered was: A1, the extraction and production of the raw materials; A2, transportation; and A3, mortar production. For the latter, concrete production processes were considered for the inputs referring to mortar production since no data for mortar production were found in Ecoinvent. Still, the production processes of both materials are similar.

Table 4. Summary of raw materials and activities used in SLM production.

Materials	
Portland Cement	Cement, blast furnace slag 6–34% {BR} | cement production, blast furnace slag 6–34% | Cut-off, U
Sand	Sand {BR} | sand quarry operation, open pit mine | Cut-off, U
Water	Tap water {BR} | tap water production, conventional treatment | Cut-off, U
Superplasticizer	Plasticizer, for concrete, based on sulfonated melamine formaldehyde {GLO} | production | Cut-off, U
Transportation	
Scenario 1	Transport, truck 10–20 t, EURO3, 100%LF, default/GLO Mass
Scenario 2	Transport, truck 10–20 t, EURO3, 50%LF, empty return/GLO Mass
Production	
Mortar production	Concrete, 25 MPa {BR} | concrete production—Only plant processes

The road modal was adopted with EURO 3 and 10–20 tons from the Ecoinvent v.3.6 database since Brazilian trucks for transporting building materials have similar characteristics [72]. Two scenarios were considered regarding the truck capacity and the form of return: scenario 1, 100% loaded and loaded on return, and scenario 2, 50% loaded and empty return, similar to the study of Caldas et al. [73]. The first scenario indicates more efficient transportation, where logistics is planned for the truck to return loaded, while the second scenario indicates less efficient transportation, which is more common for short distances where, in many cases, the truck return planning is neglected. The transportation distances of each material were measured on Google Maps, considering the average of the shortest route distances between the mortar factories in the metropolitan region of Belém and the material supplier.

Brazil is one of the largest countries, referring to territory, in the world, which could influence the transportation distances of inputs and building materials [29], especially for ASA, whose production is concentrated in the North Region, mainly in the state of Pará. Therefore, a sensitivity study was conducted to evaluate the maximum feasible transportation distance for ASA to be used as a building material. The variables adopted in the study are described in item 3.3.4.

3.3.3. Life Cycle Impact Assessment

The EN 15804 +A2 Method V1.00 was used for the life cycle impact assessment (LCIA), considering the climate change impact category, global warming potential (GWP). This method was selected following the recommendations of EN 15804 [67]. Excel spreadsheets were used for the LCA modeling.

3.3.4. Sensitivity Analysis

As previously stated, the North Region is Brazil's main producer of açaí, and about 94% of national production is concentrated in the state of Pará [2]. However, it is the region with the lowest cement consumption in the country [74]. This indicates that the other areas of the country have a higher potential for consumption of ASA, where the construction industry is more developed. In fact, many wastes that may have technical potential could have their reuse rendered unfeasible due to the issue of logistics and availability [29]. Therefore, the feasibility of ASA transportation to further distances was evaluated by a sensitivity analysis. Considering the variables in the LCA study and the context of a circular bioeconomy, the sensitivity analysis was performed for transport efficiency, as stated in item 3.3.2, and maximum transport distances of ASA. In this case, the distances for transportation of the different materials (Portland cement, sand, and superplasticizer) were considered constant to evaluate the isolated influence of the transportation distances of the ash, which was the only material coming from a waste product.

The maximum transportation distance of ASA for each transport efficiency was obtained after the initial LCA study, considering the contribution of partial cement replacement by ASA on GWP impact. The maximum distances were plotted on the map from a starting point, where the coordinates 1°37'33" S and 48°22'13" W were assumed. This point was selected as the center point between three cities: Belém, Igaraparé-Miri, and São Miguel do Guamá (Figure 3). These cities were chosen because of their importance for açaí and ash production in the state of Pará. In this case, Belém was chosen because it is the capital of the state and has a higher development in the construction sector for ASA application; also, Igaraparé-Miri is the largest producer of açaí in the state of Pará, consequently, the main source of açaí seeds; finally, São Miguel do Guamá was selected for being the red ceramic industrial pole in the state of Pará, where a considerable volume of açaí seeds is used as biomass and, consequently, becomes one of the primary sources of ASA generation in the Brazilian Amazon region.

