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Life cycle analysis and economic evaluation of cement and concrete mixes with rice husk ash: application to the Colombian context

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ABSTRACT: Rice husk residues are generated within the rice industry. In this research, the environmental impact of the use of rice husk ash is evaluated as a replacement for cement in the production of concrete in the city of Ibagué (Colombia). The environmental criteria of cement and concrete production alternatives were evaluated through life cycle analysis methodology, using SimaPro 9.3.3 software and the Recipe 2016 Midpoint (H) evaluation method. The economic cost of each of these production alternatives was included. To carry out the study, surveys and interviews had to be undertaken with rice-producing plants, aggregates, cement and concrete plants in Tolima. It was corroborated that rice husk ash (RHA) generated during the rice husk (RH) gasification process for electricity and heat production was beneficial from an environmental and economic perspective when it was used in cement and concrete in the city of Ibague (Colombia).

KEY WORDS: Cement; concrete; Rice husk ash; Life cycle assessment; Environmental impact.

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RESUMEN: *Análisis del ciclo de vida y evaluación económica de cemento y mezclas de hormigón con ceniza de cascarilla de arroz: aplicación al contexto colombiano.* Dentro de la industria arrocera se generan los residuos de cascarilla de arroz (CA). En esta investigación, se evalúa el impacto ambiental del uso de la ceniza de la cascarilla de arroz (CCA) como reemplazo del cemento en la producción de hormigón en la ciudad de Ibagué (Colombia). Se evaluó el criterio medioambiental de alternativas de producción de cemento y hormigón, mediante la metodología de Análisis de Ciclo de Vida, el uso de software SimaPro 9.3.3 y el método de evaluación Recipe 2016 Midpoint (H). Se incluyó, el coste económico de cada una de estas alternativas de producción. Fue necesario realizar encuestas y entrevistas a plantas productoras de arroz, plantas de agregados, de cemento y de concreto en el Tolima. Se corrobora que el uso de la CCA generada durante el proceso de gasificación de la CA para la producción de electricidad y calor, resulta ser beneficiosa desde el punto de vista medioambiental y económico, cuando se usa en el cemento y hormigón en la ciudad de Ibagué (Colombia).

PALABRAS CLAVE: Cemento; Hormigón; Ceniza de cascarilla de arroz; Análisis de ciclo de vida; Impacto medioambiental.

1. INTRODUCTION

The global production of crop residues has been increasing progressively in recent decades. Production is estimated at 280 Mt/year for cereal crops and 3758 Mt/year for 27 food crops (1). Waste that is produced after harvesting and processing of crops include stalks (corn), straw (rice, wheat, sugar cane), leaves, husks (rice, wheat) and seed shells (palm), among others. This puts great pressure on agricultural ecosystems (2). Agricultural waste disposal is an increasing environmental problem and concern in most countries (3).

One factor that influences this is global rice production, which has increased by 2.9 million tons since 2017 (4). Currently, the world annual rice production is estimated at 700 million tons. RH represents approximately 20% of the rice mass (3, 6). Therefore, the annual amount of waste generated in the form of RH is around 150 million tons (5).

In Colombia, there are a total of 293,179 planted hectares of rice (8). Of these, 155,519 hectares are in the Eastern Plains, which produce 177,641 tons of rice annually (8). This represents 20.84% of national production (9). A total of 55,298 hectares are in the Tolima department, with a production of 406,737 tons of rice annually (8). This represents 18% of national production. According to DANE (8), rice is the third most important product in Colombian agriculture.

One of the difficulties in the cultivation of rice is the disposal and final usage that is given to the biomass of RH this biomass. This represents just over 58,635 tons per year in Colombia. However, it is considered waste once the rice production process ends (9). Currently, most of the RH that is obtained is eliminated through open-air combustion. On other occasions it is disposed of in rivers. It is also used as bedding for animals in trucks for livestock transportation and a small part is used as fertilizer (10). These uses have a negative environmental impact and do not comply with current environmental regulations.

In addition to the food industry, the construction industry has a great environmental impact due to the generation of waste and the consumption of raw materials. In cement production, environmental impacts and CO_2 emissions are generated during the stages of extraction of raw materials, production, commercialization, use, end of useful life, recycling and final disposal.

The cement production stage is a complex process that includes the use of a large amount of raw materials and fuels (petroleum coke, coal, natural gas, fossil fuels, biomass or some waste) and energy (electricity and heat) in addition to auxiliaries, air and water (12, 13). As a result of the use and processing of this raw material, cement production has a significant environmental impact (14). Although cement production causes the formation of wastewater, solid waste and noise, the main environmental problems are associated with energy consumption and air emissions (15). Approximately between 5% and 7% of total global anthropogenic CO_2 emissions and 3% of total greenhouse gas emissions are derived from cement production (13). In addition, cement production represents approximately 12% to 15% of total industrial energy use worldwide (17). In total, for one ton of cement clinker, 0.87 tons of CO_2 are released into the atmosphere (18).However, this value can vary depending on location, technology, production efficiency, the mix of energy sources used to generate electricity, and the selection of furnace fuels. For this reason, international organizations such as the Intergovernmental Panel on Climate Change (IPCC) or the International Energy Agency (IEA) have considered it crucial that cement manufacturers implement effective CO_2 emission mitigation scenarios during the cement manufacturing stage (16).

To reduce the impacts of the agricultural industry and the construction industry, work has been done to mitigate impacts in the cement production stage by developing different mixtures with industrial waste. Industrial and agricultural by-products such as fly ash and RH are considered supplementary or replacement cementitious materials in the production of concrete, as a cement replacement fraction.

A large number of studies have indicated that RH can be used in the construction industry, due to its high silica content. RH is composed of 50% cellulose, 25-30% lignin, 15-20% silica, and 10-15% moisture. Its bulk density is small, in the range of 90-150 kg/m^3 (5). With adequate processing before use, it can be used as a component for cement manufacturing (3, 19). In some studies, rice husk ash (RHA) has been used as a pozzolanic material in the manufacture of cement in different percentages. Mineral additions to cement in the form of pozzolanic material have been used to improve the mechanical resistance and durability of mortars, associated with cost savings and the reduction of environmental impacts (20). Some researchers observed that the highest compressive strength occurred between the levels of 10 and 15% RHA replacement in concrete for all cure durations (20-27). Chao-Lung (28) found that the best cement replacement was up to 20% RHA. In their study, they obtained 28-day compressive strength in the range of 47–66 MPa.

The RHA percentage replacement level for the highest tensile strength (28 days) was observed between 10% and 20%. Compressive and tensile strength were found to decrease beyond the addition of the optimal replacement level of RHA due to caking of excess RHA and the dilution effect. Tambichik (29) also compared some articles on RHA. Ukpata (30) found that an addition of 5 to 10% RHA increased strength. A further addition of up to 15% to

25% RHA led to a slight 15% reduction in strength. A decrease in strength values was observed when the levels of RHA increased. It was observed that the water resistance of concrete with RHA as a supplementary cementing material (partial replacement of cement) was outstanding (31). The penetration of chloride ions, which is the most important characteristic for durability and the prevention of corrosion, was also excellent (32).

