CIVIL ENGINEERING - SUSTAINABLE CONCRETE

Carbon Footprint and Performance of Concrete Incorporating Agricultural Waste Ash and Recycled and Alternative Aggregates: A Review

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Abstract

It has been estimated that cement production contributes around 8% of man-made CO_2 emissions worldwide, and construction with concrete also consumes large quantities of natural aggregate. This paper reviews peer-reviewed journal articles published from 2017 onwards on the carbon footprint and properties of concrete containing agricultural waste ash as a cement substitute, and recycled concrete aggregate (RCA), steel slag and ironstone as substitutes for natural coarse aggregate. The background, processing and properties of six agricultural waste ashes and of these aggregates are described. When agricultural waste ash was used as a cement substitute at 10–20%, the global warming potential decreased by around 8–30%. However, when RCA was the only aggregate substitute, the global warming potential changed by only −9% to +3%, because cement makes up 87–96% of the carbon footprint of normal concrete. When ash and RCA were combined, the global warming potential decreased by around 7.6–29%, and the ash recovered much of the strength and durability lost through the use of RCA. Steel slag aggregate generally increased strength, and ironstone combined with gravel reduced the amount of granite used by half while maintaining more than 90% of the strength of the control, but there are few data on the carbon footprint of these aggregates. More cradle-to-grave studies using local inventory data from sub-Saharan Africa, and further research on steel slag and ironstone aggregates, are recommended.

Keywords: Agricultural waste ash; Carbon footprint; Ironstone; Life cycle assessment; Recycled concrete aggregate; Steel slag

1 Introduction

Concrete is the most consumed construction material in the world, and cement clinker production contributes significantly to industrial CO_2 emissions. Scientific literature has shown that replacing some clinker with supplementary cementitious materials (SCMs) can reduce CO_2 emissions from cement production in a cost-effective manner [1]. Cement contributes roughly 87–96% of concrete's total global warming potential (GWP), while the remaining contribution comes from other materials and processes, including aggregates, mixing water and transportation [2]. The construction industry is consuming large quantities of natural aggregate resources while also generating substantial amounts of construction and demolition waste, much of which ends up in landfills [3].

Agricultural waste ashes, such as rice husk ash (RHA), palm oil fuel ash (POFA), sugarcane bagasse ash (SCBA), corn cob ash, coconut shell ash and cassava peel ash, are rich in amorphous silica and can therefore be used as pozzolanic materials to partially replace cement [4, 5]. Recycled concrete aggregate (RCA) is obtained by crushing demolished concrete and can be used to replace natural aggregate, thereby reducing the amount of construction waste disposed of in landfills [6, 7]. However, both materials have drawbacks. The reactivity of agricultural waste ashes depends on the type of ash and the

burning conditions, and these ashes are generally associated with lower early-age strength. Replacing natural aggregate with RCA can reduce the compressive strength, stiffness (modulus of elasticity) and durability of concrete [8, 9].

Coarse aggregate can also be substituted with industrial waste products or local rock sources. Steel slag is produced at a rate of over 225 Mt annually and has been studied for use as a coarse aggregate [10, 11]. Ironstone is found in large quantities in Nigeria and has recently been used with gravel to reduce the quantity of granite in concrete [12].

The two materials can complement each other when incorporated into concrete. Ash can help fill voids and improve the microstructure around the RCA, while RCA reduces the amount of natural aggregate needed [13]–[14]. However, few studies have quantified the carbon emissions of such concrete, and the different methods used make comparisons between studies difficult [7].

The aim of this review is to examine studies that have investigated the carbon footprint and properties of concrete containing agricultural waste ashes, recycled concrete aggregate and other aggregate materials such as steel slag and ironstone. Its objectives are to: (i) provide background information on six agricultural waste ashes, how they are processed and their properties, as well as the properties of RCA, steel slag and ironstone as aggregate materials; (ii) examine how the carbon footprint of concrete is determined and why results differ from study to study; (iii) present the properties of concrete containing these materials, used individually and in combination, such as strength, durability and carbon footprint; and (iv) identify the factors that determine the carbon footprint of concrete.

All of the studies used in this review were peer-reviewed journal articles published from 2017 onwards. Articles were found using Google Scholar, ScienceDirect, SpringerLink, MDPI and Taylor & Francis. The search was conducted in October and November 2026 using keywords such as rice husk ash, palm oil fuel ash, bagasse ash, recycled concrete aggregate, steel slag, ironstone, carbon footprint and life cycle assessment, and the reference lists of these articles were also searched to find additional articles. Conference papers, theses, retracted articles and articles whose publication details could not be verified were excluded.