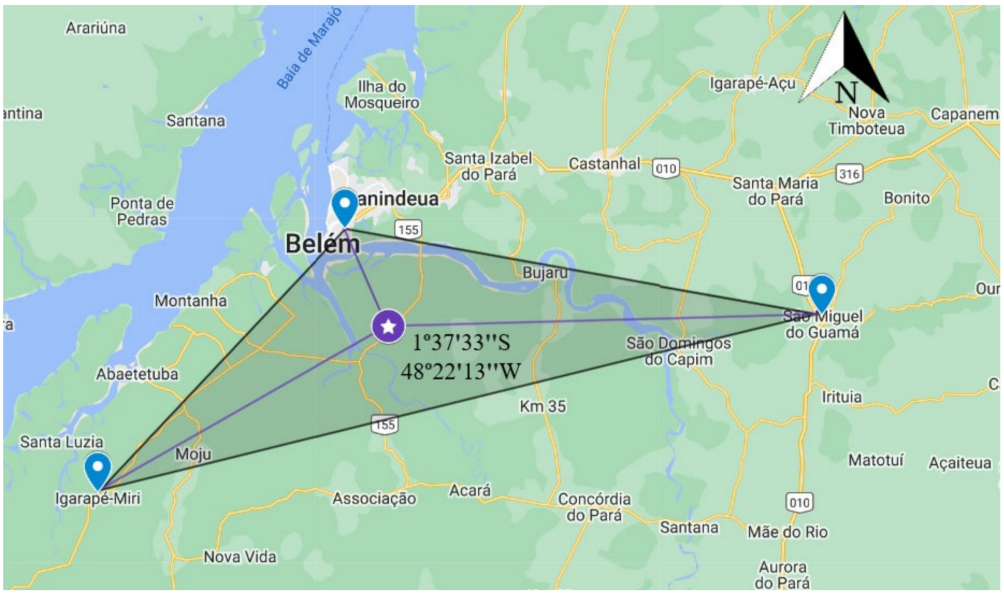


Figure 3. ASA production center in the state of Pará, Brazil.

3.4. Carbon-Efficiency Indicator for Self-Leveling Mortars

Additionally, carbon-efficiency indicators (*Carbef*) were proposed based on the experimental data, using Equation (1), according to the studies of Paiva et al. [69] and Silva et al. [75]. The results of flow time, slump flow, compressive strength, and flexural strength were considered the denominator (Exp), and the GWP values obtained in the LCA were used in the numerator, resulting in four indicators.

$$Carbef = \frac{GWP}{Exp} \quad (1)$$

where *GWP* is the CO_2 emission of the mixtures (kg CO_2 eq/m^3), and *Exp* represents the experimental results for flow time (s), slump flow (cm), compressive strength (MPa), and flexural strength (MPa).

4. Results and Discussion

4.1. Fresh State Characterization

Figure 4 presents the superplasticizer dosage curve results from the V-Funnel and flow cone tests. First, the Portland cement replacement by 5% (Figure 4a) and 10% (Figure 4b) ASA was in accordance with the parameters for flow time (6–11 s), required by current standards [59,60], for all contents of superplasticizer used. Similar results were reported by Felekoğlu et al. [76] and Turk [77] in investigations that used other mineral additions to replace Portland cement. On the other hand, in the slump flow, only the superplasticizer

content of 0.55% and 0.95% for 5% (Figure 4c) and 10% ASA (Figure 4d), respectively, were in agreement with the current standard requirements (240–260 mm) [59,60]. This behavior was previously reported in other studies with SCM [78,79].