Alternate uses of RHA have been identified. For example, it can be used as fine aggregate in mortar-type adhesives for ceramic tile placement (33), with and without pretreatments, as an addition in the manufacture of light mortars (34), and to improve the mechanical properties of durability and cement compression from the mixture with RH (35). Other research shows that RH can be used as an additive in the production of refractory bricks, fire retardants and wood particles, among others (36-38). Previous studies have been carried out that demonstrate the viability of using RHA and fly ash. Gursel (39) developed a critical review on concrete production life cycle inventory analysis. Gursel (40) analyzed the performance of the RHA ternary and quaternary concrete mix in terms of its durability, mechanical properties and its GW potential. Tong (41) analyzed the use of RHA in Vietnam by developing a low cost, low environmental impact sodium silicate solution from RHA. Sarah (42) developed a Life cycle analysis and a Life Cycle Cost of the activated concrete with alkali mixed with fly ash and RHA, in which environmental and economic factors were quantified by evaluating the emission of greenhouse gases (GHG), the impacts and environmental benefits and cost analysis of using fly ash and RHA in alkali-activated concrete compared to Portland cement concrete.Other studies have focused on the analysis and reduction of environmental impacts of Portland cement using industrial waste such as fly ash and kiln residues (43-45). Some studies have focused on the environmental effect of fly ash in concrete (46) and on the granulated residues of the kilns in the concrete (47).

Research has also been conducted that focuses on the use of RH as fuel, through the gasification process (48). Experiments have been undertaken on the combustion of rice husk and obtaining the energetic properties of this biomass and its capacity for energy generation (49). The gasification of biomass to obtain biogas and subsequently electricity is a thermochemical process in which a carbonaceous substrate (organic waste) is transformed into a combustible gas. This is carried out through a series of reactions that occur at a certain temperature, always in the presence of a gasifying agent (air, oxygen and/or water vapor). In this process, gases such as carbon monoxide, carbon dioxide, hydrogen, methane and small chain hydrocarbons are produced. The potential use of the gas obtained from the process as fuel in power generation equipment makes it interesting for the formulation of sustainable alternatives since it allows diversification of the energy matrix (9).

Although the physical, chemical and mechanical properties of rice husk ash in cement and concrete have been evaluated, studies on the environmental and economic impact of their use in the manufacture of these new materials for the production of concrete ecology should be studied in greater depth. Consequently, the goal of this study was to evaluate the environmental impacts of the use of rice husk ash as a replacement for cement in the production of concrete. This evaluation was carried out using the life cycle analysis methodology. Life cycle assessment (LCA) is a robust tool that allows the quantification of potential environmental effects in terms of impact categories (48). The analysis and quantification of the environmental impacts of cement production require an analytical and holistic approach. Life cycle analysis (LCA) methodology (51) allows the measurement and evaluation of impacts associated with the processes in each stage of the life cycle. For this study, the city of Ibagué-Tolima is chosen as the study area, since it stands out for the high production of rice in Colombia. These results are expected to generate considerable knowledge transfer between academia, industry, government and companies, and at the same time contribute to generating significant changes in the cities.

2. LIFE CYCLE ASSESSMENT (LCA) METHODOLOGY

2.1. Goal and scope definition

In this study, the extraction of RHA was evaluated as a partial replacement for Portland cement in cementitious mixes. Then, the use of cement with RHA was assessed in concrete production.

The department of Tolima-Ibagué (Colombia) was selected as the study area (Figure 1) to evaluate the environmental impacts of RHA extraction and the subsequent partial replacement of Portland cement in cementitious mixes and in concrete.

2.2. Functional unit

1 m^3 of concrete was chosen as the functional unit. For cement and RHA, 1 kg of material was chosen.

2.3. System boundary and life cycle inventory

Primary data were obtained from interviews with companies and organizations in Colombia (rice mill, concrete, cement and aggregate plants in the depart-

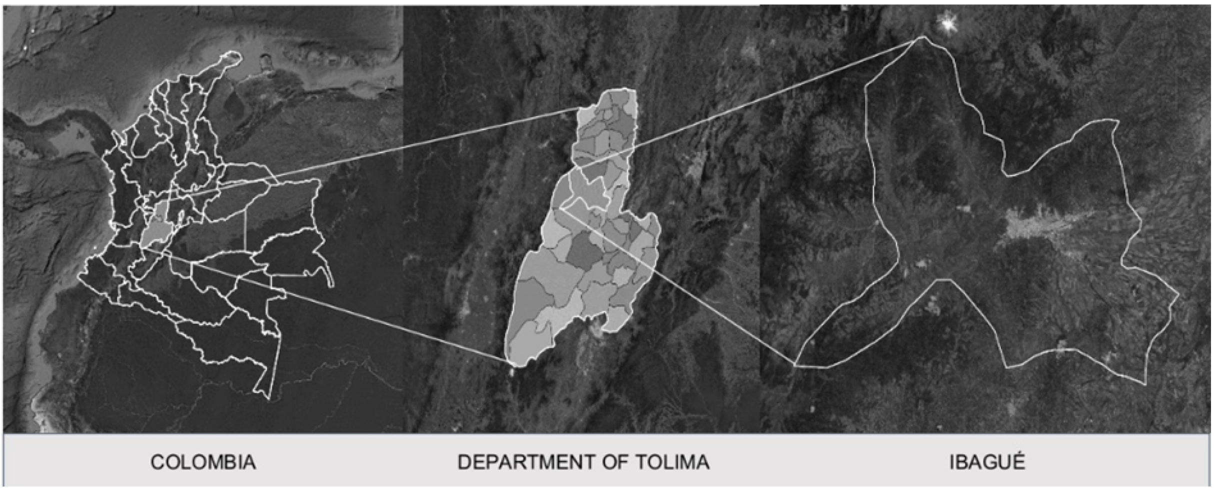

Figure 1. Department of Tolima-Ibagué (Colombia).

ment of Tolima). These data were supplemented with the Ecoinvent V3 database and adapted to the Colombian context. The location data and transport distances, which could not be obtained during the visits that were carried out, were supplemented using Google Earth Pro.

2.3.1. Transport scenarios

In the study area, there is only one cement production plant. As the existing concrete plants are located at a close distance in the city of Ibague, for this study an equidistant point was taken as the location of the concrete plant. The means of transport for the raw materials to the cement plant and the aggregates to the concrete plant was a truck of type 10-20 t EURO 5. The various transport distances are listed in Table 1.

Table 1. Transport scenarios.

Transport details for	Distance (km)
Raw materials for the cement plant	5 km
RHA to the cement plant	14 km
Aggregates to the concrete plant	36.2 km
Cement to the concrete plant	21.8 km

2.3.2. Cement Portland

The clinker process modeled for Colombia from the Ecoinvent 3 database was used as a basis. In this process, clinker is produced by sintering a mixture that consists mainly of limestone and clay at temperatures between 1400°C and 1500ºC. This clinker process was considered for the production of Portland cement, according to the Colombian technical standard NTC 121.

