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Life Cycle Assessment of Sugarcane and Energy Cane Ashes as Supplementary Cementitious Materials in Portland Cement Mortars

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Abstract

The cement industry accounts for approximately 8–9% of global greenhouse gas emissions, mainly due to clinker production. Replacing Portland cement with supplementary cementitious materials (SCMs) is a promising strategy to reduce these environmental impacts. This study evaluates the mechanical performance and environmental profile of sugarcane ash (SCA) and energy cane ash (ECA) as SCMs in Portland cement mortars. To the best of the authors' knowledge, this is the first study to integrate the mechanical performance and life cycle environmental assessment of energy cane ash as a supplementary cementitious material in Portland cement mortars. Mortars incorporating 5–20% ash were tested for compressive strength and accelerated carbonation. An attributional life cycle assessment (LCA), following ISO 14040/44 and using the ReCiPe 2016 method, was conducted with a cradle-to-gate approach. At 28 days under wet curing, 10% ECA replacement achieved slightly higher compressive strength than the reference mortar (102%), while 10% SCA replacement also achieved compressive strength similar to the reference mortar, although slightly lower than that of ECA. Both ashes significantly reduced carbonation depth, indicating improved durability. From a life cycle assessment perspective, replacing cement with 10–20% ECA reduced environmental impacts in nine of the ten impact categories evaluated, including climate change (up to 18.6%), fossil depletion, and metal depletion. SCA also improved most categories, although to a lesser extent. The superior performance of ECA is associated with its higher biomass yield and environmental credits from potassium recovery during ash washing. These results demonstrate that agro-industrial ashes, particularly energy cane ash, can enhance mortar performance while reducing environmental burdens, mitigating industrial waste accumulation, and supporting circular economy strategies and climate change mitigation, thereby offering a viable pathway toward more sustainable cement production.

Keywords: agro-industrial waste valorization; sustainable construction; circular economy; pozzolanic activity; supplementary cementitious materials; environmental performance

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1. Introduction

The civil construction sector is one of the largest contributors to climate change and environmental degradation, accounting for up to 40% of global greenhouse gas (GHG) emissions and consuming nearly 60% of total raw materials [1,2]. Within this sector, the Portland cement industry plays a significant role. Cement is an essential construction material, with global production exceeding 4.5 billion tons, and expected to increase by approximately 30% by 2050, driven by urbanization and infrastructure demand [3]. Cement production alone is responsible for around 8–9% of global GHG emissions [4–7]. A substantial proportion of these emissions is associated with the clinkerization process, which dominates the energy demand in cement production and accounts for approximately 50–70% of the GHG emissions generated throughout the process [4–7].

In this context, the use of supplementary cementitious materials (SCMs) as partial replacements for clinker has emerged as a viable strategy to reduce the environmental burdens of the cement industry. This practice can decrease the consumption of natural resources, reduce landfill disposal, and enhance the durability of cement-based materials. Studies evaluating the incorporation of industrial and agricultural waste for this purpose are particularly noteworthy [5,8–12]. In addition to mitigating the environmental impacts of Portland cement, the use of agricultural waste supports circular economy principles and strengthens industrial symbiosis. Research on the use of biomass by-products can increase their added value, support the development of a more sustainable environment, and improve human health [13,14]. Agricultural and industrial by-products such as rice husk ash [15,16] and bamboo leaf ash [8,17] have demonstrated promising pozzolanic reactivity.

Among agricultural residues, sugarcane biomass represents a particularly relevant source, especially in Brazil—the world's leading producer—with an estimated 666 million tons harvested in the 2025/2026 season [18]. The processing of sugarcane for sugar and ethanol production generates waste (including bagasse and leaves), which is commonly burned in cogeneration systems to produce electricity. It is estimated that for each ton of bagasse burned, 6.2 kg (0.62%) of ash is generated. Nowadays, Brazil produces around 4.5 million tons of sugarcane bagasse ash annually, with a forecast of 5 million tons in the coming years [19–21]. Due to the lack of established applications, much of this ash is stockpiled in industrial yards, posing environmental and logistical challenges.

In addition to conventional sugarcane, energy cane is a recently developed variety optimized for high biomass yield and second-generation ethanol production. Compared to traditional sugarcane, energy cane exhibits physiological differences that yield taller, thinner, and denser stalks, resulting in increased biomass yield [22,23]. Its higher fiber content and productivity—up to three times that of conventional sugarcane—make energy cane an attractive energy crop [23,24]. Within this context, previous studies evaluating the use of sugarcane bagasse ash as SCM have reported favorable pozzolanic reactivity, leading to improvements in mechanical properties, greater durability, greater resistance to acid and sulfate attacks, and even a reduction in the size of the pores of the cement matrix [19,21,25].

The assessment of alternative SCMs requires not only mechanical and durability testing but also environmental evaluation. Life cycle assessment (LCA) provides a robust methodology for quantifying environmental impacts and identifying trade-offs across impact categories such as climate change, human health, and resource depletion [26,27]. Several LCA studies have examined the incorporation of SCM in cement matrices, comparing its potential environmental performance with that of conventional production [6,28–31]. In particular, the use of sugarcane bagasse ash has been shown to offer a high mitigation potential across several environmental impact categories [32,33]. However, LCA studies on the use of ash from energy cane are absent from the literature.

Several studies have investigated sugarcane bagasse ash as a supplementary cementitious material (SCM), assessing its mechanical performance [19,21,25] and environmental impacts [20,34–36], demonstrating both technical feasibility and a reduction in environmental burdens compared to conventional composites. However, the emerging energy cane variety remains largely unexplored in this context, with only one study indicating that its properties show potential for use as an SCM [37].

In this context, energy cane differs significantly from conventional sugarcane in terms of biomass yield, fiber content, and agricultural management [22,23], which may substantially influence both its pozzolanic potential and its environmental profile. To the best of the authors' knowledge, no study has evaluated the mechanical performance and environmental impacts of energy cane ash as an SCM in cementitious composites.

Therefore, this study aims to assess the technical and environmental performance of Portland cement mortars incorporating sugarcane and energy cane ashes as SCMs. Mechanical performance is evaluated through compressive strength and accelerated carbonation tests, while environmental impacts are quantified using a cradle-to-gate LCA in accordance with ISO 14040/44 [38,39] and the ReCiPe 2016 [40] impact assessment method. By integrating experimental performance data with environmental modeling, this work advances knowledge on biomass-derived SCMs and provides new insights into the potential of energy cane ash as a sustainable alternative for reducing the environmental footprint of cement-based materials.

2. Materials and Methods

This study evaluated the mechanical and environmental performance of mortars incorporating sugarcane ash and energy cane ash as partial replacements for Portland cement, aiming to determine the required amounts of raw materials to achieve 1 MPa of compressive strength. These data have also been used to determine the mortar with the lowest impact scores using an LCA. The methodology for the technical assessment was based on a literature review of standards and studies on mortars with partial replacement of cement with biopozzolans. For the LCA, the ISO 14040/44 [38,39] and the relevant LCA literature were followed.

2.1. Raw Materials

To compose the cement matrix of the composites, Portland cement CPV–ARI, from the Cauê brand and with high early strength (NBR 16697:2018), was used [41]. The choice of CPV–ARI cement is due to the fact that it consists predominantly of clinker and does not have mineral additions in its composition that can interact with the materials under study.

The sugarcane used was the RB 867515 variety, obtained from a sugar- and ethanol-producing company in Pirassununga-SP. This variety was chosen because it is the most planted in Brazil, representing 15.7% of the cultivated area [42]. The energy cane was provided by the company VIGNIS S.A., which conducts a genetic improvement program in the city of Santo Antônio da Posse-SP (Brazil). In particular, the variety chosen for the experiment was the VIGNIS 5. The productivity of the varieties was 90 t/ha and 180 t/ha for sugarcane and energy cane, respectively. The energy cane and sugarcane samples were collected in the field and subsequently washed to carefully eliminate any residual soil contamination.

Silica fume powder type 920U was used as commercial pozzolan, with a high silicon dioxide content and density of 200–350 kg/m^3, supplied by Elkem ASA Materials, São Paulo (Brazil). This pozzolan was chosen for its high pozzolanic reactivity and its availability on the Brazilian market.