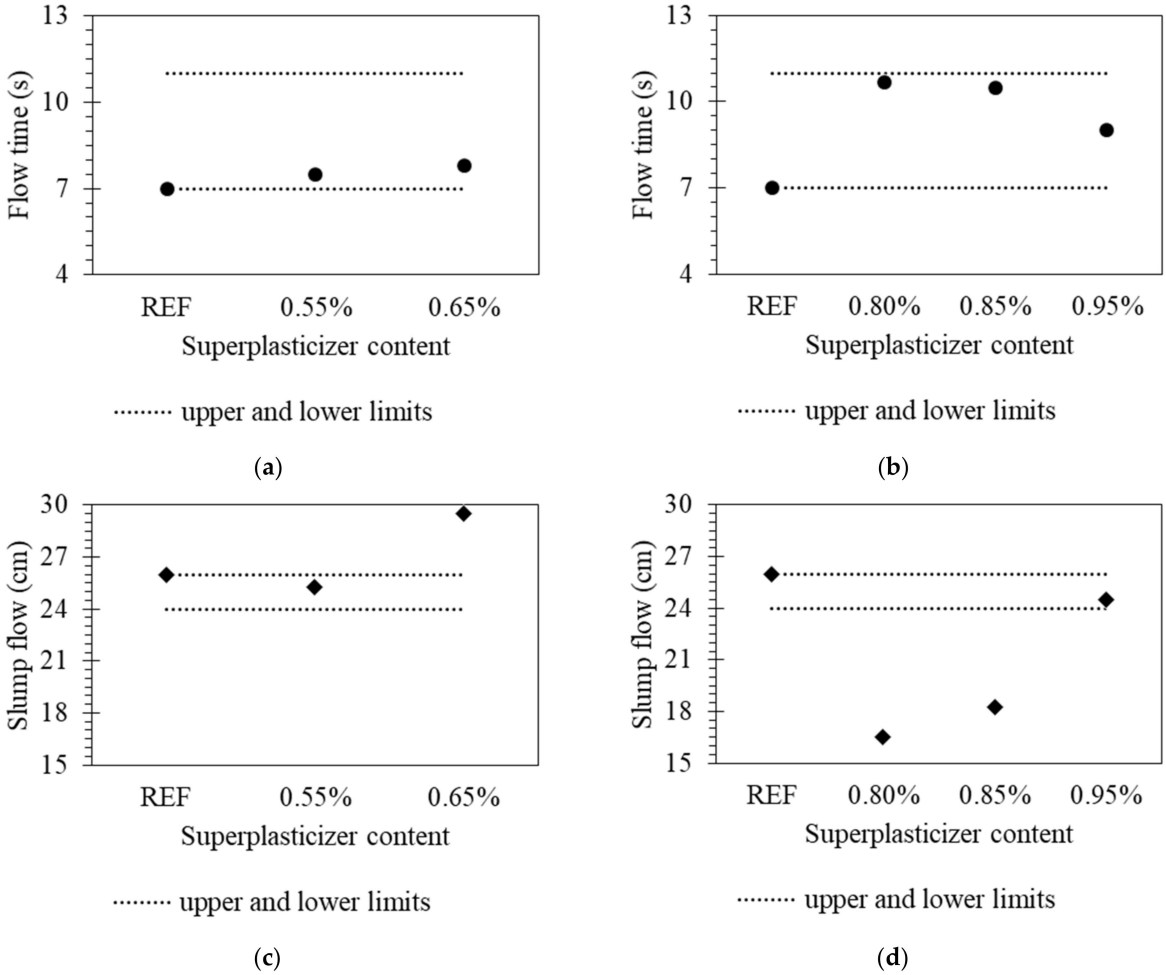


Figure 4. Flow time of mortars with 5% ASA (**a**) and 10% ASA (**b**); slump flow of mortars with 5% ASA (**c**) and 10% ASA (**d**).

The mortar with 10% ASA required more superplasticizer than the other with 5% ASA, indicating that higher ash contents reduce mortar workability. This may be related to the higher water absorption capacity, specific surface area, and small particle size of ASA, which affects the rheological properties of cement-based materials, as described in previous studies with vegetable ashes and other materials [12,24,79–81].

It is worth mentioning, that for reference mortar (REF) 0.65% superplasticizer content was needed to meet the requirements of SLM. For the ASA mortars, only 5ASA-0.55 and 10ASA-0.95 were used for characterization in the hardened state since these superplasticizer contents were in accordance with the requirements. In this case, the mortar with 5% ASA required less superplasticizer (0.55%) than the reference, indicating that with lower percentages of cement replacement by ASA the workability of mortars is improved. However, in higher ASA contents, such as 10%, the physical effects of the ash stand out.

4.2. Hardened State Characterization

Compressive strength (fc) and flexural strength (fct,fl) results are presented in Figure 5. In the former, the values for compressive strength (between 19.60 and 21.80 MPa) were similar to those reported by Pereira and Camarini [82] for self-leveling mortars. Other authors recommend that the compressive strength of SLM should be higher than 10 MPa at 28 days [83]. Therefore, all results reached this recommendation, indicating that the

application of ASA in SLM may be feasible. It is noteworthy that the mortars of this study were produced to attend social interest residential floors and encourage the use of locally available materials, with lower costs and easier acquisition for most of the Brazilian population. Thus, the results presented show a good performance of ASA as a product from the Amazon rainforest, contributing to the circular bioeconomy in the region.

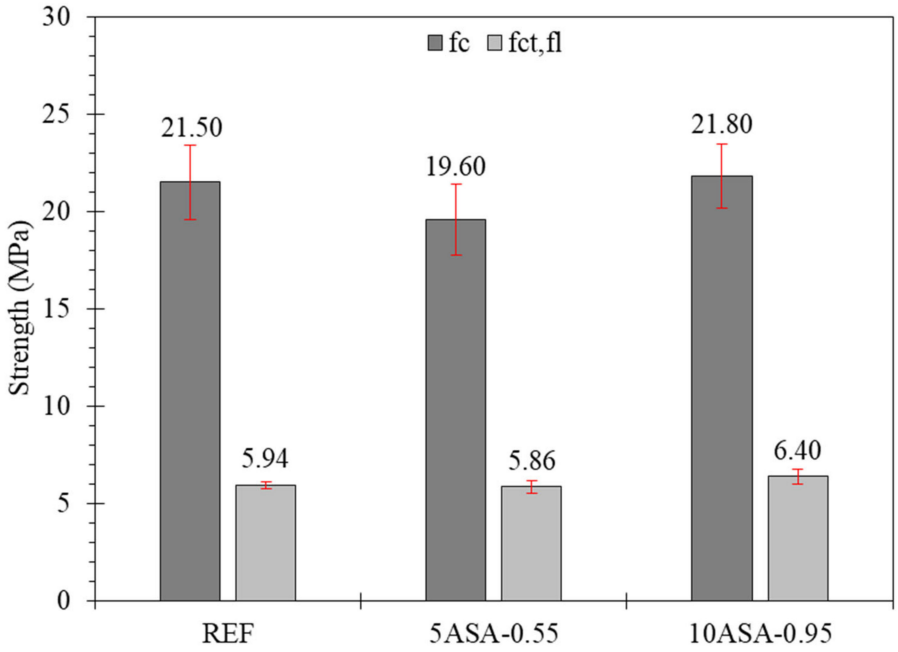


Figure 5. Results of compressive (**fc**) and flexural (**fct,fl**) strength for the SLM.