2.3.3. Rice husk ash

This procedure considers the production of 1 kg of RHA in the cogeneration of electricity and heat from RH as biomass. That is, rice husk ash (RHA) is obtained from gasification for electricity generation. Ash recovery starts from the gasification process when the rice husk enters the gasifier for the cogeneration process in which electricity and heat are generated, as shown in Figure 2 and Table 2. Disposal of rice husks is avoided and electricity is generated.

2.3.4. Pozzolanic cement

To evaluate the environmental impact of pozzolanic cement, cement alternatives were first created based on the percentage replacement of RHA with Portland cement. The results of previous studies (Table 3) were used to define the cement alternatives, indicating the maximum percentage of replacement of the ash by cement without compromising the properties of the cement or concrete by the addition of pozzolan. In general, the best results were obtained with a maximum replacement of 25% of the RHA by Portland cement. In addition, NSR 6.4.4.2 states that the maximum percentage for replacement of pozzolans is 25% (52).

For the present work, the alternatives (A1 to A6) of partial substitution by RHA in cement production were defined as shown in Table 4.

For the impact evaluation, the pozzolanic cement processes were created from Portland cement and RHA in SimaPro 9.3.3.

2.3.5. Concrete with pozzolanic cement (RHA)

To evaluate the environmental impact of concrete production, the Ecoinvent 9.3.3 base concrete process modeled for Colombia was taken as a reference.

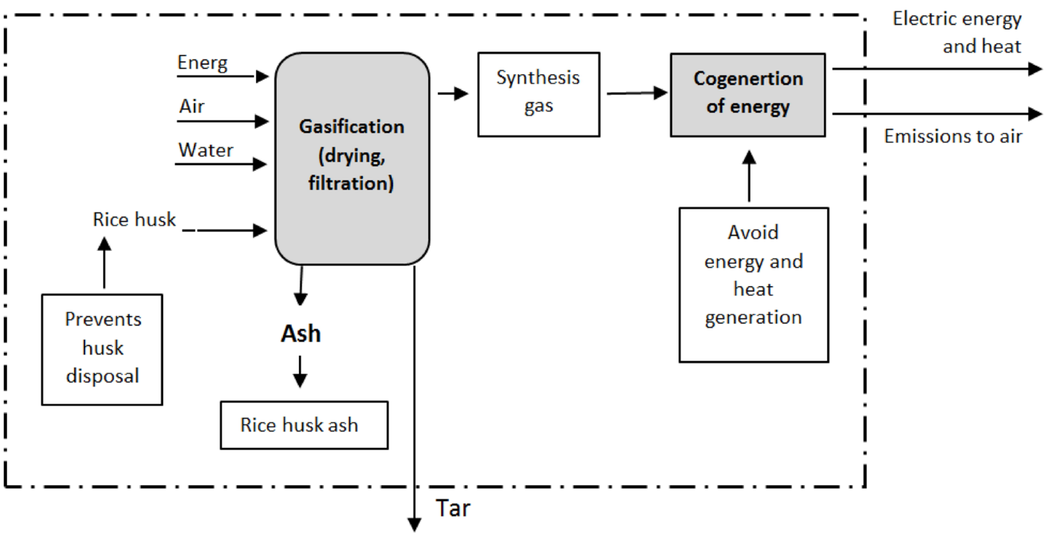

Figure 2. System boundary for Rice Husk Ash.

Table 2. Inventory data for the RHA from gasification process (1kg).

Input/output	Unit	Value	Source
Avoided products			
Electricity	kWh	1.76	**Company consulted, 2021**
Final disposal of the husk	kg	3.33	**Company consulted, 2021**
Heat	MJ	9.06	**Company consulted, 2021- Ecoinvent 3.3**
Input			
Rice Husk	kg	3.33	**Company consulted, 2021**
Synthesis Gas-Gasification	m^3	0.73	**(40); Ecoinvent 3.3**
Cogeneration	kWh	1.76	**Company consulted, 2021- Ecoinvent 3.3**
Ash crushing (electricity)	kWh	0.0067	**(40)**
Ash crushing (machines)	kg	8.21 E-8	**Company consulted, 2021- Ecoinvent 3.3**
Output			
Ash	kg	1	**Company consulted, 2021**
Tar	kg	0.3	**Company consulted, 2021**
Main emissions			
Carbon dioxide	kg	0.27	**Ecoinvent 3.3**
Water	m^3	1.61E-5	**Ecoinvent 3.3**
Nitrogen oxids	kg	4.64 E-6	**Ecoinvent 3.3**

This was adapted to the data from the study area using the references provided by the companies that were visited. In this study, the design process of a 21 MPa concrete was applied according to NSR 10, which is used for building construction and general use. Its dosage contains 350 kg of cement, 170 kg of water and a water-binder ratio (w/b) of 0.48.

The cement used for conventional concrete is Portland cement. Pozzolanic concrete is made with different percentages of RHA replacing some of the Portland cement (Table 5). What was interesting in this study was to keep all the variables constant and only substitute the traditional Portland cement for the different pozzolanic cements (with different percentages of rice husk ash) to find out the environmental and economic advantages of this substitution. In this way, the amount of binder (binder= PC+RHA) remained constant, what changed was the percentage of Portland cement within the total binder, as can be seen in Table 5.The system limits for concrete are shown in Figure 3.

Table 3. Previous studies that have used RHA.

Author	Rice husk ash replacement percentages (%)	w/b
Saraswathy (26)	5%-10%-15%-20%-25%-30%	0.53
Ganesan (53)	5%-10%-15%-20%-25%-30%-35%	0.53
Chao -lung (28)	10%-20%-30%	0.39-0.44-0.50
Ferraro (23)	7,5%-15%	0.44
Rawaid (54)	25%	
Mattey (55)	20%	0.40-0.43
Salazar (56)	20%-40%	0.48
Gursel (20)	10%-15%-20%	0.33
Hu (57)	0% -5%-10%-15%	0.50
Chetan (58)	5%-10%-15%-20%,10%	0.43
Rumman (59)	0%-8%-10%	0.43-0.45-0.47
Jittin (5)	20%	
Depaa (60)	15%	0.45
Sathurshan (61)	5%-10%-15%-20%-25%	0.34

W/b=water/binder

Table 4. Alternatives for the production of pozzolanic cement.

Material	Alternatives		Cement Portland (%)	Rice Husk Ash (%)
Cement	A1	PC100-RHA0	100	0
	A2	PC95-RHA5	95	5
	A3	PC90-RHA10	90	10
	A4	PC85-RHA15	85	15
	A5	PC80-RHA20	80	20
	A6	PC75-RHA25	75	25

Table 5. Concrete mix alternatives.

Material	Alternatives		w/b	W (kg)	PC (kg)	RHA (kg)	FA (kg)	CA (kg)	Addi-tives (kg)
Concrete	A7	C-PC100-RHA0	0.48	170	350	0	700	1050	2.2
	A8	C-PC95-RHA5	0.48	170	332.5	17.5	700	1050	2.2
	A9	C-PC90-RHA10	0.48	170	315	35	700	1050	2.2
	A10	C-PC85-RHA15	0.48	170	297.5	52.5	700	1050	2.2
	A11	C-PC80-RHA20	0.48	170	280	70	700	1050	2.2
	A12	C-PC75-RHA25	0.48	170	262.5	87.5	700	1050	2.2

W= Water; W/b=water/binder; PC=Cement Portland; RHA= Rice Husk Ash; CA= Coarse Aggregate; FA= Fine Aggregate; Binder= PC+RHA.