2.2. Obtaining Energy Cane and Sugarcane Ashes

To obtain the ashes, sugarcane and energy cane stalks and leaves were separately calcined in a resistive furnace (Jung, model 10013, 7000 W, Blumenau, Santa Catarina, Brazil) at 600 °C for 1 h, with a heating ramp of 4 °C/min. The ashes were removed immediately after burning and cooled at room temperature (25 ± 3 °C). This condition was chosen because calcination at 600 °C for 1 h is sufficient to remove the organic matter while preserving silica predominantly in its amorphous form, thereby avoiding its transformation into crystalline phases and maintaining its pozzolanic reactivity [43,44]. The ashes resulting from the different parts of sugarcane and energy cane were named accordingly: sugarcane stalk ash (SCAS), energy cane stalk ash (ECAS), sugarcane leaf ash (SCAL), energy cane leaf ash (ECAL), sugarcane ash (a mixture of stalk and leaf ashes) (SCA), and energy cane ash (a mixture of stalk and leaf ashes) (ECA). After calcination, they were ground in a rotary ball mill (Tecnal, Piracicada, São Paulo, Brazil) at 200 RPM for 30 min, yielding particle sizes mostly below 20 µm. Soluble products, mainly potassium, chlorine, and sulfur, were extracted by washing: first, 5 g of ash was mixed with 500 mL of deionized water at 60 °C for 5 min under stirring (IKA C-MAG HS 10–220 V, IKA-Werke, Staufen, Germany) and filtered; then, the ashes were stirred with 200 mL of deionized water at 60 °C for 3 h, filtered, and oven-dried at 60 °C for 24 h [45]. Removing these compounds is important to avoid interference with cement hydration and to increase silica content. Moreover, the washing effluent, rich in potassium, can be reused in the fertigation of sugarcane or other crops.

2.3. Methodology for Evaluating the Influence of Biopozzolans on Portland Cement Mortars

For the mortar studies, specific mixtures of washed stalk ashes and leaf ashes from sugarcane (SCA) and from energy cane (ECA) were used. These mixtures were chosen for these analyses as they reflect the industrial reality in which both parts are burned together. Thus, in the case of SCA, it consists of 44% stalk ashes and 56% leaf ashes, while ECA consists of 47% stalk ashes and 53% leaf ashes.

To assess the influence of biopozzolans on the performance of Portland cement mortars, mortars with the mix 1:2.5:0.5 (cement–sand–water) were evaluated on a mass basis (weight) and different replacements of cement, namely, 0%, 5%, 10%, and 20% of washed SCA or ECA and 10% silica fume. These proportions were chosen because they represent the mortar dosage of traditional concrete, with a cement consumption of around 300 kg/m^3, a sand content equal to 750 kg/m^3, and a water/binder ratio of 0.5 [46]. The specimens were submitted to compressive strength and accelerated carbonation tests. To this end, they were molded in a cylindrical shape measuring 5 cm × 10 cm (diameter × height) and kept under wet curing (RH = 95 ± 2%), in an environment with a temperature of 25 ± 2 °C until test ages (7, 14, and 28 days).

The mortars evaluated in this study and their corresponding acronyms are as follows: reference mortar (MREF), mortar with 10% silica fume (M10SF), mortar with 5% sugarcane ash (M5SCA), mortar with 10% sugarcane ash (M10SCA), mortar with 20% sugarcane ash (M20SCA), mortar with 5% energy cane ash (M5ECA), mortar with 10% energy cane ash (M10ECA), and mortar with 20% energy cane ash (M20ECA).

2.3.1. Compressive Strength Test

The compressive strength test was performed on 5 specimens of each mixture at 7 and 28 days under wet curing for each dosage studied, in accordance with ABNT NBR 5739 [47]. Cylindrical specimens measuring 5 cm × 10 cm (diameter × height) were tested and rectified at their bases. The evaluation took place using the EMIC universal testing machine, model DL-30000 (EMIC, São José dos Pinhais, Paraná, Brazil), equipped with a 50 kN load cell.

2.3.2. Accelerated Carbonation

After reaching the test ages of 1, 7, and 28 days under wet curing, the specimens were sealed on their curved side and at the flush base surface, always opting for the worst finish. The specimens were then subjected to an accelerated carbonation test in a climate chamber with temperature and humidity control (Espec, model EPL–4H, Hudsonville, Michigan, USA), with an internal volume of 1 m^3, CO_2 concentration of 10%, humidity of 65%, and 23 ± 2 °C). A CO_2 concentration of 10% was selected because it is widely adopted in accelerated carbonation tests as a compromise between reducing the testing time and preserving carbonation mechanisms representative of natural exposure. Higher CO_2 concentrations may alter the carbonation mechanism and reaction products, whereas lower concentrations require substantially longer testing periods [48,49]. The evolution of carbonation depth was evaluated using a phenolphthalein acid–base indicator.

2.4. Life Cycle Assessment Methodologyb

An attributional LCA was performed to evaluate the environmental impacts of replacing cement in mortars with sugarcane or energy cane ashes (0, 5, 10, and 20%) or with 10% silica fume. The results aim to identify the raw material combination with the lowest impacts for use in mortars and cementitious composites, promoting more environmentally friendly alternatives for the construction industry. Although the study focuses on mortars, the objective is to extend its use to concrete compositions.

The mortars produced fall under Class I of ABNT NBR 6118:2023 [50], which covers concretes with compressive strengths between 20 and 50 MPa at 28 days. Since all mortars met the required strength class, the functional unit was defined as the amount of mortar required to achieve 1 MPa of compressive strength, allowing a performance-based comparison among mixtures with different mechanical efficiencies. Although the carbonation tests revealed differences in durability-related performance among the mixtures, these were not incorporated into the functional unit because the present study adopted a cradle-to-gate perspective, which excludes the use phase and service life considerations. Therefore, the functional unit reflects equivalent structural performance in terms of compressive strength rather than equivalent durability. The reference flows were calculated accordingly by considering the amount of material used for each mixture and the compressive strength obtained in the laboratory. For each composition, the amount of material used in each cylindrical specimen was recorded. Then, this amount was divided by the average compressive strength obtained at 28 days for the specimens of the same composition, measured in MPa. This enabled the determination of the amount of material required to achieve 1 MPa of compressive strength at 28 days, as presented in Table 1. This method allows for the evaluation of the efficiency of each mixture in terms of compressive strength per unit of material used, facilitating comparisons across compositions and optimizing resource use.

Table 1. Reference flows considered for each mortar assessed, for the functional unit of 1 MPa.

Mortars	Acronyms	Raw Materials (kg)					
		Cement	Sand	Silica Fume	Sugarcane Ash	Energy Cane Ash	Water
Reference Mortar	MREF	0.0028	0.0069	0.0000	0.0000	0.0000	0.0014
Mortar with 10% Silica Fume	M10SF	0.0030	0.0082	0.0003	0.0000	0.0000	0.0017
Mortar with 5% sugarcane ash	M5SCA	0.0031	0.0081	0.0000	0.0002	0.0000	0.0016

Table 1. *Cont.*

Mortars	Acronyms	Raw Materials (kg)					
		Cement	Sand	Silica Fume	Sugarcane Ash	Energy Cane Ash	Water
Mortar with 10% sugarcane ash	M10SCA	0.0024	0.0068	0.0000	0.0003	0.0000	0.0014
Mortar with 20% sugarcane ash	M20SCA	0.0025	0.0079	0.0000	0.0006	0.0000	0.0016
Mortar with 5% energy cane ash	M5ECA	0.0032	0.0083	0.0000	0.0000	0.0002	0.0017
Mortar with 10% energy cane ash	M10ECA	0.0025	0.0071	0.0000	0.0000	0.0003	0.0014
Mortar with 20% energy cane ash	M20ECA	0.0026	0.0082	0.0000	0.0000	0.0007	0.0016

A cradle-to-gate system was adopted, including raw material extraction and processing, transport to the mortar industry, and mortar production. For cement (Figure 1), the boundaries encompassed the extraction of limestone, clay, iron ore, and gypsum; cement manufacture; and transport to the mortar site.

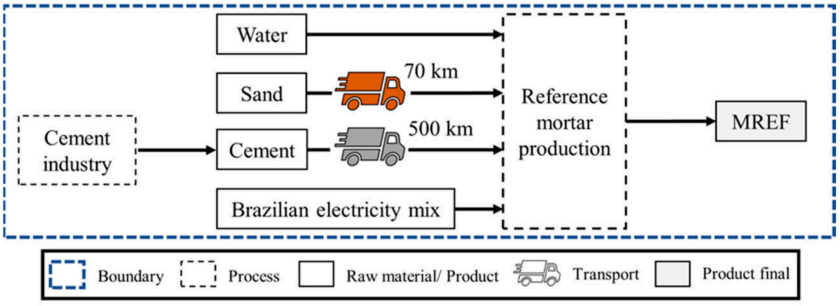

Figure 1. System boundaries of the reference mortar.