Apparently, ASA influenced the values of the compressive strength of SLM. For 5% ASA there was a decrease of 1.9 MPa (8.84%) compared to the reference at 28 days. On the other hand, for 10% ASA there was an increase of 0.3 MPa (1.40%). However, there were no statistical differences between the compressive strength results of the reference and the mixtures with ASA ($p < 0.05$). In other words, using ASA to replace up to 10% of the Portland cement achieved the same compressive strength as the reference mortar. This indicates that ASA could be used as a substitute for Portland cement, possibly due to the filler effect of the fine particles of ash (see Table 2). Other studies have shown that smaller particles can concentrate in the interfacial zone between aggregate and cement matrix, filling voids (filler effect) and, therefore, improving mechanical strength [84,85].

Regarding flexural strength, the values obtained were very close (between 5.94 and 6.40 MPa). Indeed, Pereira and Camarini [82] also described similar values for self-leveling mortars with Portland cement replacement by ceramic residue at 15% and 25%. However, there was a statistical difference between the flexural strength of 5ASA-0.55 and 10ASA-0.95, indicating an improvement for 10% ASA, but no significant differences were found between the reference and both mortars with ASA. As for compressive strength, using up to 10% ASA does not significantly affect the flexural strength results, indicating the feasibility of using ASA as a partial replacement for Portland cement. In fact, higher replacement levels should be evaluated in future research, as the results suggest that ASA could positively affect flexural strength, taking into account that 10% ASA mortars had better mechanical behavior than 5% ASA. As previously observed, this can also be attributed to the filler effect [12,86–88]. Furthermore, flexural strength is an essential test for floor mortars, such as SLM. In this sense, the results indicated that SLM with ASA could be an interesting alternative for residential floor production using locally available resources.

This study designed REF mortars for 20MPa compressive strength for social-interest residential floors. Higher strengths might be achieved with the proper design for industrial applications, and the results suggest that ASA would have no impact on performance. This indicates that ASA can be applied for other uses rather than social-interest housing. Then,

ASA has the potential to become an important material for the sustainable development of the Brazilian Amazon region.

4.3. Life Cycle Assessment of Self-Leveling Mortars

4.3.1. GHG Emissions Assessment

Figure 6 shows the GHG emissions obtained in the LCA study considering two transport scenarios: more efficient (100% LF) and less efficient (50% LF) transportation. As expected, Portland cement was the component with the highest contribution to GHG emissions for both scenarios. In the first case (100% LF), cement was responsible for 88.17%, 87.66%, and 86.31% of total GHG emissions of REF, 5ASA-0.55, and 10ASA-0.95, respectively. These values were similar to those of Farinha et al. [43] (about 85%), where the authors evaluated the environmental impact of mortars with different industrial wastes. Similarly, Moreno-Juez et al. [44] indicated that CO_2 emission is mainly based on Portland cement due to clinker production processes [89,90]. The next significant contribution was transportation, with nearly 8% of total mortar emissions. Then, sand, superplasticizer, and mortar production presented smaller percentages (<2%), indicating that their contribution was almost irrelevant. Similar results were found in the literature for cement-based materials [33,91].

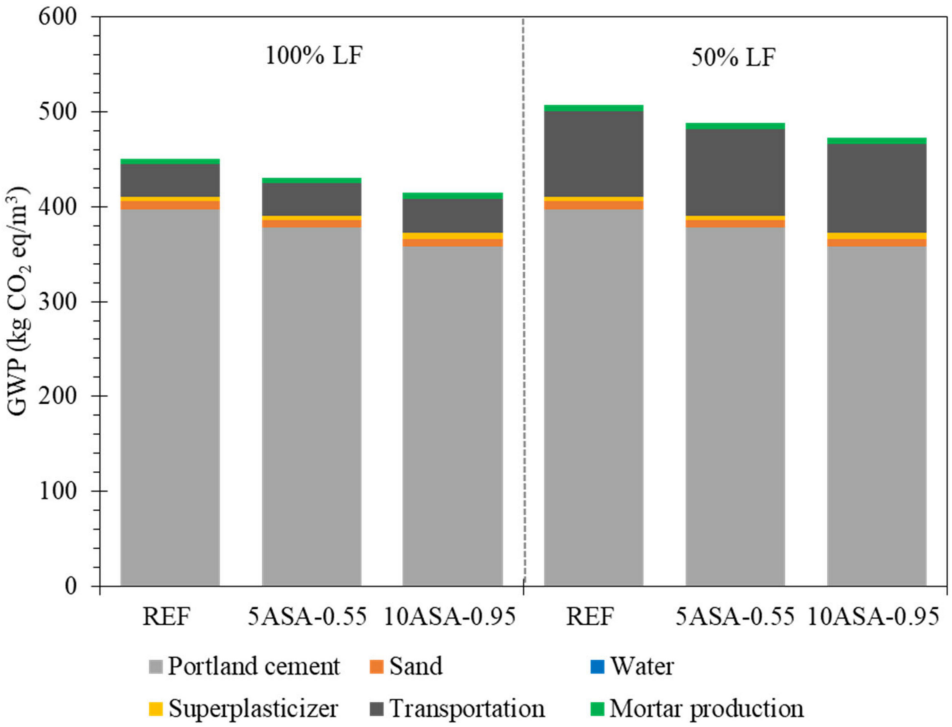


Figure 6. GWP impact of mortars for more efficient transportation (100% LF) and less efficient transportation (50% LF).