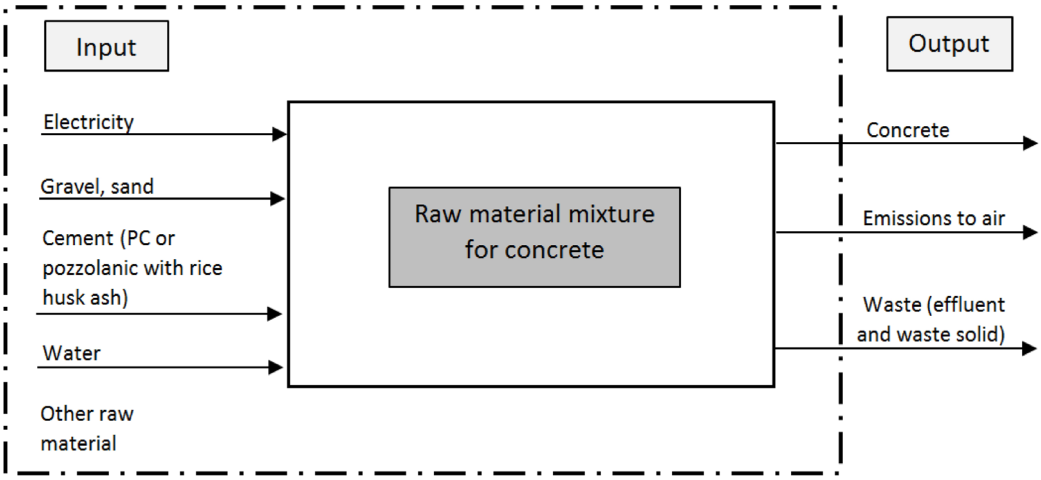

Figure 3. System boundary for concrete.

2.4. Life cycle impact assessment

To define which impact categories to evaluate, other LCA studies that address the use of RHA in concrete were considered (Table 6). SimaPro 9.3.3 software was used to organize the inventory data and perform the impact assessment. SimaPro is a popular life cycle analysis tool that can be used to quantitatively measure the environmental impact of a product or service.

The result of the inventory data obtained with SimaPro 9.3.3 is a long list of emissions and resource consumption. The software includes several methods for interpreting this list. The method that is best

Table 6. Impact categories used in studies related.

Impact categories	A	E	GW	SOD	HCT	HNCT	MRS	FPMF	LU	FRS	WC
Silalertruksa (62)	X	X	X		X	X	X				
Rodriguez (63)			X	X					X		
Kwofie (64)	X		X		X	X		X			
Unrean (65)	X	X	X	X	X	X	X				
Quispe (66)	X	X	X								X
Mikhail (67)	X	X	X	X	X	X	X		X	X	X
Lat (68)	X	X	X								
Varadharajan (69)			X	X	X	X		X	X	X	X
Thengane (70)	X	X		X	X	X		X		X	
Garces (71)	X	X	X	X						X	
Caldas (72)	X	X	X	X			X			X	
Sarah (42)	X	X	X	X	X	X	X				
Briones (73)	X	X	X				X	X		X	
Sarah (74)	X		X	X	X	X	X	X	X	X	
Alcazar (75)	X	X	X	X	X	X				X	X
Sampaio (76)	X	X	X	X			X	X		X	

A= Acidification; E= Eutrophication; GW= Global Warming; SOD= Stratospheric Ozone Depletion; HCT= Human Carcinogenic Toxicity; HNCT= Human Non-Carcinogenic Toxicity; MRS= Mineral Resource Scarcity; FPMF= Fine Particulate Matter Formation; LU= Land Use; FRS= Fossil Resource Scarcity; WC= water consumption.

suited for the impact categories chosen in this study is Recipe2016 Midpoint (H). This method has been used by several well-known authors on this topic, such as: (64, 66, 67, 69, 73, 76, 77). This approach was chosen because it provides unambiguous values that can be used to compare concrete with different alternatives, as used in the study by (77). Midpoint effects are considered more precise because they correspond to a higher level of empirical evidence. As in (77), the midpoint effect results were considered to evaluate the different forms of effects produced by each constituent of the concrete and its process.

3. RESULTS AND DISCUSSION

3.1. Rice husk ash (RHA)

Electricity and heat are generated through the process of obtaining ash through the gasification of RH. The processes that have impacts in all categories when RHA is obtained are electricity (high voltage-cogeneration) and synthetic gas, see Figure 4.

The greatest impact from the use of electricity required during the electricity and heat cogeneration process occurs in the ozone layer depletion category at 43%, followed by 35% in the mineral resource scarcity category and 6 % in the water consumption category. Syngas production has impacts on water consumption (4%), mineral resource scarcity (3%) and eutrophication (3%). These impacts are due to the use of electricity and water during the process. There is a minimum impact of 0.2% on land use due to waste disposal in landfills. These results coincide with the study by (67) who found impacts from biomass gasification in the mineral resource scarcity category and impacts on land use.

The process of obtaining rice husk ash in the global warming category was improved at environmental level. This process saves energy due to the fact that heat and electricity are generated by cogeneration (renewable energy). Therefore, the energy savings also prevent the generation and release of carbon dioxide into the environment, which minimises the impact of global warming. The impacts in this category (global warming) were insignificant with respect to the savings or impacts avoided in it since the production of electricity from fossil fuels was avoided.

According to (66), the production of 1 MJ from RH has lower impacts on global warming, acidification and eutrophication categories than the production of 1 MJ from coal. This corroborates the advantages of energy production from RH (in a cogeneration process from husk) that has ash as a by-product. According to (66), if RH is used as a source of thermal energy instead of coal, the environmental impact decreases by 97% in the global warming category for each MJ generated. The results also suggest that gasification has up to 12 times lower impacts per kWh than combustion (67). In general, providing energy from residual biomass in small farming communities would significantly reduce environmental impacts and improve waste management practices (67). Likewise, the category of water consumption had a low environmental impact since the process of cogeneration of heat and electricity requires lower water consumption than that required to produce electricity from fossil energy sources (Figure 4).