2 Agricultural waste ash

Large quantities of crop wastes, such as husks, bagasse, shells, cobs and peels, are generated each year. These wastes are either burnt on open ground or sent to landfill, which pollutes the air and occupies land [15, 16]. When combusted, crop waste can produce ash with a high content of amorphous silica [4, 17]. This silica reacts with the calcium hydroxide produced during cement hydration to form additional calcium silicate hydrate (C-S-H), the main strength-producing compound in concrete, so agricultural ash can be used as a partial replacement for cement [5, 17]. Under ASTM C618 [18], a material is classified as a pozzolan if its combined SiO_2 + Al_2O_3 + Fe_2O_3 content is at least 70% and its strength activity index is at least 75%. The agricultural ashes reviewed in this section are rice husk ash (RHA), palm oil fuel ash (POFA), sugarcane bagasse ash (SCBA), corn cob ash (CCA), coconut shell ash (CSA) and cassava peel/pulp ash (CPA).

2.1 Rice husk ash (RHA)

Rice husk is the outer protective layer of the rice grain and is removed during milling. Global paddy production in 2021/22 was around 714.2 Mt, which corresponds to about 142.84 Mt of husk, since 1

t of paddy produces around 0.2 t of husk and 0.05 t of RHA [17]. Disposing of rice husk causes problems, and burning it in open areas produces low-quality ash while polluting the environment [16, 17].

Many researchers have investigated RHA because of its high amorphous silica content. Endale et al. [17] found that SiO_2 exceeded 70% in all the studies they reviewed, reaching as high as 97%, with an amorphous silica content of around 85–95%.

Several factors must be considered when producing RHA. Burning at 500–700 °C for about one hour produces amorphous ash, whereas at temperatures above 800 °C the silica becomes crystalline, which lowers its reactivity [16]. A study of different Nigerian rice varieties found that burning at 600 °C for 4 h produced better ash than burning at 400 °C for 6 h [19]. The ash is then milled to increase its fineness; ground RHA typically has an average particle size of 6–10 μm, with particles smaller than 45 μm, and milling for 80 min reduced the median size to 0.68 μm [16]. Studies generally report 10–20% as a suitable level of cement replacement with RHA [17].

2.2 Palm oil fuel ash (POFA)

Palm oil fuel ash is a waste product generated during the production of palm oil. During oil extraction, the fibres, shells and empty fruit bunches are burnt as fuel in the mill boilers, and the resulting ash is known as POFA. It is estimated that POFA makes up about 5% of the total residue burnt [20]. POFA is typically discarded in open spaces next to palm oil mills or in landfills, which harms the environment [20, 21].

Because of its high silica content, POFA can be used as a supplementary cementitious material that takes part in the pozzolanic reaction. Alsubari et al. [22] showed that the calcium hydroxide content decreased when heat-treated POFA was used in cement paste, indicating that the POFA was reacting with the products of cement hydration.

POFA is produced in mill boilers operating at temperatures of about 800–1000 °C [20], and it must be treated before use in concrete. It is first dried at around 105 °C for 24 h and sieved through a 300 μm sieve to remove larger unburnt material [20, 23]. The POFA is then milled until the particles are smaller than 45 μm [20]. Some researchers have also heat-treated POFA at around 500 °C for 60 min to burn off any remaining unburnt carbon [20].

The chemical composition of POFA can vary greatly. Its SiO_2 content ranges from 42% to 70% and its LOI is close to 10%, while its combined $SiO_2 + Al_2O_3 + Fe_2O_3$ content is often close to the ASTM C618 limit of 70%, so different POFAs have been classified as Class C, F or N [20, 23].

2.3 Sugarcane bagasse ash (SCBA)

Sugarcane bagasse is the material left behind when the juice is extracted from sugarcane. It is typically burnt as fuel in the boiler houses of sugar factories, and the leftover material is known as sugarcane bagasse ash. Burning one tonne of bagasse produces between 25 and 40 kg of ash, and China alone produces between 1.25 and 2 Mt of SCBA each year [15]. Most SCBA is used as fertiliser or sent to landfill [15, 24]. Research into SCBA as an alternative binder has also been carried out in Nigeria because of the high price of cement [25].

SCBA has gained research interest because of its high amorphous silica content [5]. However, ash taken straight from the sugar mill, where it is burnt under uncontrolled conditions, can contain less than 50% amorphous silica, so it may need further processing [15].

The boiler houses of sugar factories burn bagasse at temperatures of 550–1000 °C, and burning above 800 °C or for long durations produces crystalline silica [15]. When the ash was re-calcined at 600–900 °C for 90 min, the highest pozzolanic activity was obtained at 700 °C, and above this temperature the silica converted to cristobalite [15]. Grinding is also key to increasing the pozzolanic activity of SCBA. Raw SCBA has a particle size of about 107.9 μm, much larger than that of cement (23.32 μm), and ball milling for 60 min produced the greatest increase in surface area [24].