Although the mixture with 10% ASA had the highest amount of superplasticizer among all mortars (0.95%), there was a gain of only 2.27 kg CO_2 eq/m^3 compared to the reference, representing an increase of 0.64% of the total GHG emissions of this mortar. Thereby, the use of superplasticizer does not significantly affect the SLM's global warming potential (GWP) impact compared to the other materials.

In general, using 5% and 10% of ASA as a partial cement replacement decreased the total GWP in scenario 1 by 20.08 (4.46%) and 36.33 (8.06%) kg CO_2 eq/m^3, respectively, compared to the reference. However, if only the replacement of Portland cement by ASA is considered, there is a reduction of 19.89 and 39.72 kg CO_2 eq/m^3 for 5 and 10% of ASA, respectively. This result was directly influenced by the decrease in Portland cement content on mortars with ASA. Since ASA is a waste product reused to replace original materials,

it has no previous environmental impacts associated [92]. However, these results could change if allocation were considered, especially by mass. Different studies have shown that allocation can discourage the use of wastes or byproducts since their impacts could increase [28,93].

On the other hand, in scenario 2 (50% LF), there was an increase in GHG emissions of 12 to 14% in the cases analyzed compared to scenario 1. Although Portland cement contribution decreased to the range between 75.66% and 78.36%, transportation had more significant growth, reaching values close to 18%. The latter was attributed to the efficiency of the transportation of the materials, mainly ASA. Finally, sand, superplasticizer, and mortar production were kept with small contributions, less than 2% each. So, scenario 2 had higher GHG emissions than scenario 1, mainly due to transport efficiency.

In addition, ASA decreased the GHG emission in scenario 2 due to lower Portland cement content, similar to that observed in scenario 1. Again, ASA does not contribute to GHG emissions due to its waste nature, so any percentage of cement replacement will result in lower GWP. However, ASA transportation contributes CO_2 emissions, which may compromise its use, depending on distances and efficiency. Although the results were similar to those found in the literature, the comparison cannot be direct because each study has different considerations of the LCIA methods, impact categories analyzed, and other considerations [43–45,94].

4.3.2. Sensitivity Analysis

Local availability is an important factor when considering new materials for industrial applications. In the case of ASA, it is produced mainly in the state of Pará in Brazil, which could influence its use in other regions of the country, mainly due to road transportation. Previous studies have shown that transportation significantly impacts GHG emissions during the life cycle of mortars [95,96], which is more noticeable in countries with larger territories, such as Brazil [28]. Figure 7 shows the sensitivity analysis of the maximum transport distance of ASA for the two scenarios studied, considering de GWP impact of cement replacement by 5 and 10% ASA.

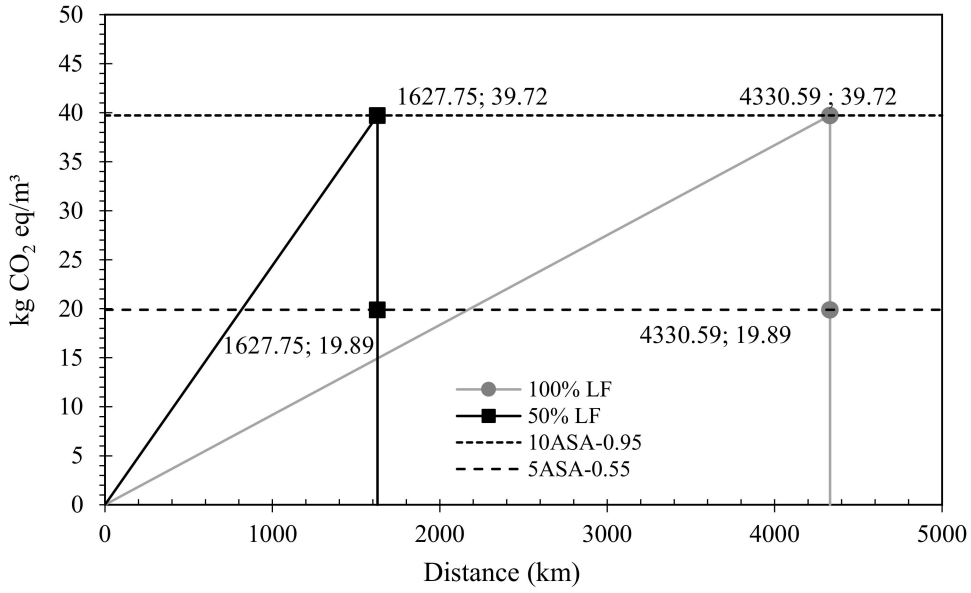


Figure 7. Maximum transport distances of ASA according to GWP impact of SLM mortars.

As previously mentioned, (item 4.3.1), Portland cement was responsible for the most significant contribution to GHG emissions. The partial substitution of Portland cement for 5 and 10% ASA represents a decrease of 19.89 and 39.72 kg CO_2 eq/m^3, respectively. These values were considered the maximum GHG emission (Figure 7–vertical axis) for ASA to be environmentally feasible. Then, the transport distance (Figure 7–horizontal axis)

to match this emission for each replacement level of Portland cement was considered the maximum transport distance. In scenario 1 (100% LF), the maximum distance is up to 4330.59 km, while in scenario 2 (50% LF), the maximum distance is up to 1627.75 km, a reduction of 62.41% compared to 100% LF. Therefore, transportation efficiency can make the use of ASA far from the production center in the Amazon region unfeasible. Regardless of the replacement level of 5 or 10% of ASA, the maximum transport distances are the same, due to the proportional relationship (2:1) between the GHG emission and the cement replacement level by ASA.