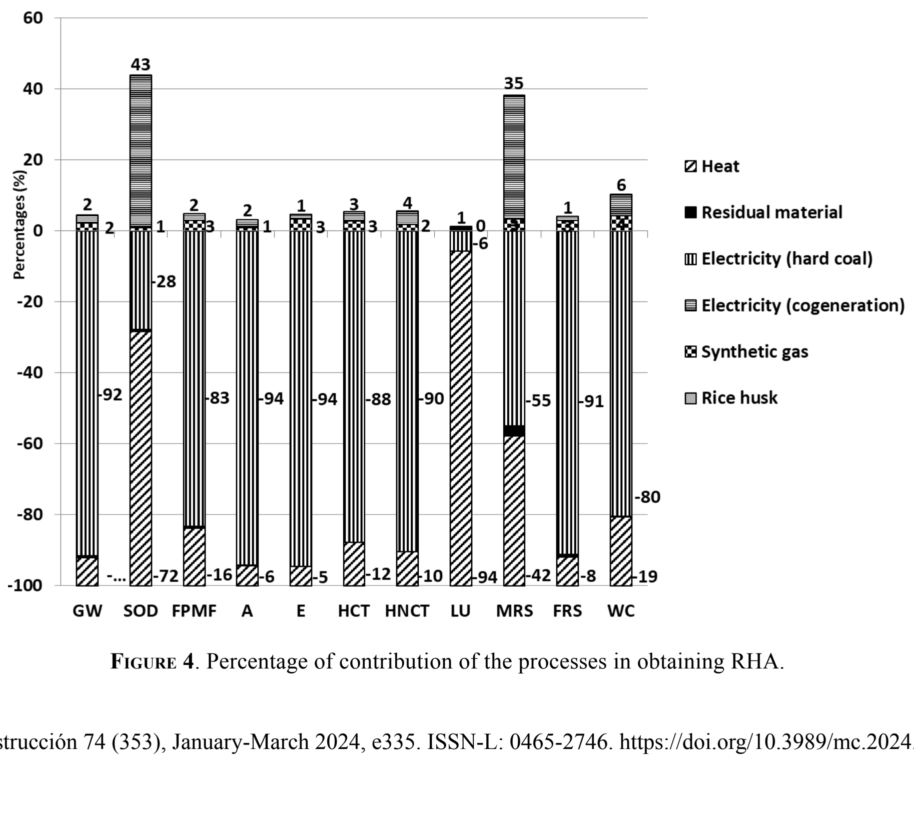

FIGURE 4. Percentage of contribution of the processes in obtaining RHA.

3.2. Comparison of the cements

Figure 6 shows that the cement alternative that has the greatest environmental impact is PC100-RHA0. The greatest impacts were on global warming (100%), mineral resource scarcity (100%), fossil resource scarcity (100%), fine particulate matter formation (100%), human carcinogenic toxicity (100%), eutrophication (97%) and acidification (85%) categories. As the clinker percentage decreases and the RHA percentage increases, the environmental impacts decrease in all impact categories.

The global warming category decreases as the RHA content increases. The reason for these results is that when ash is obtained, impacts are avoided due to the electrical energy and heat that are generated during the process and due to the impacts avoided by the non-disposal of RH. Although electricity consumption is necessary during the cogeneration process, the amount is much less than the electrical energy generated during the process. These positive results of lower CO_2 emissions for RHA compared to cement coincide with the study carried out by Hu (57), in which 157 kg CO_2 eq/ton are required for the RHA compared to that required for cement, which is 801.6 kg CO_2 eq/ton. Likewise, in the study by Hu (57), the energy required to obtain RHA was -353.5 MJ/ton, in terms of savings.

The process of obtaining Portland cement contributes to impacts in the global warming category due to the high energy consumption in the process of obtaining clinker. However, obtaining rice husk ash does not generate impacts in this category due to the energy savings from the cogeneration of electricity and heat during its production process.

The cement alternative with the highest RHA replacement (PC75-RHA25) was found to lead to savings in all impact categories compared to PC100-RHA0. The greatest impact was on global warming. However, these results were much lower than those obtained for PC100-RHA0. The total greenhouse gases emission and energy consumption in the cement industry can be reduced by using waste materials to replace virgin materials (clinker/coal). This agrees with what was found by (78).

In other impact categories evaluated for PC75-RHA25, the following savings were found: SOD (-100%), A (-100%), E (-100%), human non-carcinogenic toxicity (HNCT) (-100%), LU (-100%), WC (-100%), FPMF (-95%), MRS (-71%), HCT (-53%) and FRS (-37%). This is because when the Portland cement process was compared with the process for obtaining RHA, the pozzolanic material had lower impacts in these categories (Figure 5).

The results show that Portland cement had higher environmental impacts mainly due to the use of raw materials and fossil fuels. The use of ash as an alternative material helps to reduce the environmental impacts. This is in line with the results of (78). Mendes (79) also quantified the number of environmental aspects and impacts of mortar production with and without RHA and compared these impacts. They found fewer impacts in the mortar with ash compared to the mortar without RHA, in the processes of generation of rice husk ash, beneficiation of rice husk ash and RHA transportation. Once again, this shows the advantages of using RHA in binders. Impacts related to air emissions (CO_2, NO_x, PM, CO and SO_2) decreased with the increase in supplementary cementitious materials according to

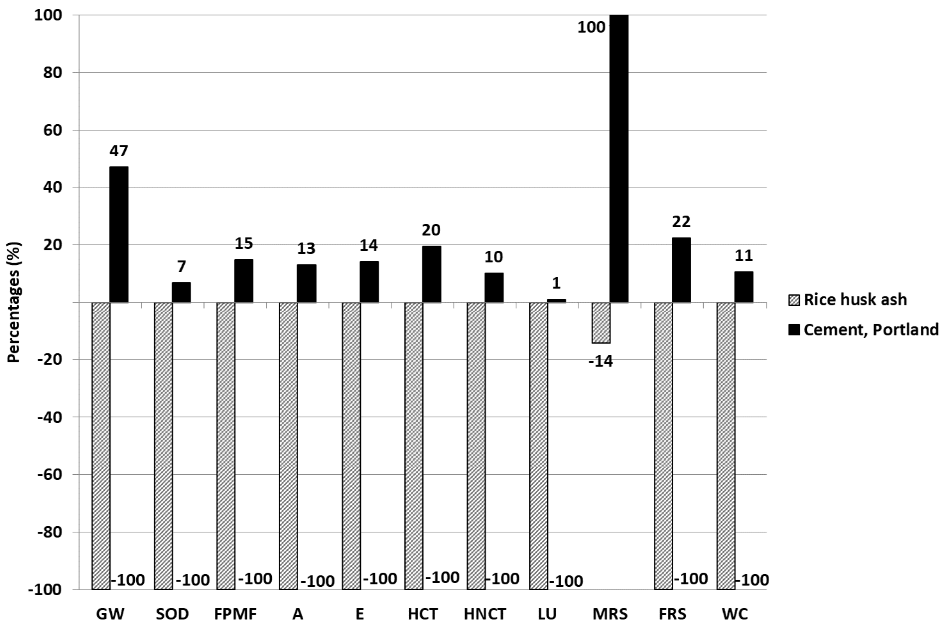

FIGURE 5. Comparison of the characterization results of the different cements evaluated.

(76). The use of pozzolanic cement as a binder for concrete preparation reduces the raw material consumption and reduces the environmental impacts of cement production (77).

Regarding water consumption, cementitious mixes with a higher percentage of Portland cement contribute to impacts in this category. By increasing the percentage of rice husk ash in the mixes, savings are found in this category. This is due to the fact that in the process of obtaining rice husk ash, savings result from the cogeneration of electricity and heat (and therefore these processes and the associated water consumption are avoided). This differs from obtaining Portland cement, which requires high energy consumption, and therefore water, in the clinker production process.