For mortars with silica fume (Figure 2), the boundaries included raw material extraction, production, transport to the cement industry (where 10% of the cement is replaced), and subsequent transport to the mortar site. Silica fume is a by-product of ferrosilicon or silicon metal production.

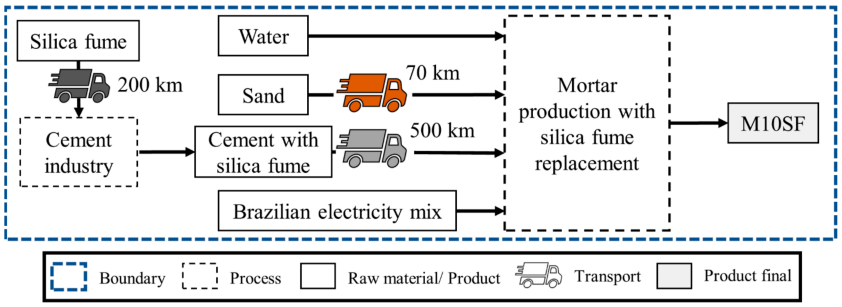

Figure 2. System boundaries of the mortar with silica fume.

For mortars with cane ashes (Figures 3 and 4), the system considered cane cultivation and harvesting, sucrose extraction (yielding bagasse), combustion of bagasse and straw to obtain ash, ash grinding and washing, transport to the cement industry for partial replacement, and transport of cement–ash blends to the mortar site.

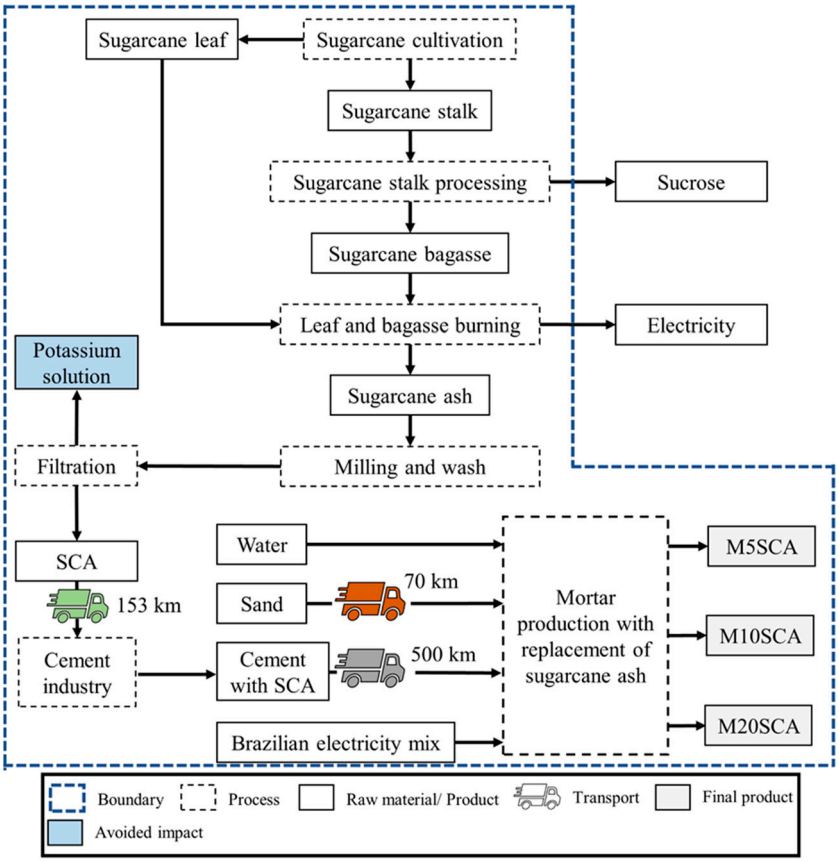

Figure 3. System boundaries of the mortar with sugarcane ash (SCA).

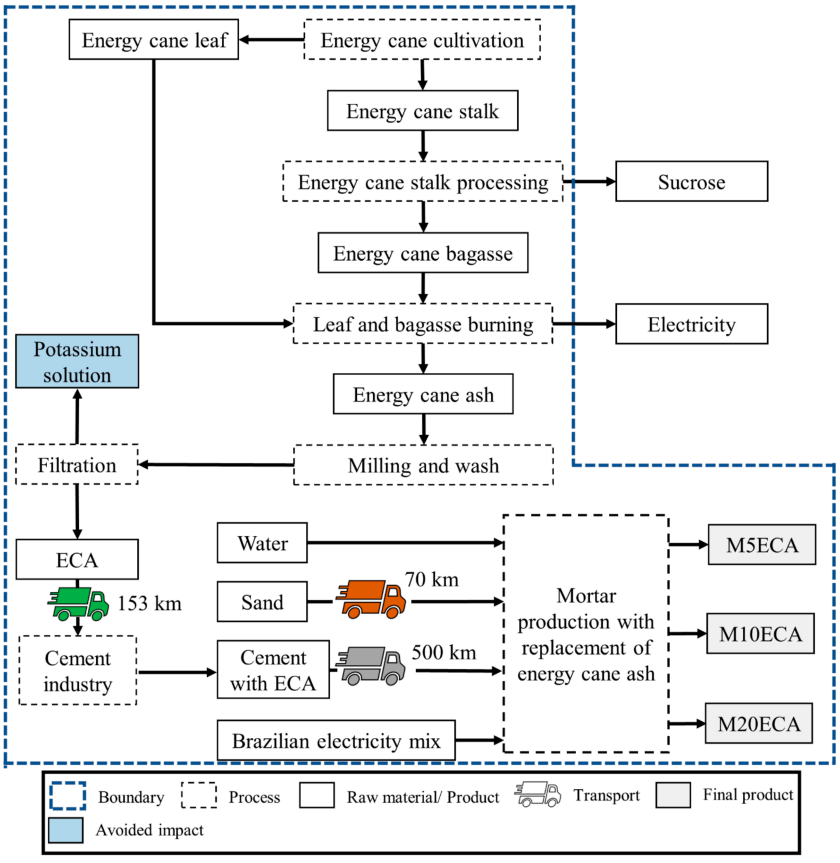

Figure 4. System boundaries of the mortar with energy cane ash (ECA).

No allocations were applied to Portland cement, sand, silica fume, and mortar, as they are the only products of their processes. For sugarcane and energy cane, environmental burdens were distributed among products using a mass-based criterion based on Spósito et al. [20]. It must be noted that, for both energy and sugarcane, the ash quantities resulting from the burning process were determined in the laboratory, where ash from bagasse and leaves was separately quantified.

For sugarcane, the first allocation occurs at harvest: 9.39% of impacts are assigned to straw and 90.61% to stalk. During processing, 77.25% of stalk impacts are attributed to sucrose and 22.75% to bagasse. Bagasse and leaves are burned for cogeneration, producing ash as a residue without additional burdens. It is estimated that ashes account for 0.28% of the impacts associated with bagasse and 0.35% of those associated with straw. For energy cane, 15.37% of cultivation impacts are attributed to straw and 84.83% to stalk. When the stalk undergoes processing, the products obtained are sucrose and energy cane bagasse. In this second stage, 58.95% of the impacts are allocated to sucrose and 41.05% to bagasse. Cogeneration yields ashes, similar to sugarcane; no impacts from energy cogeneration are allocated to the ashes. It is considered that energy cane ashes represent 0.70% of the impacts related to bagasse and 0.80% of those related to leaf.

Both ashes were washed to remove potassium, as it may compromise the durability of cement. Water consumption was measured at 700 mL per 5 g of ash. Approximately 90% of the wash water used in the ash extraction process was experimentally recovered, while 10% remained retained in the filter cake. The potassium concentration in the recovered wash water was experimentally determined following CETESB/ANA [51] sampling procedures and APHA [52] analytical methods, yielding values of 1370 mg L^{-1} for sugarcane ash and 1800 mg L^{-1} for energy cane ash.

Based on these measured concentrations, the amount of potassium available in the recovered wash water was quantified and translated into an equivalent amount of avoided potassium fertilizer production, assuming substitution through fertigation. This avoided production was then used to calculate the environmental credits attributed to potassium recovery in the life cycle assessment. After washing, the ashes were ground and transported for use.