The maximum transport distances for both scenarios are presented in Figure 8, considering the radial distance from the start point in the production center (Figure 3). In scenario 1, ASA could be transported all over Brazil and even exported to most countries in South America. This indicates that ASA could become an important material for national and international market development. On the other hand, in scenario 2 the ash would reach only some states in three regions of Brazil (North, Northeast, and Midwest). In this case, 11 of the 26 Brazilian states were partially reached, and the Federal District and other six states were completely included: Pará (PA), Amapá (AM), Tocantins (TO), Maranhão (MA), Piauí (PI), and Ceará (CE). The results showed that transport efficiency plays an important role in the GHG emissions of mortars produced with ASA. Similar finds were reported by Paiva et al. [69] in earth-based mortars with bamboo particles and Caldas et al. [97] in wood shavings for bio-concretes. The sensitivity analysis allows stating that ASA can be easily applied in the entire state of Pará, where 94% of the açaí production is concentrated, confirming its use as a regional material.

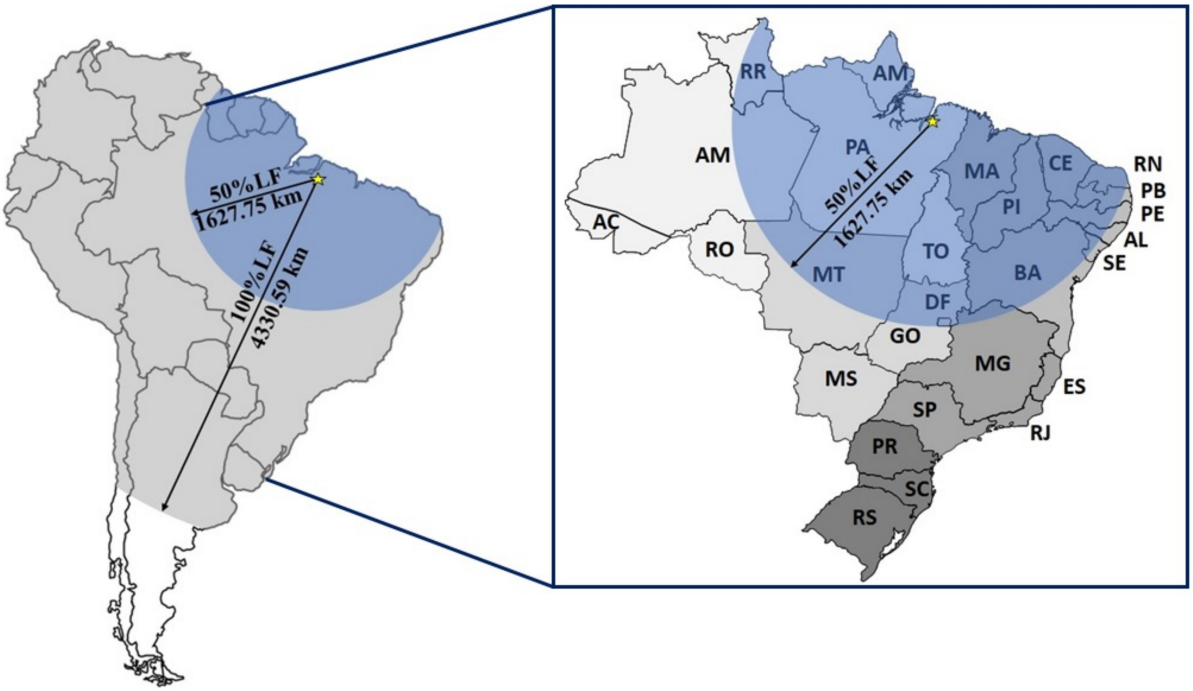


Figure 8. Representation of maximum transport distances of ASA in Brazil and South America.