Likewise, the impacts on the mineral resource scarcity category were lower with the increase in RHA content, which resulted in 100%, 94%, 89%, 83%, 77% and 71% in PC100-RHA0, PC95-RHA5, PC90-RHA10, PC85-RHA15, PC80-RHA20 and PC75-RHA25, respectively. This is because, when the process of obtaining cement with obtaining rice husk ash was compared, it was found that obtaining Portland cement generates higher impacts in this category than obtaining rice husk ash. This is due to the consumption of raw materials extracted from nature to manufacture cement (limestone, clay, gypsum and iron ore), unlike the process of obtaining rice husk ash that uses a by-product of the rice industry.

Obtaining rice husk ash uses a by-product of the rice industry. Therefore, when it is compared to cement production, it presents savings in the scarcity of natural resources category. In addition, (74) found that there are environmental benefits as the impacts due to the disposal of RHA are reduced, since a residue becomes a valuable product and therefore a natural resource.

3.3. Comparison of the concretes

As can be seen in Figure 6, concrete with Portland cement (C-PC100-RHA0) had the greatest environmental impacts in all the categories evaluated. The greatest impacts were in the global warming (100%), fine particulate matter formation (100%), acidification (100%), eutrophication (100%), human carcinogenic toxicity (100%), mineral resource scarcity (100%), fossil resource scarcity (100%) and water consumption (100%) categories. The process that contributed the most to these impacts in all the categories evaluated was the production of Portland cement. However, concrete with a higher percentage of pozzolanic cement had lower impacts in the global warming and fossil resource scarcity category than concrete without RHA. This coincides with Chen Lo (80) in their study in which the use of ash in concrete also reduced the carbon footprint in relation to conventional concrete between 10% and 20% and in which the process that contributed the most to the impacts on concrete was Portland cement. Manjunatha (77) also found that these impacts decreased considerably in comparison to conventional

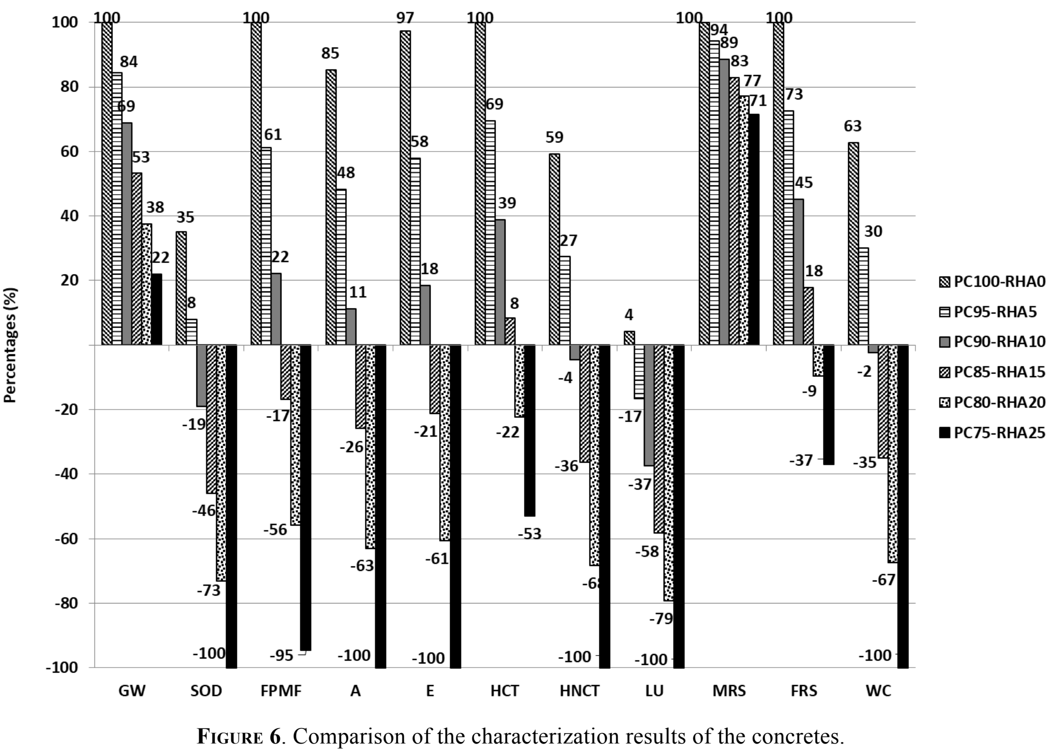

Figure 6. Comparison of the characterization results of the concretes.

concrete. Better results were obtained with a higher RHA replacement percentage (25%). However, this replacement percentage in the cement should not be increased, since previous studies show (Table 2) that if this ash replacement percentage is increased in the cement, the properties of the cement or concrete can be compromised by the addition of pozzolan.

Likewise, concrete with Portland cement (C-PC100-RHA0) had the lowest impact in the land use category (56%). This is because in this category the impact of cement production is minimal (11%) compared to the process of sand extraction (82%). The concrete with the lowest environmental impacts was the concrete with the highest RHA replacement percentage (C-PC75-RHA25). This concrete had the greatest environmental impacts in the mineral resource scarcity (73%), water consumption (57%) and global warming (29%) categories, also due to the production of Portland cement and the process for obtaining gravel.Environmental savings were also present in the other categories. The greatest savings were in the human non-carcinogenic toxicity (-100%), land use (-100%) and stratospheric ozone depletion (-100%) categories. This was due to the savings caused by the use of RH cement in the concrete, in agreement with what was found by other authors (77).

In general, all the types of concrete that were evaluated had impacts in the global warming and water consumption category. These impacts were greater when cementitious mixes with higher Portland cement content were used. When cementitious mixtures with a higher rice husk ash content were used, the impacts in this category were lower. This is because the process of obtaining rice husk ash is associated with the cogeneration of electricity and heat from rice husks. Therefore, the generation of electricity by means of fossil fuels is avoided, which implies lower CO_2 emissions and less water consumption.

Another category in which all the concretes that were evaluated had impacts is the mineral resources extraction category. In this category, as the CP content in the concretes increases, the impacts increase. This is due to the consumption of raw material extracted from nature to obtain Portland cement. By increasing the percentage of rice husk ash, the impacts decrease because a by-product of the rice industry is used to obtain this concrete, instead of the raw material extracted from nature in the case of Portland cement. The use of rice husks as a replacement for cement in the production of concrete is a research area with great environmental benefits in Colombia, as has been shown by other studies (20, 27, 39-42). RHA is an agricultural residue generated during the milling of rice. Therefore, it can help reduce the environmental impact and promote sustainable practices, under a life cycle approach. In the department of Tolima, current annual production of rice is 406,737 tons, of which it is estimated that 20% is RHA (3, 6). Therefore, it could be said that the department of Tolima has replacement potential in the manufacture of 81,347 tons of RHA concrete, as a pozzolanic material that favours the formation of cementitious compounds.