Various chemical, mineralogical and physical tests are used to determine how pozzolanic SCBA is. For SCBA from Ethiopia, XRD showed a large amorphous region at 15–30° 2θ together with quartz and cristobalite, and SEM images showed porous particles [26]. Prabhath et al. [24] classed their processed SCBA as a Class F pozzolan and reported that processed SCBA exceeded the 75% strength activity index, whereas raw SCBA did not.

2.4 Corn cob ash (CCA)

Corn cob is the central core that remains after the kernels have been removed from the maize ear. More than 5 million tonnes of maize cobs are generated annually in Nigeria, and, like other agro-wastes, they are disposed of by open burning, discarded on farmland or sent to landfill [27]. Other maize residues have also been investigated in Nigeria; Adeniji and Ayegbusi [28] characterised corn sheath ash, obtained from the leaves surrounding the cob, using X-ray fluorescence to assess its suitability as a supplementary cementitious material.

Research into CCA as a cementitious material has gained attention because of its high silica (SiO_2) content of between 45% and 64% [29, 30], which allows it to be used as a potential pozzolanic material to lower the cement content of a mix.

CCA can be processed in several ways, which determine its characteristics. Fadele and Otieno [30] produced CCA either by burning in a drum furnace at around 700 °C or by pyrolysis followed by calcination at 800 °C for at least 2 h, and then milled it in a vibratory disc mill, producing D50 values of 12.41 μm and 6.11 μm respectively.

The composition of CCA depends on its source and how it is burnt, and the ash typically contains high amounts of K_2O [29, 30]. XRD analysis by Fadele and Otieno [30] showed that their CCA was mostly crystalline, with an amorphous content of only 1.9–2.4% compared with 58% for fly ash, and the authors concluded that CCA behaves more as a filler than as a pozzolan.

2.5 Coconut shell ash (CSA)

Coconut shell is the hard, woody layer that surrounds the edible part of the coconut. Of the estimated 50 billion coconuts harvested each year, 85% of the shells are regarded as waste [31]. In Nigeria, coconut shell has been studied both as an ash to partially replace cement and as a lightweight coarse aggregate. Adeniji et al. [32], for example, used coconut shell to partially replace coarse aggregate, with RHA partially replacing cement, in reinforced concrete exposed to a chloride environment.

CSA has been classified as a Class N pozzolan, which means it can be used to partially replace cement [33]. Using CSA as a partial cement replacement has also been shown to reduce the embodied carbon of concrete [31, 34].

CSA is produced by washing and drying coconut shells, which are then burnt and ground into a fine powder. Joshua et al. [33] washed and air-dried coconut shells obtained from Badagry, Lagos, then pulverised them, burnt them above 700 °C for 3 h and sieved the ash through a 75 μm sieve.

The chemical composition of CSA varies between sources. In a review of several studies, Bheel et al. [35] found that CSA can contain 37.9–44.05% SiO_2, 14.6–24.12% Al_2O_3, 8.17–15.48% Fe_2O_3 and 3.25–4.98% CaO, with an LOI of 6.51–11.94% and a specific gravity of around 1.33. Optimum replacement levels of 10% for strength [34] and 20% when strength and global warming potential were considered together [31] have been reported.

2.6 Cassava peel/pulp ash (CPA)

Cassava is one of the most widely cultivated root crops in tropical areas, and large quantities of cassava peel and pulp are generated as waste when it is processed into food products. Nigeria produced approximately 63 Mt of cassava in 2021, making it the largest producer in the world with roughly 20% of global production [36]. Cassava processing centres in Nigeria are estimated to produce about 40 Mt of waste each year [37], much of which is left in the open to degrade, causing harm to humans and the environment [38]. Cassava peels make up roughly 20–35% of the mass of the tuber, and disposing of this waste by burning or landfilling results in emissions of roughly 195–361 kg CO_2 per tonne [39].

Reported values of $SiO_2 + Al_2O_3 + Fe_2O_3$ range from 65.6% to 88.6% depending on the study, so many cassava peel ashes can satisfy the 70% requirement for a pozzolan [39]. In Nigeria, Adeniji and Ayegbusi [28] characterised cassava pulp ash using X-ray fluorescence to classify it as a supplementary cementitious material, and Adeniji and Ayegbusi [40] investigated the use of cassava pulp ash, corn sheath ash and ground granulated blast furnace slag as cement replacements in self-compacting concrete (SCC).

CPA is produced by air-drying the peels, burning them, and then grinding and sieving the ash. Burning temperatures of 500–850 °C have been used, with 700 °C commonly adopted, and the ash has been sieved to between 75 and 150 μm [39].