Transport was modeled considering that it is made by truck and that the mortar site is located at São Paulo state. Average distances were adopted from previous studies: 153 km between sugar/alcohol industries and cement plants (32 t trucks) [53], 70 km for sand (45 t trucks) [54], 200 km for silica fume (32 t trucks), and 500 km between cement and mortar plants (32 t trucks) [55]. The composition of the Brazilian energy mix was obtained from the National Energy Balance [56] (Table 2). Energy use included 1.5 kW for a 400 L mixer (Menegotti, Jaraguá do Sul, Santa Catarina, Brazil) (TCPO, 2010) and 34.2 kWh/t for ash grinding in a ball mill [57]. Secondary data were obtained from GaBi 6 and Ecoinvent 3.8 (Table 3). The GaBi 6 database was used for electricity modeling, as it allows adjustment of the Brazilian energy mix to reflect current conditions, ensuring representativeness and reliability.

Table 2. Total electricity supply by source [56].

Energy Sources	Amount (%)
Hydro	61.9
Wind	11.8
Solar	4.4
Sugarcane bagasse	4.7
Black liquor	2.5

Table 2. *Cont.*

Energy Sources	Amount (%)
Other renewables	0.8
Natural gas	6.1
Nuclear	2.1
Net imports	1.9
Steam coal	1.2
Diesel oil	0.9
Other non-renewables	1.8

Table 3. Secondary data and respective sources used for the LCA of mortars.

Inputs	Explanation of Inputs	Flows Software Gabi	Data Source
Cement	Cement used in the production of mortars	BR: cement production, Portland ecoinvent 3.8	Ecoinvent 3.8
Transport cement	Transport used from the cement industries to the mortar industries	RoW: transport, freight, lorry 16–32 metric ton, EURO4 ecoinvent 3.7.1	Ecoinvent 3.7.1
Sand	Sand used in the production of mortars	BR: sand quarry operation, extraction from river bed ecoinvent 3.7.1	Ecoinvent 3.7.1
Transport Sand	Transport used from industries to mortar industries	RoW: transport, freight, lorry > 32 metric ton, EURO4 ecoinvent 3.7.1	Ecoinvent 3.7.1
Water	Water used in the production of mortars and washing of ash	BR: tap water production, conventional treatment ecoinvent 3.7.2	Ecoinvent 3.7.2
Electricity	Electricity used in the ash grinding and mortar mixing processes, modified according to the Brazilian energy matrix presented in Table 4.	BR: Electricity grid mix Brazil (2022) <Mfg>	Gabi 6 (Modified according to Table 2)
Silica fume	Silica fume used as a partial replacement for cement	RoW: steel production, electric, low-alloyed ecoinvent 3.7.1	Ecoinvent 3.7.1
Transport silica fume	Transport used from the silica fume industries to the cement industries	RoW: transport, freight, lorry 16–32 metric ton, EURO4 silica ecoinvent 3.7.1	Ecoinvent 3.7.1
Sugarcane stalk ash	Sugarcane ash allocated from the sugarcane bagasse production process by 0.28%	BR: Bagasse Sugarcane ecoinvent 3.7.1	Ecoinvent 3.7.1 (Allocated)
Sugarcane leaf ash	Sugarcane ash allocated from the sugarcane production process at 0.35%	BR-SP: sugarcane production ecoinvent 3.7.1	Ecoinvent 3.7.1 (Allocated)
Energy cane stalk ash	Energy cane ash allocated from the sugarcane bagasse production process by 0.70%, twice the productivity being considered.	BR: Bagasse Sugarcane ecoinvent 3.7.1	Ecoinvent 3.7.1 (Modified and allocated)

Table 3. *Cont.*

Inputs	Explanation of Inputs	Flows Software Gabi	Data Source
Energy cane leaf ash	Energy cane ash allocated from the sugarcane production process by 0.80%, twice the productivity being considered.	BR-SP: sugarcane production ecoinvent 3.7.1	Ecoinvent 3.7.1 (Modified and allocated)
Potassium	Potassium removed in the process of washing sugarcane and energy cane ash	BR: Inorganic potassium fertiliser, as K_2O (Reverse) ecoinvent 3.8	Ecoinvent 3.7.1
Wash water	Water removed in the washing process	BR: tap water production, conventional treatment (Reverse) ecoinvent 3.7.2	Ecoinvent 3.7.2
Transport ashes	Transport used from the industries where sugarcane ash and energy cane are obtained to the cement industries	RoW: transport, freight, lorry 16–32 metric ton, EURO4 ecoinvent 3.7.1	Ecoinvent 3.7.1

The impact assessment followed the ReCiPe 2016 v1.1 method [40], given the absence of a consolidated Brazilian methodology. The hierarchical perspective of ReCiPe 2016 assessment method was adopted, with results presented for the 10 impact categories selected for their relevance to mortar production as well as environmental and health aspects [20,32,33]. The impact categories and their respective acronyms are as follows: climate change, including biogenic carbon (CC+) measured in kg CO_2 equivalent; fine particulate matter formation (FPMF) measured in kg $PM_{2.5}$ equivalent; fossil depletion (FD) in kg oil equivalent; freshwater consumption (FC) in cubic meters; human toxicity, cancer (HT, cancer) in kg 1,4-dichlorobenzene equivalent; land use (LU) in annual crop equivalents per year; metal depletion (MD) in kg copper equivalent; stratospheric ozone depletion (SOD) in kg CFC-11 equivalent; terrestrial acidification (TA) in kg SO_2 equivalent; and terrestrial ecotoxicity (TE) in kg 1,4-dichlorobenzene equivalent. All LCA calculations were performed using GaBi 6 software [58].

3. Results

3.1. Characterization of Raw Materials

The chemical characterization, X-ray diffraction, particle size distribution, density values of sugarcane and energy cane ashes were previously published in Lyra et al. [37,59]. The chemical characterization main values are presented in Tables 4 and 5 and were used as the basis for this study.

Table 4. Chemical composition (% in oxides) and loss on ignition of sugarcane and energy cane ash. SCAS: Sugarcane stalk ash, ECAS: energy cane stalk ash, SCAL: sugarcane leaf ash, ECAL: energy cane leaf ash [37,59].

Oxides (%)	Unwashed						Washed					
	SCAS	ECAS	SCAL	ECAL	SCA	ECA	SCAS	ECAS	SCAL	ECAL	SCA	ECA
MgO	9.9	3.86	12.67	8.49	11.34	6.43	26.96	20.15	9.93	5.12	16.02	10.75
SiO_2	6.34	4.46	28.47	45.73	18.82	27.11	34.92	40.67	60.59	65.16	51.42	58.49
P_2O_5	6.09	5.51	2.97	2.87	4.42	4.18	9.19	15.97	2.74	2.5	5.04	6.36
SO_3	10.17	4.21	13.08	5.56	11.93	5.01	0	0	0.77	0.92	0.5	0.66
K_2O	51.96	47.48	19.07	11.37	38.29	27.75	7.36	5.39	5.16	6.35	5.95	4.5

Table 4. *Cont.*

Oxides (%)	Unwashed						Washed					
	SCAS	**ECAS**	**SCAL**	**ECAL**	**SCA**	**ECA**	**SCAS**	**ECAS**	**SCAL**	**ECAL**	**SCA**	**ECA**
CaO	10.91	6.41	20.86	21.42	11.6	14.64	17.76	13.56	16.77	16.58	17.12	15.39
TiO_2	0	0	0.18	0.31	0	0.11	0.27	0.75	0.42	0.43	0.37	1.2
MnO	0	0.06	0.31	0.25	0.17	0.17	0.62	0.23	0.5	0.22	0.54	0.25
Fe_2O_3	0.06	0.12	0.42	1.13	0.27	0.67	2.23	0.53	2.36	1.78	2.22	1.69
Cl	4.3	27.5	1.82	2.66	2.85	13.58	0.17	2.29	0.41	0.46	0.1	0.04
ZnO	0	0	0	0	0	0	0.27	0.13	0	0	0.32	1.44
L.O.I.	0.27	0.39	0.17	0.22	0.21	0.30	0.25	0.33	0.35	0.47	0.31	0.43

Table 5. Chemical composition (% in oxides) and loss on ignition of cement and silica fume [37,59].

Oxides (%)	Cement	Silica Fume
Al_2O_3	3.06	<0.10
SiO_2	19.27	95.1
SO_3	3.64	–
K_2O	0.62	0.91
CaO	66.85	0.25
TiO_2	0.27	<0.10
Fe_2O_3	3	0.35
Na_2O	–	0.26
MgO	–	0.33
L.O.I.	3.29	1.7

Potassium, chlorine, and sulfur are present in significant amounts in the ashes and may compromise the durability of cementitious systems, promoting alkali–aggregate reactions, reinforcement corrosion, and delayed ettringite formation, respectively. Due to their solubility, these compounds can be effectively removed by washing, thereby increasing the relative silica content. Silicon, concentrated mainly in sugarcane leaves, enhances the potential pozzolanic activity of the washed ashes.