3.4. Sensitivity analyses

Sensitivity analyzes were performed to assess the influence of greater distances traveled by the RHA from the rice mill to the cement plant. This sensitivity analysis for transportation distances has been evaluated by other authors such as (76). The transport distance that was considered in Sections 3.2 and 3.3 is 14 km (Table 1). In this section, only the processes are compared when this distance is varied, to determine how viable the replacement of rice husk ash is by increasing its transportation distance. The cement production with the highest percentage of ash replacement (25%) at a distance of 14 km was compared with this same production process, with the distance varied to 60 km and 100 km (Figure 7). Transport turned out to be a variable that was negligible compared to the positive environmental impacts of the use of RHA in cement, as shown in Figure 7. When RHA transported over a distance of 100 km from the mill to the cement plant is used in the cement to make C-PC75-RHA25 concrete, it still has environmental advantages, as shown in the Figure 8. In this case, the environmental impacts were compared in the categories of concrete C-PC75-RHA25 in which the ash was transported 14 km, or 60 km to 100 km. These results indicate that the variation in the transport distance of rice husk ash to the cement plant (up to 100 km) does not negatively affect the environmental impacts of cement and concrete production with this pozzolanic material (Figure 7 and Figure 8).

3.5. Economic evaluation

The economic criteria were evaluated considering the production costs for the products that were manufactured. The method used to calculate the economic costs was based on an economic study of construction materials conducted by (81, 82) used this method to study a new concrete with recycled gypsum cement and recycled aggregates. Other authors such as (83) have used this method to analyze different concrete alternatives with recycled aggregates from construction and demolition waste (CDW). The objective of this study was to determine and then compare the approximate costs of the alternatives for cement and concrete production.

The reference costs for aggregates, cement and concrete were calculated by adding the cost of producing

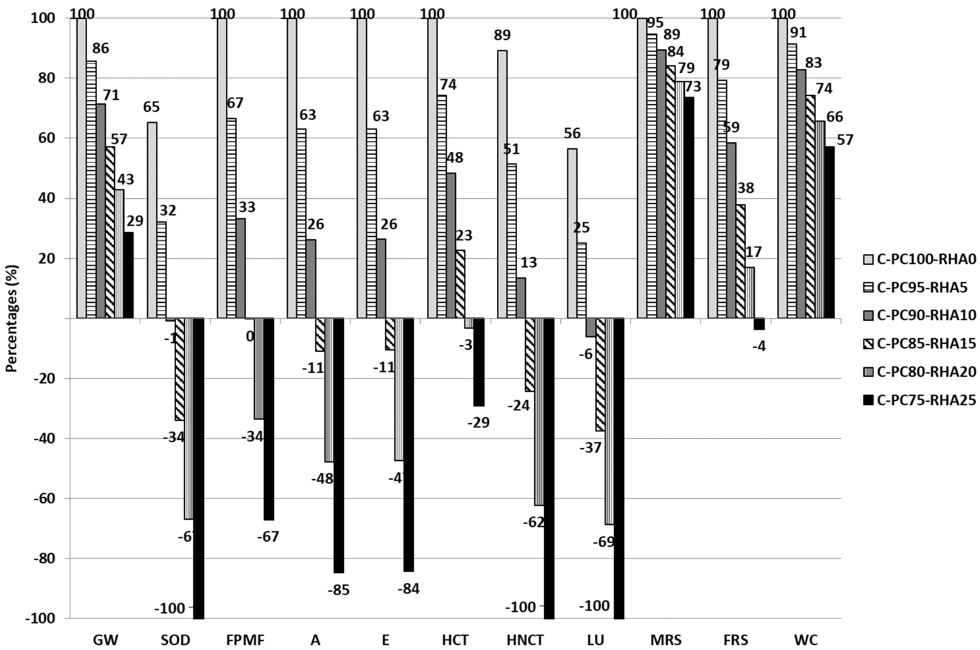

Figure 7. Sensitivity analysis considering changes in transportation distances for cement.

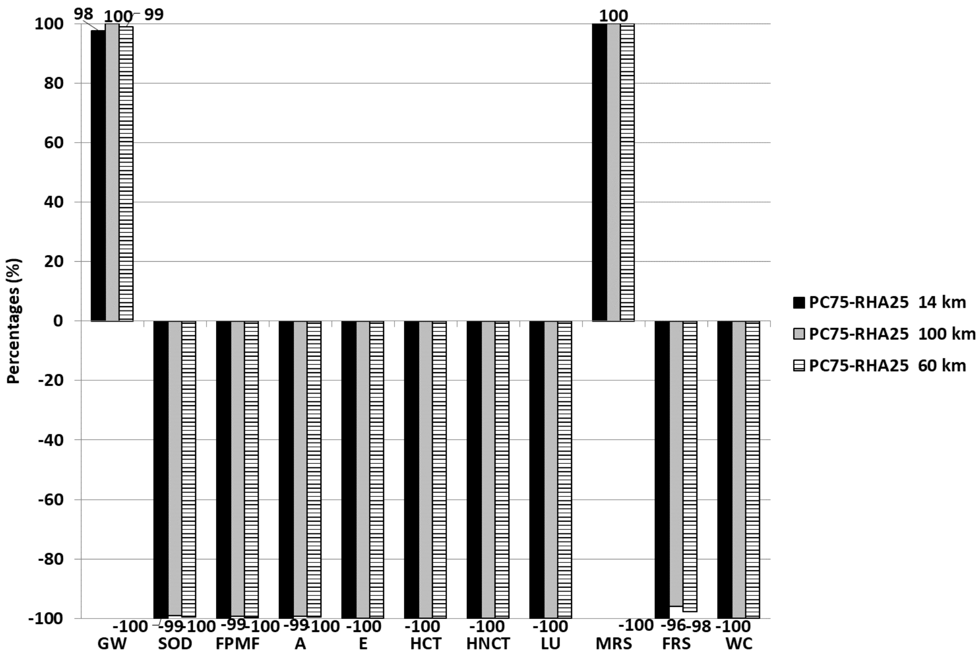

Figure 8. Sensitivity analysis considering changes in transportation distances for concrete.

each material. The production costs for the materials were determined based on the costs reported by the companies and plants surveyed in Colombia. The data were collected in different years from different companies or plants with similar production capacities. These data were supplemented with secondary information on material production costs. The transportation distance was considered a constant since it was the same for all alternatives. For this reason, it was not included in the total price of the concrete. The production and sales costs of the materials that make up the concrete are shown in the Table 7, which indicates the source of the information.

Different combinations of PC with RHA in different proportions were made and the price of each alternative was determined using the cost of the ma-

Table 7. The production and sales costs of the materials.

Material	Cost of production or sale ($/kg)	Source
Portland Cement	0.288	Requested company, 2022
Rice husk ash	0.156	Visited company, 2022
Fine aggregate	0.003	Visited company, 2022
Coarse aggregate	0.005	Visited company, 2022
Water	0.001	Ibal, 2022
Retardant additive	1.647	Visited company, 2022
Plasticizer additive	2.459	Visited company, 2022

Table 8. The production costs of the cement alternatives.

Material	Alternatives		Total price ($/kg)
Cement	A1	PC100-RHA0	0.29
	A2	PC95-RHA5	0.28
	A3	PC90-RHA10	0.27
	A4	PC85-RHA15	0.27
	A5	PC80-RHA20	0.26
	A6	PC75-RHA25	0.26

terial PC and RHA given in Table 7. We managed to substitute 25% of PC with RHA because the resistant property of cement was maintained. A larger substitution would mean losses in its resistance, as presented in Table 4. Only Chao (84) presented an economic study of alternatives.