The composition of CPA varies depending on its source. The specific gravity of CPA ranges from 1.74 to 2.53, its K_2O content can be as high as 13.1%, and it slows the setting of cement paste [39]. Its high potassium content may increase the risk of alkali–silica reaction, which has not yet been well investigated [39].

3 Recycled and alternative aggregates

Aggregate makes up most of the volume of concrete. Approximately 12 billion tonnes of concrete are used worldwide each year, and 70–80% of this by mass is natural aggregate [10]. Using recycled or alternative aggregates can therefore help to conserve natural resources and reduce the amount of waste sent to landfill.

3.1 Recycled concrete aggregate (RCA) from construction and demolition waste

Construction and demolition (C&D) waste is created when new buildings are constructed or existing structures are renovated or demolished. Over 35% of the total waste created in the European Union is C&D waste, amounting to around 1000 Mt per year, or about 2.2 t per person [6]. A significant portion of this waste is sent to landfill, with approximately 60% estimated to be disposed of in this way [41]. In Nigeria, concrete, reinforcement and timber form the largest share of construction waste, at about 15–20%, and Lagos, which accounts for approximately 60% of the construction work in Nigeria, has five landfill sites that accept C&D waste [42].

Using RCA in concrete has many benefits, as it reduces the use of natural aggregates and sends less waste to landfill, although transport distances affect how environmentally friendly it is [43].

RCA is produced by crushing concrete, removing any unwanted materials and sieving the recycled concrete into different aggregate sizes. RCA has old cement mortar attached to the natural aggregate, which weakens the aggregate, and many methods have been researched to improve it. Heating the RCA to 300–500 °C, accelerated carbonation, polymer impregnation and coating with pozzolanic slurries can all reduce the effect of the old mortar [44].

Because of the attached mortar, RCA absorbs more water than natural aggregate. Coarse RCA from concrete waste had an average 24-hour water absorption of 4.9% and a saturated surface-dry density of 2442 kg/m^3, compared with a water absorption of 1.0–2.5% and a density of 2600–2700 kg/m^3 for natural limestone aggregate [6]. Standards such as EN 206 limit the use of recycled aggregate, for example by requiring a Los Angeles coefficient of no more than 50 and restricting the replacement of natural aggregate to 50% in dry conditions and 30% in more aggressive exposure classes [6].

3.2 Steel slag aggregate (SSA)

Steel slag is formed when impurities in the molten steel react with flux materials such as lime, forming a molten layer that cools and solidifies. With 1878.5 Mt of crude steel produced in the world in 2022, over 225 Mt of steel slag is thought to be created each year [10]. In Nigeria, Ife Iron and Steel produces hundreds of tonnes of steel slag every year [45].

Steel slag has been studied as a substitute for natural coarse aggregate. Concrete produced with steel slag aggregate tends to have a higher density and improved strength and durability compared with concrete produced with natural aggregate, but it has lower workability [10].

The main drawback of steel slag is its volume instability. Because steel slag contains free lime (CaO) and free magnesia (MgO), it can expand when these compounds hydrate; CaO and MgO expand by approximately 98% and 148% respectively on hydration. Expansion caused by MgO can continue for many years [10]. To combat this, steel slag must be treated before it is used as aggregate. The potential expansion of steel slag aggregate can be tested using ASTM D4792 [46].

Steel slag aggregate is usually denser and harder than natural aggregate. Steel slag has a density of 3000–3900 kg/m^3, compared with 2400–2800 kg/m^3 for granite, and its main oxides are CaO, SiO_2, iron oxides and MgO [10]. Adeniji et al. [11] found that their steel slag aggregate had an SiO_2 content of 34.125%, a specific gravity of 3.07, a bulk density of 1680 kg/m^3, an ACV of 21.28% and an AIV of 8.37%, all of which were within the acceptable limits for use in structural concrete.

3.3 Ironstone aggregate

Ironstone can be described as a sedimentary rock with a high content of iron oxides, and abundant quantities of it are found in Nigeria. The Agbaja ironstone, located in Kogi State, is known to be the largest iron ore deposit in Nigeria, with reserves of 1250–2000 Mt [47]. Since the ironstone contains a high amount of phosphorus, it is hard to refine into steel, which is why it has remained largely unused as an iron ore [47]. A large quantity of this material is therefore available and could be used as an alternative to the crushed granite normally used as coarse aggregate.

Adeniji et al. [12] studied hybrid coarse aggregates in which 0–100% of the granite was replaced with ironstone and gravel at intervals of 25%. A total of five mixes were designed for a target strength of 20 MPa with a water–cement ratio of 0.50. The aggregates were analysed for particle size distribu-

tion, specific gravity, bulk density, aggregate crushing value and aggregate impact value, and their chemical and mineralogical composition was determined using SEM/EDX. Apart from this study, few journal articles published since 2017 have looked into ironstone as a coarse aggregate, so little is known about the durability, long-term behaviour and carbon footprint of this material, which is a clear gap in the literature.