According to ABNT NBR 12653 [60], the minimum requirement of 50% for the combined content of SiO_2, Al_2O_3, and Fe_2O_3 was only achieved after washing: 51.42% for sugarcane ash and 58.49% for energy cane ash. The alkali and sulfur contents were also reduced to acceptable levels, while the loss on ignition remained below 6% in both cases. By contrast, silica fume, included here for comparison, consists of approximately 95% SiO_2.

The X-ray diffraction patterns are illustrated in Figure 5 for comparison with silica fume. After washing, the removal of soluble crystalline phases facilitated the identification of residual components. The mineralogical composition of the ashes before washing has been previously reported by the authors [37], showing intense diffraction peaks associated with potassium-bearing phases, such as sylvite and arcanite. The marked reduction of these phases after the washing process, together with the XRF results, confirms the effective removal of soluble potassium compounds.

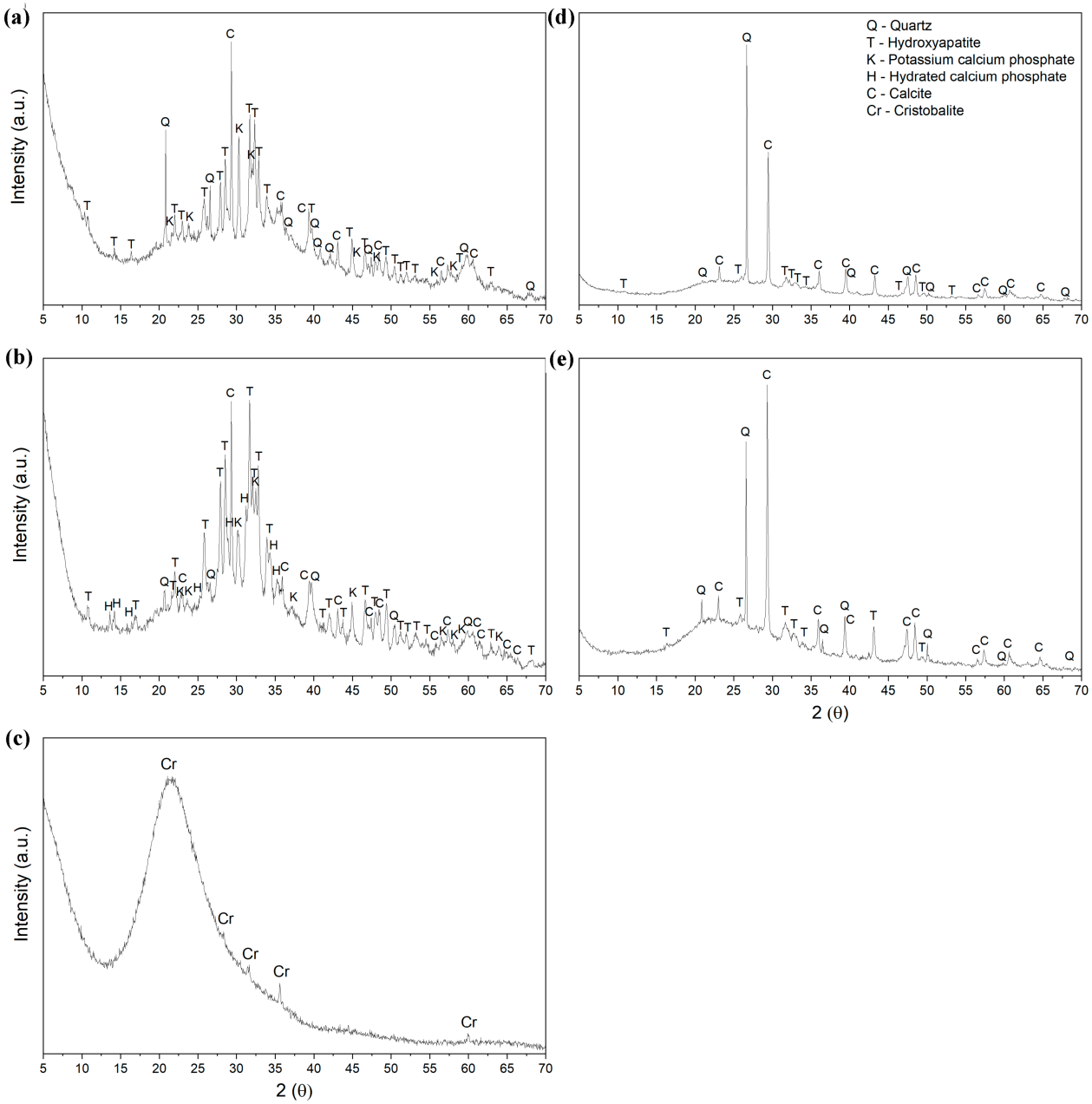

Figure 5. X-ray diffraction patterns of the pozzolans, (**a**) SCAS: Sugarcane stalk ash, (**b**) ECAS: energy cane stalk ash, (**c**) SCAL: sugarcane leaf ash, (**d**) ECAL: energy cane leaf ash, and (**e**) silica Fume.

For stalk ash, from both energy and sugarcane, quartz, calcite, and traces of hydroxyapatite were predominant, while SCAL and ECAL showed higher quartz and calcite contents, consistent with their chemical composition. The quartz detected is likely associated with soil contamination from the leaves, while no crystalline forms of silica (e.g., tridymite or cristobalite) were identified at the calcination temperature of 600 °C, indicating that the remaining silica is predominantly amorphous and potentially reactive. Silica fume, in turn, exhibited an almost entirely amorphous profile, with only small cristobalite peaks.

The particle size distribution is summarized in Table 6, along with silica fume and cement. For both cane varieties, stalk ashes (SCAS and ECAS) showed smaller average particle diameters than leaf ashes (SCAL and ECAL). Most ashes showed mean diameters below 20 μm, except for ECAL (21.21 μm), which is still within the expected range for pozzolanic activity. In contrast, the densified silica fume exhibited a higher apparent mean

diameter (36.63 µm), reflecting agglomeration during handling rather than its intrinsic particle size.

Table 6. Equivalent particle diameter of raw materials. D10: particle size below which 10% of the material is located; D50: particle size below which 50% of the material is located; D90: particle size below which 90% of the material is located. SCAS: Sugarcane stalk ash, ECAS: energy cane stalk ash, SCAL: sugarcane leaf ash, ECAL: energy cane leaf ash [37,57].

Raw Material	D_{10} (µm)	D_{50} (µm)	D_{90} (µm)	Mean Diameter (µm)
SCAS	2.12	10.62	35.73	12.3
ECAS	2.57	13.96	42.44	17.14
SCAL	1.86	9.31	31.08	13.52
ECAL	3.47	16.53	44.41	21.21
Silica fume	6.15	32.15	73.64	36.63
Cement	3.94	12.71	24.15	15.5

The actual density (g/cm^3) of the analyzed materials was determined with the following average values and corresponding standard deviations: the ash from the SCAS showed an average value of 2.54 ± 0.01 g/cm^3; the ash from the ECAS, 2.40 ± 0.01 g/cm^3; the ash from the SCAL, 2.46 ± 0.02 g/cm^3; and the ash from the ECAL, 2.46 ± 0.01 g/cm^3. For comparison, silica fume has a density of 2.30 g/cm^3 (information provided by the manufacturer), and cement 3.10 g/cm^3. As expected, the ashes and silica fume exhibited lower densities than cement due to their higher internal porosity. This characteristic may influence mortar density but also favors packing and reactivity when used as supplementary cementitious materials.

3.2. Assessment of the Influence of Biopozzolans on the Performance of Portland Cement Mortars

The results of the compressive strength of mortars (Figure 6) show that at 7 days, the reference mortar reached 32.38 MPa, which is the highest value obtained.