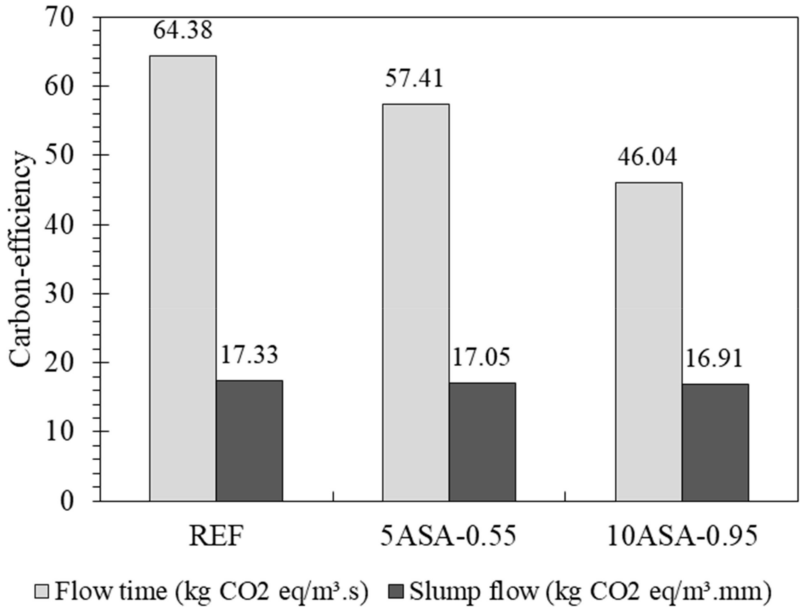
Based on the previous assessment (Figure 6), transportation was one of the activities with the highest impact on GWP, just behind Portland cement. Then, the sensitivity analysis confirmed that transporting the ash to other regions may not be environmentally feasible due to the long road distances, for example, if the transport efficiency of scenario 2 is considered, which is closely related to the construction industry scenario [98,99]. Therefore, ASA transportation is only feasible if logistics and transport efficiency are considered.

In addition, ASA showed great potential as a filler in cement-based materials. Therefore, using ASA as cement replacement could be attractive for the sustainable development of the Brazilian Amazon, stimulating the circular bioeconomy by reutilizing a regional

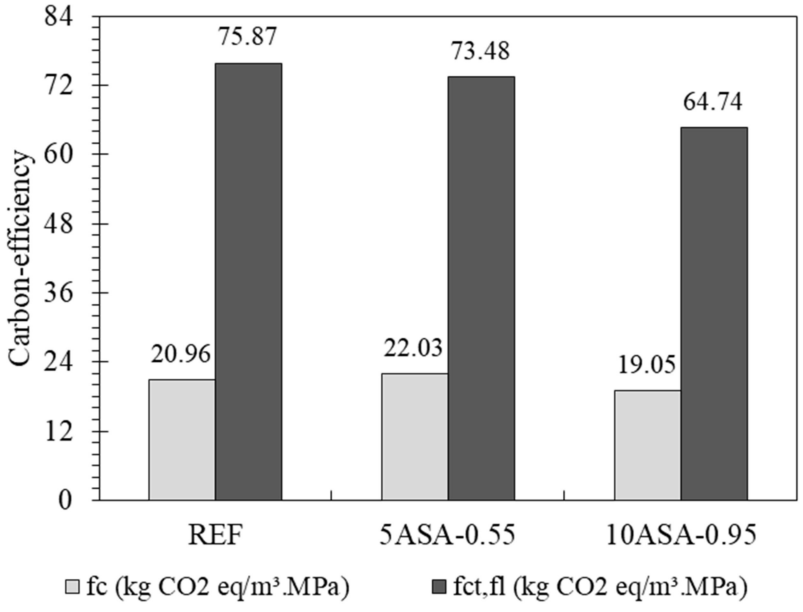
residue and contributing to the decarbonization of the cement industry at the same time. Additionally, this study contributes to the paradigm shift in the construction industry, reusing waste and reducing the consumption of natural resources [100].

4.3.3. Evaluation of Carbon-Efficiency Indicators

This section presents the carbon-efficiency indicators of self-leveling mortars produced with ASA, considering their properties in both fresh (Figure 9a) and hardened states (Figure 9b).



(**a**)



(**b**)

Figure 9. Carbon-efficiency indicators for fresh state (**a**) and hardened state (**b**) properties.

When considering flow time and slump flow, the carbon-efficiency indicators showed an improvement for the mixtures with ASA. For slump flow, the improvement was 1.62% and 2.43% for mortars with 5% and 10% ASA, respectively. For flow time, the improvement values were considerably higher, 10.82% and 28.49% for 5 and 10% ASA, respectively. The

results indicate that the properties in fresh state can be used as carbon-efficiency indicators for self-leveling mortars, as these properties respect the standard recommendations. In addition, the use of more significant amounts of superplasticizer did not significantly affect the GWP impact of SLM, as previously described. Thereby, using ASA for SLM production positively reduced GHG emissions while maintaining the fresh state properties.

Regarding the properties in hardened state, an improvement in carbon-efficiency indicators was also observed for flexural strength, with values of 3.15% and 14.67% for mixtures with 5 and 10% of ASA, respectively. For the compressive strength indicators, the result was negative for the mortar with 5% ASA (−5.07%), which is due to the decline in compressive strength compared to the reference and, therefore, there was an increase in GHG emissions per MPa. However, this indicator was improved in the mortar with 10% ASA (9.12%) due to the better performance of this SLM on compressive strength compared to the reference. This situation shows that further research is necessary, considering other percentages of cement replacement by ASA. In addition, the results indicate that the proposed indicators could be used to compare other similar studies and could also be used in new studies with SLM and with different SCM.