4 Carbon footprint

Most of the carbon footprint of concrete comes from the cement used in it. The production of cement contributes around 8% of global anthropogenic CO_2 emissions and 36% of construction-related emissions [48]. It is estimated that calcination contributes around two-thirds of the greenhouse gas (GHG) emissions from cement, with the rest coming mainly from fuel combustion [48]. Using cleaner fuels will not prevent the emissions from calcination. Therefore, replacing part of the clinker with supplementary cementitious materials such as agricultural waste ash is one of the most direct ways of reducing the carbon footprint of concrete.

Nigeria is currently the leading cement producer in Africa [49], with a production capacity of 58.9 Mt per year shared among at least 12 cement manufacturers across the country [50]. If Nigeria continues with its current practices, GHG emissions from its cement industry could increase nearly threefold by 2050 compared with their 2015 value. The key strategies identified for limiting this growth are energy efficiency, reducing the amount of clinker used in cement production and controlling demand [49].

According to ISO 14067, the carbon footprint of a product is the sum of the GHG emissions and removals in a product system, expressed in CO_2 equivalents (CO_2-eq). It is based on a life cycle assessment (LCA) that uses climate change as the single impact category [51].

According to ISO 14040 and ISO 14044, an LCA has four steps: goal and scope definition, life cycle inventory, life cycle impact assessment and interpretation [52, 53]. EN 15804 breaks down the life cycle of a construction product into modules A1–A3 (raw material supply, transport and manufacturing, known as the product stage), A4–A5 (transport to site and construction), B1–B7 (use stage), C1–C4 (end-of-life stage) and D (benefits and loads beyond the system boundary). An LCA that covers only the product stage is called a cradle-to-gate analysis. One that covers all stages from raw material extraction to disposal is known as a cradle-to-grave analysis, and one that also includes the reuse of the material after disposal is a cradle-to-cradle analysis [53]. However, an assessment limited to modules A1–A3 can miss 30–40% of a building's GHG emissions [54].

The emission factors used by Kurda et al. [2] for the main raw materials, 0.898 kg CO_2-eq/kg for CEM I, 0.029 kg CO_2-eq/kg for coarse natural aggregate and 0.005 kg CO_2-eq/kg for coarse RCA, show why cement makes up such a high percentage of the carbon footprint of concrete. Kurda et al. [2] found that their reference concrete had a carbon footprint of 362 kg CO_2-eq/m^3, and cement made up 87–96% of the GWP of their mixes.

Although most studies reported emissions per 1 m^3 of concrete, comparing carbon footprints without considering compressive strength can be misleading. A lower-strength mix may emit less CO_2 per cubic metre but require a greater volume of concrete to carry the same load, making it appear more environmentally favourable per cubic metre than it really is when compared with a stronger mix [7]. Strength-normalised indicators help address this limitation, with CO_2 intensity (CI) and eco-strength

efficiency (η) being commonly used measures [55, 56]. The two indicators are reciprocals of each other and are calculated as follows:

$$CI = \frac{E}{f_c} \tag{1}$$

$$\eta = \frac{f_c}{E} \tag{2}$$

Here, CI represents CO_2 intensity, expressed in kg CO_2-eq m^{-3} MPa^{-1}, while η represents eco-strength efficiency, the reciprocal of CI. E denotes emissions per cubic metre of concrete produced (kg CO_2-eq m^{-3}), and f_c is the compressive strength of concrete or mortar (MPa), typically measured at 28 days or later.

Most studies assigned zero upstream environmental burden to agro-waste ash and RCA when treating them as waste materials, accounting only for the processing and transportation associated with their use in concrete. However, when a supplementary cementitious material is treated as a co-product rather than a waste, assigning it a share of the emissions from its original production process can substantially increase its estimated carbon footprint. For example, Kurda et al. [3] reported fly ash global warming potential values ranging from approximately 0.009 kg CO_2-eq/kg with no allocation to 4.18 kg CO_2-eq/kg under mass allocation. Clearly stating the allocation approach is therefore important because different methods can produce results that are difficult to compare directly.

Studies have also used different inventory datasets to estimate emissions from cement production and electricity consumption. Local or generic inventory data can lead to substantial differences in reported emissions. Therefore, absolute carbon footprint values should be compared with caution, while percentage changes relative to each study's own reference mix can be useful for comparing the reported benefits of different replacement strategies.