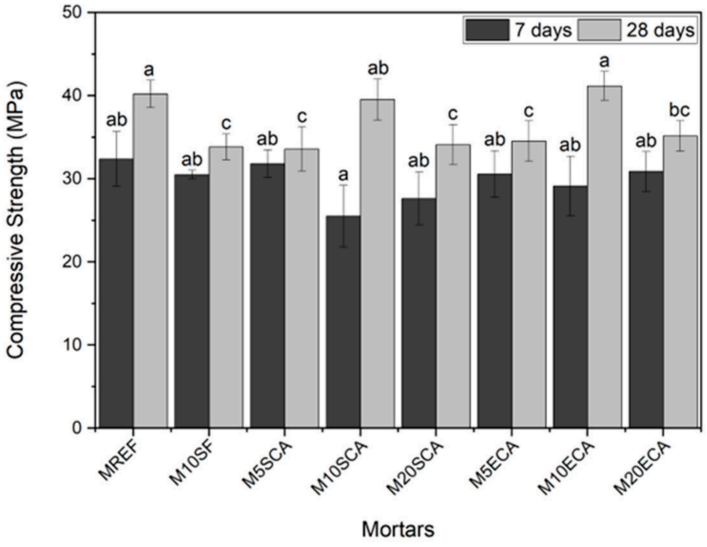

Figure 6. Compressive strength (MPa) of mortars with partial replacement of cement by pozzolans, after 7 days and 28 days of curing. Different lowercase letters indicate statistically significant differences among the mixtures according to Tukey's multiple comparison test at the 5% significance level ($p < 0.05$). Columns sharing at least one letter are not significantly different.

Strengths relative to the reference were as follows: 94.23% (M10SF), 98.25% (M5SCA), 78.77% (M10SCA), 85.28% (M20SCA), 94.43% (M5ECA), 89.96% (M10ECA), and 95.39% (M20ECA). Only M10SCA showed a significant statistical difference; all other mortars performed similarly to the reference. After 28 days, strengths increased, with the reference reaching 40.18 MPa. The lowest values were for M10SF, M5SCA, M20SCA, and M5ECA (83–86% of reference), while M10SCA and M20ECA reached 98.34% and 87.46%, respectively. The highest value was obtained for M10ECA (102.43% of reference), though without a significant difference from the reference. Among the substitution levels evaluated, the 10% replacement level provided the best overall mechanical performance for both sugarcane varieties. However, because only three discrete replacement levels were investigated, this result should not be interpreted as indicating a universal optimum substitution level.

This behavior is consistent with previous studies on sugarcane bagasse ash (SCBA), which report optimal replacement levels between 10% and 15%, where pozzolanic reactions contribute to strength development without significantly reducing clinker content [20].

At higher replacement levels, the literature generally reports a reduction in mechanical performance due to dilution effects and lower clinker availability [20]. However, in the present study, even mixtures with 20% replacement maintained acceptable strength levels, suggesting that both SCA and ECA exhibit sufficient reactivity to compensate, at least partially, for clinker reduction. The superior performance observed for ECA can be attributed to its higher silica content and improved reactivity after washing, which enhances the formation of secondary calcium silicate hydrate (C–S–H).

Carbonation depth after 1, 7, and 28 days is shown in Figure 7.

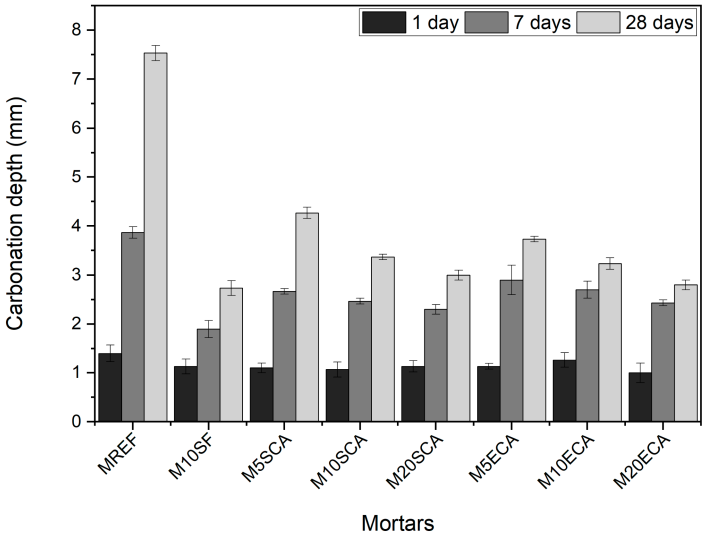

Figure 7. CO_2 penetration depth in mortars after 1, 7 and 28 days of carbonation.

All pozzolanic mortars showed reduced carbonation compared to the reference, with final reductions of 60% (M10SF, M10SCA, M20SCA, M10ECA, M20ECA), 50% (M5ECA), and 40% (M5SCA). Thus, pozzolans significantly improved durability, especially at 20% replacement, which performed comparably to 10% silica fume. In the context of carbonation, 20% replacement provides more pozzolanic material than 10% and decreases the available CH, thus forming C-S-H (hydrated calcium silicates). These C-S-H products, derived from the pozzolanic reaction, close the pores and make carbonation more difficult. Therefore, the role of pozzolans is more significant in reducing carbonation potential than in increasing compressive strength. This explains, for example, why a 5% replacement results in more carbonation as there are fewer closed or blocked pores.

Notably, the results suggest that the role of SCMs in enhancing durability may be more pronounced than their effect on compressive strength. Even mixtures with moderate strength gains exhibited substantial reductions in carbonation, highlighting the importance of microstructural densification. This finding reinforces the need to consider durability indicators alongside mechanical properties when evaluating the performance of alternative binders.

3.3. Life Cycle Assessment

The LCA results for the functional unit of 1 MPa for the eight mortars (Table 7) show that the mortar with 10% silica fume had the worst environmental performance in nine of the ten categories, while M20SCA performed worst in only one. In contrast, M20ECA achieved the best results in six categories and M10ECA in one, with similar scores to M20ECA in the others. M20SCA, M10SCA, and MREF each performed best in one category. Overall, replacing cement with 10–20% energy cane ash improved environmental performance, primarily by reducing cement consumption and the by-products generated during ash production and washing. The differences between the best and worst performances ranged from 20% for LU to 99% for HT-C, confirming that both commercial and biomass-based pozzolans significantly influence the environmental profile of mortars.

Table 7. Environmental impacts of the eight production systems for different mortars per functional unit (1 MPa). The lowest impacts (more beneficial) are shaded in green and the greatest (more harmful) in red.

Impact Categories	MREF	M10SF	M5SCA	M10SCA	M20SCA	M5ECA	M10ECA	M20ECA
CC+	2.72×10^{-3}	3.22×10^{-3}	3.09×10^{-3}	2.40×10^{-3}	2.44×10^{-3}	2.95×10^{-3}	2.24×10^{-3}	2.21×10^{-3}
FPMF	2.61×10^{-6}	3.44×10^{-6}	2.94×10^{-6}	2.27×10^{-6}	2.24×10^{-6}	2.85×10^{-6}	2.17×10^{-6}	2.16×10^{-6}
FD	3.55×10^{-4}	4.87×10^{-4}	3.99×10^{-4}	3.06×10^{-4}	2.93×10^{-4}	3.83×10^{-4}	2.88×10^{-4}	2.76×10^{-4}
FC	1.79×10^{-5}	2.53×10^{-5}	2.76×10^{-5}	2.83×10^{-5}	4.96×10^{-5}	2.66×10^{-5}	2.70×10^{-5}	4.30×10^{-5}
HT-C	2.29×10^{-3}	1.85×10^{-1}	2.42×10^{-3}	1.73×10^{-3}	1.20×10^{-3}	2.27×10^{-3}	1.53×10^{-3}	1.01×10^{-3}
LU	1.46×10^{-4}	1.75×10^{-4}	1.71×10^{-4}	1.40×10^{-4}	1.52×10^{-4}	1.70×10^{-4}	1.42×10^{-4}	1.65×10^{-4}
MD	5.83×10^{-6}	1.49×10^{-5}	6.30×10^{-6}	4.59×10^{-6}	3.69×10^{-6}	5.97×10^{-6}	4.19×10^{-6}	3.31×10^{-6}
SOD	9.58×10^{-10}	1.19×10^{-9}	9.95×10^{-10}	6.88×10^{-10}	4.21×10^{-10}	9.84×10^{-10}	6.94×10^{-10}	5.51×10^{-10}
TA	7.04×10^{-6}	8.60×10^{-6}	7.96×10^{-6}	6.15×10^{-6}	6.10×10^{-6}	7.72×10^{-6}	5.92×10^{-6}	5.99×10^{-6}
TE	1.01×10^{-2}	1.23×10^{-2}	1.13×10^{-2}	8.70×10^{-3}	8.25×10^{-3}	1.09×10^{-2}	8.14×10^{-3}	7.71×10^{-3}

Figure 8 presents the contribution analysis of the life cycle stages of the mortars to the evaluated impact categories, allowing the identification of environmental hotspots for each mortar.