The six proposed cement alternatives are listed in Table 8.

The methodology for calculating the economic criteria was based on data for the production of 1 kg of Portland cement (PC) for the alternatives of mixing with rice husk ash (RHA). From the results obtained, it appears that the alternative with 100% PC (A1) is cheaper than the other alternatives. In the second alternative (PC95-RHA5), the final price of cement/kg is reduced by 2.3%. In the last alternative (PC75-RHA25), the final cost was reduced by 11.5% (Table 8). On the other hand, the production costs of the six proposed concrete alternatives are listed in Table 9.

In this case, the economic criteria are based on the required data for the final price of 1 m^3 of concrete for the cement alternatives proposed above (A1-A6) together with the price of pozzolanic cement ($/350 kg). For this reason, there are six alternatives (A7 to A12). The first alternative A7 with 100% PC (A1) was cheaper than the other alternatives.

In concrete there are economic advantages between 2.1% and 10.3% of the final price when PC and RHA are used compared to A7 (100% PC),

Table 9. The production costs of the concrete alternatives.

Material	Alternatives		W ($/170 kg)	Pozzolanic cement ($/350 kg)	FA ($/700 kg)	CA ($/1050 kg)	RAd ($/1,1 kg)	PAd ($/1,1 kg)	Total cost/m^3
Concrete	A7	C-PC100-RHA0	0.1	100.8	2.0	4.9	1.8	2.7	112.3
	A8	C-PC95-RHA5	0.1	98.5	2.0	4.9	1.8	2.7	110.0
	A9	C-PC90-RHA10	0.1	96.2	2.0	4.9	1.8	2.7	107.6
	A10	C-PC85-RHA15	0.1	93.9	2.0	4.9	1.8	2.7	105.3
	A11	C-PC80-RHA20	0.1	91.6	2.0	4.9	1.8	2.7	103.0
	A12	C-PC75-RHA25	0.1	89.3	2.0	4.9	1.8	2.7	100.7

W= Water; C= Concrete; PC= Cement Portland; CA= Coarse Aggregate; FA= Fine Aggregate; Rad= Retardant additive; Pad= Plasticizer additive.

estimated at \$112.3 m^3. That is, a difference between \$2.3 and \$11.6. Alternative A12 is the most economical because less cement is used in the mix with RHA. When Chao (84) replaced 30% RHA, the concrete had mechanical properties closer to those of conventional concrete, and the total cost of concrete was reduced by 7.16%. Partial replacement of cement with rice husk ash can thus lead to significant cost savings and reduce the negative environmental impact of cement production. In addition to the economic advantages mentioned above, a great possibility opens up in Colombia and in the department of Tolima. Utilising RHA in concrete production may provide an opportunity to reduce reliance on traditional cementitious materials that are energy intensive and have a high carbon footprint (16). This is in line with Colombia's commitment to sustainable development and climate change mitigation. Furthermore, the use of RHA can contribute to the development of a circular economy by turning agricultural waste into a valuable resource.

4. CONCLUSIONS

This study evaluates the environmental impacts of cement and concrete mixes with rice husk ash, applied to the Colombian context. The following conclusions can be drawn:

- Obtaining the RHA implies a saving of environmental impacts in all the categories evaluated. These results were observed by comparing the production of Portland cement with obtaining RHA. This is because impacts are avoided in obtaining the ash due to the electrical energy and heat that are generated during the process and due to the impacts avoided due to the non-disposal of RH. Although consumption of electricity is necessary during the cogeneration process, it is less than the electrical energy generated during the process. The process of obtaining rice husk ash in the global warming category turned out to be beneficial at an environmental level since it presents energy savings as heat and electricity are generated in this process by cogeneration (renewable energy).
- It was concluded that the cement alternative that has the greatest environmental impact is PC100-RHA0. As the percentage of clinker decreases and the percentage of RHA increases, the environmental impacts decrease in all impact categories. The lowest impacts are found when 25% of RHA is used.
- Concrete with Portland cement (C-PC100-RHA0) has the highest environmental impacts in all the evaluated categories and the concrete with the lowest environmental impacts turns out to be the concrete with the highest percentage of RHA replacement (C-PC75-RHA25). By using cementitious mixtures with a higher content of rice husk ash, the impacts on the global warming, water and mineral resource scarcity categories were lower, since the process of obtaining husk ash is associated with the cogeneration of electricity and heat from the rice husk. This means that the generation of electricity by means of fossil fuels is avoided, which implies lower CO_2 emissions and less water consumption. In addition, by increasing the percentage of rice husk ash, the impacts decrease because a by-product of the rice industry is used to obtain this concrete, instead of raw material extracted from nature as in the case of Portland cement.
- Within the sensitivity analysis, cement production is compared with the highest ash replacement percentage (25%), at a distance of 14 km and the same cement, but with an ash transport distance of 60 km and 100 km. Transportation turns out to be a variable that is negligible compared to the positive environmental impacts of the use of RHA in cement.
- The use of the RHA generated during the RH gasification process for the production of electricity and heat turns out to be beneficial from the environmental perspective since it generates savings in environmental impacts in all the categories evaluated when it is used in cement and in concrete.
- The use of RHA as a partial replacement for cement in concrete production results in significant economic advantages compared with conventional concrete. In addition, the negative environmental impact in cement production is cut considerably. In the case of concrete, all alternatives offer economic benefits.

The results open up great possibilities in Colombia and in the department of Tolima. The use of RHA in the production of concrete can provide an opportunity to reduce reliance on traditional cementitious materials that are energy intensive and have a high carbon footprint. To take advantage of these opportunities, more research and development efforts are required. Collaboration between academic institutions, government agencies and the private sector can play a crucial role in advancing the use of rice hulls in cement production. Future research can focus on deepening and optimising production processes, determining the appropriate mixing proportions of RHA in concrete, and evaluating the performance and long-term durability of RHA-based concrete under Colombian environmental conditions.

In addition, the use of rice hulls in the manufacture of concrete can boost the circular economy by turning agricultural waste into a valuable resource. This can encourage sustainability and the development of more environmentally friendly practices in the construction industry.

It is important to highlight that the successful implementation of the use of rice husks in the manufacture of concrete in Colombia will require awareness and the adoption of favourable policies by the relevant stakeholders. It is also necessary to establish quality standards and proper regulations to ensure the performance and safety of concrete made from rice husks. The use of rice husks as a replacement for cement in the production of concrete shows promising results and offers opportunities in the Colombian context. This approach can contribute to sustainable development, reduce carbon emissions and promote the efficient use of agricultural waste. Ongoing research and collaborations are key to facilitating the full use of this alternative material in the construction industry.

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Authorship contribution statement

Sindy Suárez Silgado: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Software, Writing - original draft, Writing - review & editing.

Lucrecia Calderón: Formal analysis, Funding acquisition, Investigation, Visualization, Writing - original draft, Writing - review & editing.

Carolina Betancourt: Investigation, Visualization, Writing - original draft, Writing - review & editing.

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