Concrete can absorb CO_2 throughout its lifetime through carbonation, and this can help counteract some of the emissions produced during cement manufacture. From 1930 to 2019, cement materials are estimated to have sequestered 21.02 Gt of CO_2, which is about 55% of the process emissions over that period [57]. Recycled aggregate stored under natural conditions for a few months sequestered 5.4–12.6% of the CO_2 released in producing the cement it contained [58]. Carbonation can also affect the properties of concrete; Ikumapayi et al. [59] found that accelerated carbonation improved the compressive strength, flexural strength and water absorption of concrete.

5 Results and discussion

In this section, the results obtained from each of the reviewed studies are discussed. The results for each agricultural waste ash are discussed first, followed by those for recycled and alternative aggregates, concrete that contains both agricultural waste ash and recycled concrete aggregate, and the factors that control the carbon footprint. Tables have been created to show what each author found, including the replacement percentage used, the strength, the durability and the carbon footprint. Where n.r. is shown, the value was not reported.

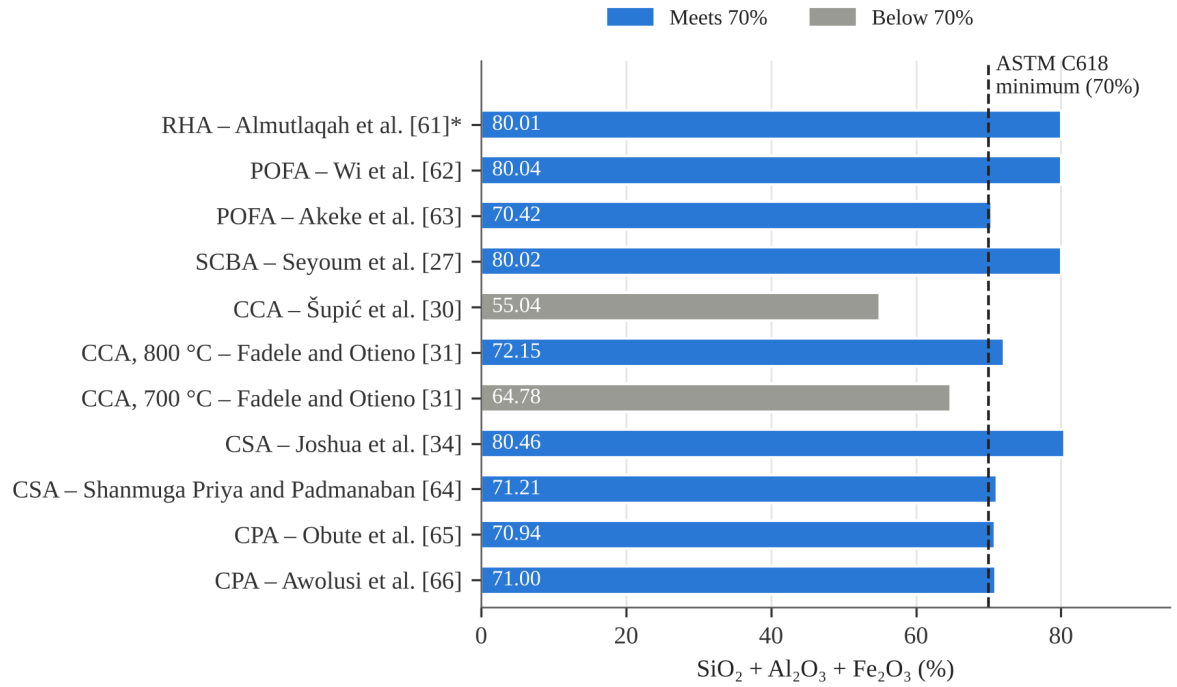
5.1 Agricultural waste ash

Table 1 shows the chemical compositions of the ashes from the studies that were analysed. Most of the ashes achieved a value above 70% for SiO_2 + Al_2O_3 + Fe_2O_3, which is the minimum required by ASTM C618, although some were only just above this value. CCA varied the most, with the sample

from Šupić et al. [29] achieving only 55.04%, while Fadele and Otieno [30] found that their ash only met the requirement when it was burnt at 800 °C. Many of these ashes also had a high K_2O content, which could cause alkali–silica reaction [26, 29]. This shows that where the ash comes from and how it is burnt and ground play a big part in its quality. Figure 1 compares the combined SiO_2 + Al_2O_3 + Fe_2O_3 content of each ash with the ASTM C618 minimum of 70%.

Table 1. Chemical composition of agricultural waste ashes (%).