Cement production is the stage that contributes the most to CC+ as it is the main raw material used in its manufacturing, accounting for 78 to 95% of the impact in this category, depending on the mortar composition. The M10SF mortar has the highest impact score in this category, 18.54% higher than that of MREF, as it requires more material, especially cement, to reach 1 MPa. Although silica fume production has lower GHG emissions than clinker, its emissions are higher than those of sugarcane and energy cane ashes, accounting for 9% of this category in M10SF.

It is important to highlight that most GHG emissions from cement production arise from clinker pyroprocessing, where raw materials are heated to high temperatures (1800–2000 °C). In this process, approximately 50% of CO_2 emissions originate from fossil fuel combustion, mainly coal and fuel oil, while the remaining 50% comes from limestone decarbonation during clinker formation [61,62]. Additional emissions also stem from transportation throughout the supply chain.

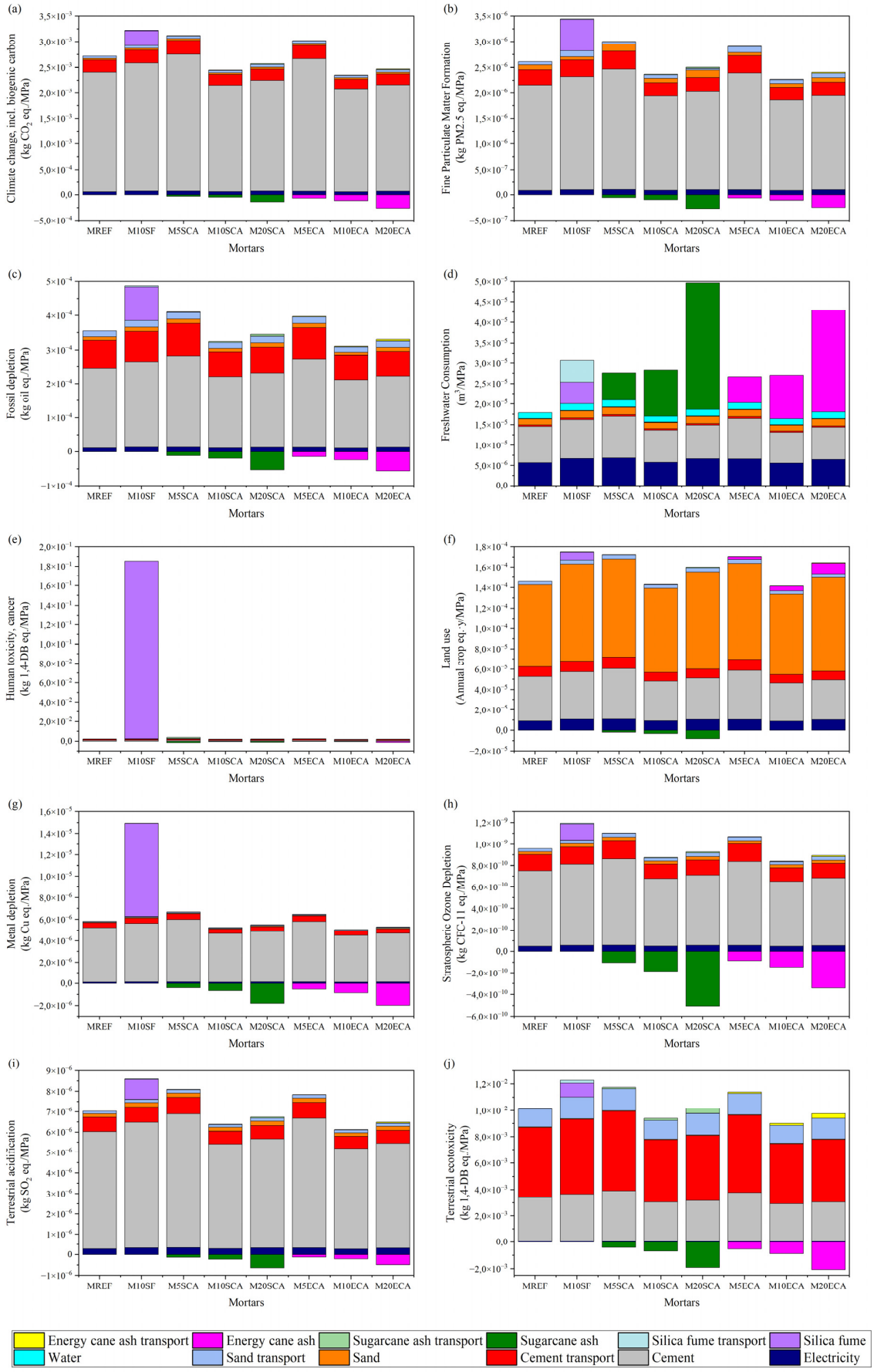

Figure 8. Contribution of the life cycle stages considered for the analyzed mortars to the impact categories.

Despite the reduction in cement consumption, mortars with 5% replacement using sugarcane or energy cane ashes achieved higher CC+ scores than MREF, as achieving the functional unit of 1 MPa required greater overall material consumption, and consequently, more cement. Conversely, M10ECA and M20ECA showed the lowest CC+ scores, 17.62% and 18.62% lower than MREF, respectively, because they require less cement to achieve the same strength. Furthermore, ashes from both cane types have a beneficial effect on CC+ due to CO_2 fixation during photosynthesis, as well as avoided burdens associated with potassium recovered from ash washing, which can be applied in agriculture and thus offset part of the environmental load from potassium production.

For FPMF, M10SF shows the worst performance, mainly due to its higher cement and silica fume consumption, being 32% higher than MREF. Cement contributed between 64% and 79%, depending on the mortar composition, while in M10SF, silica fume accounted for 18% of this category. For both cement and silica fume production, fine particles are primarily generated during the extraction of natural raw materials. In addition, particle formation also occurs during combustion in extraction equipment and in raw material processing, especially through grinding and crushing. Similar to CC+, mortars with 5% ash replacement exhibit higher impact scores than the reference mortar, due to the greater consumption of Portland cement. Although sugarcane ash production contributes to fine particle formation—mainly through agrochemical production in the field and fuel combustion for transport and harvesting—it results in a net negative contribution to this impact category, owing to the avoided burdens of K fertilizer production. Thus, the avoided burdens outweigh the emitted ones. M10ECA and M20ECA mortars have the lowest impact scores, being 16.89% and 17.15% lower than MREF, respectively, also due to reduced Portland cement consumption.

M10SF mortar exhibits the highest FD score, 37.10% above MREF, due to high diesel consumption during the extraction and processing of both silica fume and cement. In cement production, fossil resource use is particularly high during clinkerization, when raw materials are heated to elevated temperatures. Diesel is also consumed to transport raw materials to mortar industries. Cement contributes 61–66% of FD, depending on the mortar; transportation 18–24%; and silica fume 20% in M10SF. Mortars with 10% and 20% sugarcane ash show the lowest FD scores, 18.98% and 22.29% below MREF, as avoided burdens compensate for fossil resource consumption.

The highest FC scores are observed for M20SCA and M20ECA, 178% and 141% higher than MREF, respectively, due to water use in cane irrigation, ash production, and potassium extraction. Some water is returned through filtration, but part remains in the ashes and evaporates. Mortars with SCA show greater impacts (24–62%) than those with ECA (23.8–58%), since energy cane yields twice as much biomass per area, requiring less water. Consequently, 5% and 10% ash mortars also have higher FC than MREF. M10SF shows a 41% higher FC than MREF, attributable to higher consumption of cement and silica, as well as water use during silica fume production, particularly in cooling. Cement contributes 17–50%, silica 18%, and electricity 13–32%, reflecting Brazil's predominantly hydroelectric energy matrix.

Silica fume contributes substantially to HT-C, accounting for ≈99% in M10SF, making it the worst-performing mortar in this category, 79% higher than MREF. This is due to high fossil fuel use for machinery and transport, as well as the metallic silicon industry, both of which increase human toxicity. For the other mortars, the main contributors to HT-C are cement transportation (38–42%) and cement production (37–40%). Mortars M20SCA and M20ECA show reductions of 47.58% and 55.82%, respectively, compared to MREF.