In addition, the long-term availability of construction materials is another crucial aspect to consider when applied in the construction industry. As mentioned before, ASA is a waste product from biomass power generation, a sector that has been growing in Brazil, unlike some SCM that comes from coal-fired power generation (fly ash), which operations might decrease considerably by 2050 due to climate change agreements [97,101]. Tropical countries, such as Brazil, have the availability of SCM from biological sources, such as RHA and SCBA. These materials are not widely used for industrial applications yet, but several studies have shown that they can improve the mechanical properties of cement-based materials and also add environmental benefits [9–15]. However, these biomasses' production is usually concentrated in the South and Southern regions of Brazil, and transportation could disable their use in other regions. In this sense, it is essential to think of local products for industrial use, where the use of ASA tends to be a long-term alternative for the Brazilian Amazon region since açaí production has been growing in the last few years [2]. Thereby, the present study demonstrated that using ASA as cement replacement in self-leveling mortars represents a good strategy, both in terms of mechanical performance and GHG emissions aspects. Thus, this work contributes to studies about novel alternative materials for the construction industry, focusing on regional availability in favor of a circular bioeconomy, especially in the North Region of Brazil. The application of ASA as cement replacement in other cement-based materials, such as concrete, should also be evaluated.

Finally, it is noteworthy that the deforestation of the Amazon rainforest has been gradually increasing in recent years, and it has nearly doubled since 2018 as the government has rolled back legal protections and enforcement measures [102,103]. Pará is one of the states with the largest degraded area in the country [102], which can also be related to açaí. According to Freitas et al. [104], many species of trees were cut down to make room for açaí cultivation. This Amazon "açaization" affects the local biodiversity and the entire forest ecosystem. The current lack of public policies for environmental protection worsens this problem even more.

On the other hand, açaí is an important source of income and employment for the riverside population and small farmers. Therefore, the sustainable development strategy should also include açaí plantations and land competition for food production, so that the sustainable cultivation of the plant can favor the socio-economic development of the Amazon region while preserving the biodiversity and the local ecosystem [105]. The impacts of açaí cultivation were not in the scope of this study, since the focus here was on the waste product from açaí processing (ASA) and GHG emissions. Future research should evaluate the social and environmental impacts from açaí cultivation in the Brazilian Amazon, such as water depletion, land use, eutrophication and acidification due to fertilizers, and biodiversity loss.

5. Conclusions

This study investigated the influence of açaí seed ash (ASA) as cement replacement on the technical and environmental performance of self-leveling mortars (SLM) in terms of GHG emissions. The following conclusions can be drawn based on the results reported:

- In fresh state, all mortars attended the requirements for SLM with the correct dosage of superplasticizer. However, the increase in ASA content caused a reduction in the workability of mortars, as higher superplasticizer content was required with 10% ASA due to the high specific surface of the ash. However, the increase in superplasticizer content did not significantly impact the global warming potential of ASA mortars.
- In hardened state, there were no statistical differences between the compressive and flexural strength of ASA mortars and the reference. Therefore, the mechanical performance of SLM was maintained when replacing cement by ASA up to 10%. This behavior suggests that the filler effect of ASA particles may justify its use as cement replacement.
- In general, ASA decreased the GHG emissions of mortars up to 8% due to Portland cement replacement, considering the production in the state of Pará, Brazil. However, transportation of ASA to other regions of the country is only feasible when considering more efficient transportation. Otherwise, transportation emits GHG, which may compromise ASA use for longer distances. Therefore, using ASA as a regional construction material may encourage a circular bioeconomy approach for the sustainable development of the Brazilian Amazon.
- The use of 10% ASA as a partial cement replacement considerably decreased the environmental impact of SLM when the results of the fresh and hardened tests were normalized. In this case, the carbon-efficiency indicators proposed in this work were suitable to describe the influence of fresh and hardened properties on the life cycle GHG emissions of self-leveling mortars. Thus, they could be used in new studies with different materials.

This work showed that ASA could be technically and environmentally feasible for producing self-leveling mortars, encouraging the use of locally available materials for social-interest construction purposes and contributing to a circular bioeconomy approach in the Brazilian Amazon region. Further research should be conducted on the influence of previous ash treatment and its application on concrete. Studies on the hydration and durability of cement-based materials containing ASA could be performed in future works. In addition, a cradle-to-grave scope could be used, and other potential environmental impacts could be assessed in the LCA modeling to verify ASA influence. Finally, the influence of allocation impacts of ASA should be evaluated in future studies.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su142114436/s1, Table S1: Data used in the LCA modeling of each mortar.

Author Contributions: Conceptualization: J.H.A.R., A.A.d.S., M.A.B.d.O., L.d.S.C., L.R.C., N.B.R.M. and R.D.T.F.; methodology: J.H.A.R., A.A.d.S., M.A.B.d.O. and L.d.S.C.; formal analysis and investigation: J.H.A.R., A.A.d.S., M.A.B.d.O. and L.d.S.C.; writing—original draft preparation: J.H.A.R., A.A.d.S. and M.A.B.d.O.; writing—review and editing: J.H.A.R., A.A.d.S., L.R.C., N.B.R.M. and R.D.T.F.; supervision: L.R.C., N.B.R.M. and R.D.T.F. All authors have read and agreed to the published version of the manuscript.

Funding: This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior—Brasil (CAPES)—Finance Code 001.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to acknowledge the financial support from Coordenação de Aperfeiçoamento de Pessoal de Nível Superior—Brasil (CAPES), and Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq). In memoriam of Luiz Cláudio dos Santos Matni.

Conflicts of Interest: The authors declare no conflict of interest.

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