Ash	Study	SiO_2	Al_2O_3	Fe_2O_3	CaO	K_2O	LOI	SiO_2+Al_2O_3+Fe_2O_3	≥ 70%?
RHA	Almutlaqah et al. [60]	79.86	n.r.	0.15	1.11	3.23	13.49	≥ 80.01	Yes
POFA	Wi et al. [61]	70.90	5.63	3.51	3.78	5.66	10.10	80.04	Yes
POFA	Akeke et al. [62]	62.80	4.60	3.02	7.60	n.r.	9.42	70.42	Yes
SCBA	Seyoum et al. [26]	65.06	10.88	4.08	1.14	6.60	4.75	80.02	Yes
CCA	Šupić et al. [29]	45.76	5.91	3.37	14.08	13.10	2.40	55.04	No
CCA (800 °C)	Fadele and Otieno [30]	63.68	4.42	4.05	2.37	11.22	n.r.	72.15	Yes
CCA (700 °C)	Fadele and Otieno [30]	59.37	2.79	2.62	1.26	15.83	n.r.	64.78	No
CSA	Joshua et al. [33]	66.32	8.79	5.35	6.25	3.26	4.28	80.46	Yes
CSA	Shanmuga Priya and Padmanaban [63]	49.44	18.32	3.45	2.21	n.r.	n.r.	71.21	Yes
CPA	Obute et al. [64]	51.76	11.32	7.86	6.89	6.43	n.r.	70.94	Yes
CPA	Awolusi et al. [65]	39.26	16.98	14.76	5.03	4.36	n.r.	71.00	Yes



* Al_2O_3 not reported; value is SiO_2 + Fe_2O_3 only.

Figure 1. Combined SiO_2 + Al_2O_3 + Fe_2O_3 content of the agricultural waste ashes in Table 1 compared with the ASTM C618 minimum of 70%.

5.1.1 Rice husk ash

Rice husk ash (RHA) has been studied extensively due to its high amorphous silica content. The burning method can significantly influence its carbon benefit: one study found that at 20% cement replacement, RHA produced using a fluidised-bed combustor reduced CO_2-equivalent emissions by 24%, whereas RHA from a grate furnace achieved only a 7.7% reduction [66]. Ro et al. [67] found that using RHA to replace 15% of the cement decreased the CO_2-eq emissions of the binder by 15% and reduced the chloride penetration charge by about half, although the 28-day strength was around 15% lower. In Nigeria, Adeniji et al. [32] showed that when RHA was used to replace cement and coconut shell was used to replace coarse aggregate, the compressive strength decreased as the replacement level increased. However, the 10% mix achieved a 28-day compressive strength of 16.09 MPa and lowered the corrosion rate of the reinforcement from 18.52 mm/year in the control sample to 6.17 mm/year, while at 15–20% the corrosion rate was higher. The results reported for RHA are summarised in Table 2.

Table 2. Reported results for concrete and mortar containing rice husk ash.

Study	Replacement studied	Strength	Durability and other properties	Carbon footprint
Adeniji et al. [32]	RHA (cement) + coconut shell (coarse aggregate), 0–20%	Strength fell with replacement; 16.09 MPa at 10% (28 d)	Corrosion rate 18.52 → 6.17 mm/year at 10%	n.r.
Almutlaqah et al. [60]	20%, as received and re-burnt	Untreated RHA below 75% SAI	Heat of hydration 185.5 vs 249.3 J/g	n.r.
Ro et al. [67]	15%	28-day strength ≈ 15% lower	Chloride charge ≈ halved	−15% CO_2-eq (binder)

Study	Replacement studied	Strength	Durability and other properties	Carbon footprint
Suárez Silgado et al. [68]	RHA blends (Colombia)	n.r.	Economic advantages	Environmental advantages
Xi et al. [69]	Optimised mixes, 40–60 MPa	Target strength met	Higher cost	−12.2 to −17.5 kg CO_2-eq/m^3
Öztürk et al. [56]	Database, > 1000 mixes, RHA + other pozzolans	Eco-strength efficiency assessed	+65% cost efficiency	≈ −25% CO_2
Rigon et al. [66]	20% (fluidised bed / grate furnace)	n.r.	Still beneficial when transported > 400 km	−24% / −7.7% CO_2-eq
Fernando et al. [70]	Fly ash–RHA alkali-activated concrete	n.r.	Activators 74% of emissions	+12% GHG vs Portland cement concrete
Hu et al. [71]	15% (improved burning)	Higher mortar strength	Better sulfate resistance	Lower CO_2 and energy
Passuello et al. [72]	RHA-derived activator (alkali-activated binder)	n.r.	n.r.	> 70% lower GWP than Portland cement

5.1.2 *Palm oil fuel ash*

Palm oil fuel ash (POFA) is associated with some of the largest published reductions in concrete's carbon footprint. Replacing 0–40% of cement with POFA in M60 high-strength concrete lowered CO_2 emissions by 9–37%; at the optimum replacement level of 20%, compressive strength increased by 5% and flexural strength by 25% [73]. A mixture containing up to 60% POFA and 10% limestone powder satisfied the ACI 363R requirements for high-strength concrete, lowered CO_2 emissions by 44–62% compared with cement concrete of similar strength, and cut heat generation by approximately half [74]. The use of POFA can also increase durability. Concrete with 20% POFA had a chloride penetration charge of 276.3 C, while that of the control was 731.7 C, and its water permeability was approximately 50% lower [23]. The results reported for POFA are summarised in Table 3.