For LU, M10SF shows the highest score, 19.82% above MREF. Across all mortars, sand extraction is the main contributor, accounting for 54–63%, while cement production

contributes 24–30% due to the extraction of natural resources (clay and limestone). For sugarcane and energy cane ashes, crop cultivation induces land transformation, occupation, and vacancy. Energy cane, despite yielding more ash per area, causes greater land alteration. The avoided burden from potassium recovered during ash washing offsets sugarcane impacts, but not those from energy cane. M10SCA and M10ECA perform best, 4.10% and 2.97% below MREF, due to lower cement and sand consumption to reach the functional unit.

M10SF mortar exhibits the highest MD score, 156.23% above MREF, mainly due to the consumption of aluminum, manganese, iron, chromium, and nickel in silica fume production, which accounts for 58% of the impact. Cement also contributes significantly (37–88%, depending on the mortar), as it contains iron and aluminum in clinker production. Consequently, M5SCA and M5ECA, with higher cement content, also show high MD scores. M20SCA and M20ECA perform best, as potassium recovered from ash washing offsets part of the impact, reducing MD by 36.61% and 43.14% relative to MREF.

Cement is the main contributor to SOD (63–73%, depending on the mortar), as clinkerization releases CFCs, bromine, chlorine, and fluorine, which deplete ozone. Cement transportation adds 14–16% to this impact. Silica fume production in M10SF accounts for 12% of SOD, which is 24.56% higher than in MREF. Although sugarcane and energy cane cultivation contribute to SOD, the by-products from ash washing offset this impact by avoiding the production of potassium fertilizer, resulting in a net negative contribution. Consequently, M20SCA and M20ECA show the best performance, 56.04% and 42.49% lower than MREF, respectively.

Clinker production is the main contributor to TA, with cement accounting for 72–87% of this impact, due to emissions of nitrogen dioxide, ammonium, phosphates, and sulfur. In M10SF, silica fume contributes 11%, resulting in the worst performance in this category, 22.12% higher than MREF. Cane cultivation also contributes to soil acidification, but the impact is offset by by-products. Consequently, M10ECA and M20ECA show the lowest scores, 15.94% and 14.90% below MREF, respectively.

For TE, cement transportation dominates all mortars (46–52%), followed by cement production (29–33%) due to fossil fuel use in transport and kilns. In M10SF, silica fume and its transport account for 10%, making it the highest TE score, 21.41% above MREF. For ash-containing mortars, agrochemical use in cane cultivation contributes to TE, but the avoided impacts from by-products offset this, resulting in a net negative contribution. Consequently, M20SCA and M20ECA have the lowest TE scores, 19.60% and 23.86% below MREF, respectively.

From an environmental perspective, the LCA results demonstrate that clinker manufacturing remains the dominant hotspot, accounting for approximately 80–85% of environmental impacts across categories. Consequently, replacing cement with biomass ashes significantly reduces impacts, primarily by reducing clinker consumption. This trend is widely reported in the literature, where the incorporation of sugarcane bagasse ash (SCBA) reduces greenhouse gas emissions and resource consumption [20,35]. In addition, as concerns CC+, CO_2 fixation by sugarcane crops through photosynthesis contributes to a positive carbon balance, further improving environmental performance.

4. Discussion

The results of this study highlight the potential of incorporating SCA and ECA as SCMs in Portland cement mortars, both from a mechanical and environmental perspective. Notably, mortars incorporating 10% ECA exhibited slightly higher compressive strength than the reference mixture, while SCA achieved comparable performance. This enhancement can be attributed to the combined effects of pozzolanic reactivity and physical filler

action. The fine ash particles may have improved particle packing and reduced pore volume, particularly at early ages, whereas the pozzolanic reaction likely promoted the formation of additional C-S-H gel, resulting in a denser microstructure and enhanced mechanical performance [63,64]. At higher replacement levels, minor reductions in strength are expected due to clinker dilution and slower pozzolanic kinetics, emphasizing the importance of optimizing substitution rates [62].

An important finding of this study is the reduction in carbonation depth observed for both ashes. Contrary to the commonly reported increase in carbonation with SCM incorporation, the improved durability may result from pore refinement and decreased CO_2 diffusivity within the mortar matrix, which compensates for any reduction in portlandite content [63]. This highlights the dual benefit of ECA and SCA: they enhance both mechanical properties and long-term durability, a critical consideration for sustainable construction applications [63,64].

From an environmental standpoint, both ECA and SCA represent an improvement; however, ECA consistently showed superior results, particularly at replacement levels of 10–20%. This can be attributed to the higher biomass productivity of energy cane, which reduces environmental burdens per unit of ash produced [22,23], as well as to its slightly better mechanical performance, suggesting enhanced pozzolanic reactivity. In particular, mixtures containing 10–20% ECA achieved both improved environmental performance and comparable or superior mechanical properties. Conversely, low replacement levels (e.g., 5%) resulted in higher environmental impacts due to increased material consumption required to achieve the same functional unit, highlighting the importance of optimizing substitution rates.

The environmental benefits are reinforced by the consideration of environmental credits associated with potassium recovery during ash washing. While previous studies typically treat SCBA as a low-impact residue, the present results demonstrate that ash processing can generate valuable co-products. By utilizing co-products from sugarcane processing and residual water from ash washing, the production of additional materials can be avoided, further reducing the environmental impacts. This approach aligns with circular economy principles and highlights the potential for integrating agricultural and construction systems through resource recovery.

The adoption of a functional unit based on compressive strength (1 MPa) facilitates performance-based comparison between mixtures, addressing a limitation in previous LCA studies that overlooked differences in mechanical efficiency [34]. On the one hand, it allows for a more realistic assessment of environmental performance, particularly when substitution levels influence strength development. On the other hand, it provides valuable insights into trade-offs between environmental and mechanical performance. While such trade-offs are commonly reported [20], they can be minimized when performance-based functional units are adopted. If a conventional mass or volume-based functional unit (e.g., 1 kg or 1 m^3 of mortar) had been adopted, the environmental comparison would primarily reflect differences in material composition rather than engineering performance. Under this approach, mixtures with higher cement replacement would likely exhibit even lower environmental impacts because the reduction in clinker content would be evaluated independently of compressive strength. However, such a comparison would overlook differences in mechanical efficiency among the mixtures, making it less suitable for assessing materials intended to provide equivalent structural performance. For this reason, a strength-based functional unit was considered more appropriate for the objectives of the present study. While these findings support the valorization of agro-industrial residues, there are still opportunities for improvement. These include enhancing agricultural practices through better agrochemical management and optimized planting and harvesting

schedules, increasing efficiency in bagasse combustion for energy generation [65], and adopting renewable fuels in transport and industrial processes. Furthermore, the environmental performance of cement mortars could be further improved by replacing fossil fuels with renewable energy sources, reinforcing the role of integrated strategies in advancing the decarbonization of the construction sector.

This study presents some limitations. The cradle-to-gate LCA excludes use and end-of-life stages, and the assumption of equivalent durability may not reflect long-term performance differences. In addition, the results are based on laboratory-scale processes and secondary data, introducing uncertainties, particularly regarding transport, agricultural practices, and potassium recovery efficiency. Finally, the findings are region-specific and may not be directly applicable to other contexts. Future studies should address long-term durability, economic feasibility, and industrial-scale implementation to support wider adoption in the construction sector.

5. Conclusions

This study evaluated the influence of sugarcane and energy cane ashes, which were processed into biopozzolans, on the mechanical and environmental performance of Portland cement mortars. The experimental results showed that replacing 10% of cement with either ash produced compressive strengths similar to or higher than the reference mortar, with energy cane ash yielding a slight increase of 3.78%, indicating higher pozzolanic reactivity and performance potential, particularly for energy cane residues.

The comparative LCA revealed that, in most cases, replacing 10–20% of cement with ash, whether from sugarcane or energy cane, improves environmental performance. In nine out of the ten impact categories analyzed, ash led to reduced environmental burdens. Notably, sugarcane ash and energy cane ash also help mitigate the accumulation of residues in industrial yards while decreasing cement consumption, which is highly carbon-intensive. Energy cane ash, in particular, demonstrated the best environmental performance, excelling in seven categories: one for 10% replacement and six for 20% replacement. This is attributed to lower cement usage and to co-products generated during ash production and washing, which help avoid emissions from the production of alternative products, such as fertilizers. Its superior environmental profile is also associated with higher biomass yield per hectare, increased SiO_2 content, and potential for circular resource recovery.

Overall, this study demonstrates that ECA and SCA can effectively contribute to the decarbonization of cement-based materials while supporting circular economy strategies. By transforming agro-industrial residues into high-value SCMs, the construction sector can simultaneously reduce greenhouse gas emissions, improve material durability, and integrate agricultural and industrial systems through resource recovery, advancing the sustainability of built environments.

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