Table 3. Reported results for concrete and mortar containing palm oil fuel ash.

Study	Replacement studied	Strength	Durability and other properties	Carbon footprint
Umer et al. [75]	10–25% POFA + jute fibre	Up to +26% (10% POFA + 0.10% fibre)	n.r.	Lowest embodied carbon at 25% POFA
Menaka and Bhuvaneshwari [73]	0–40% (M60), optimum 20%	+5% compressive, +25% flexural at 20%	n.r.	−9 to −37% CO_2
Sanit-in et al. [74]	Up to 60% POFA + 10% limestone powder	Met ACI 363R high-strength requirements	Heat generation ≈ halved	−44 to −62% CO_2 at equal strength

Study	Replacement studied	Strength	Durability and other properties	Carbon footprint
Amran et al. [23] (review)	20%	n.r.	Chloride charge 276.3 vs 731.7 C; water permeability ≈ 50% lower	n.r.
Hamada et al. [21]	High-volume ultrafine POFA	Best strength at 20–40%	n.r.	n.r.
Wi et al. [61]	Micro-POFA in mortar	Optimum 10%	n.r.	n.r.

5.1.3 Sugarcane bagasse ash

A study in Pakistan found that 10% SCBA was the optimum replacement level for strength. SCBA also reduced alkali–silica reaction expansion, and the mix containing 15% SCBA recorded the lowest CO_2 emissions [76]. The overall environmental impact of mortars containing 20% SCBA decreased by 14% when cured at 21 °C and by 31% when cured at 45 °C. Curing at the higher temperature also produced higher strength [77]. In Nigeria, however, untreated SCBA lowered the compressive strength of M15 concrete at every replacement level, from 25.93 MPa to 18.96 MPa [25], which shows that SCBA needs to be treated before it is used. The results reported for SCBA are summarised in Table 4.

Table 4. Reported results for concrete and mortar containing sugarcane bagasse ash.

Study	Replacement studied	Strength	Durability and other properties	Carbon footprint
Ullah et al. [76]	Various levels	Optimum 10%	Reduced alkali–silica reaction expansion	Lowest CO_2 at 15%
Olopade and Ngene [25]	Untreated SCBA, M15 concrete	25.93 → 18.96 MPa as SCBA increased	n.r.	n.r.
Francioso et al. [77]	20% (mortar)	Higher strength with 45 °C curing	n.r.	Overall impact −14% (21 °C), −31% (45 °C)
Sakib et al. [78]	20% (SAI); 15% optimum (mortar)	SAI 91% (7 d), 93% (28 d)	n.r.	n.r.
Prabhath et al. [24] (review)	Up to 15%	Strength improved	≈ 12% cheaper than M25 at 15%	n.r.
Seyoum et al. [26]	Mortar	Optimum 5–10%	$Na_2O + K_2O$ = 8.66% (ASR risk)	n.r.
Xu et al. [15] (review)	Various levels	Optimum 15–25%; SAI of 75% needs D80 ≈ 60 µm	n.r.	n.r.

5.1.4 Corn cob ash, coconut shell ash and cassava peel/pulp ash

The use of corn cob ash (CCA), coconut shell ash (CSA) and cassava peel/pulp ash (CPA) has not been researched as much as that of RHA, POFA and SCBA, and their results vary more, as shown in Table 5. Studies on CCA showed that 10% was the optimum in roller-compacted concrete, giving a compressive strength of 32.88 MPa with 0.50% jute fibre and a lower embodied carbon than the control mix

[79]. When CCA replaced 50% of the cement by volume in masonry mortar, it lowered CO_2 emissions from 256.85 to 166.54 kg/t, or around 35%, but it also lowered the strength by around 48% [29]. Ranatunga et al. [31] showed that the strength of concrete containing 15% and 20% CSA was comparable to that of the control (27.31 and 26.94 MPa respectively, compared with 27.05 MPa), and the GWP of the concrete containing 20% CSA was lowered from 397 to 325 kg CO_2-eq/m^3; this trade-off between strength and GWP is shown in Figure 2. CPA reduced the strength of mortar from 22.92 MPa to 15.63 MPa at 20% replacement [80], and a review found that the 28-day strength is typically reduced by 15–30% when CPA replaces 5–15% of the cement [39]. However, CPA can increase the resistance of self-compacting concrete to acid and sulfate attack [37]. None of the reviewed studies reported the carbon footprint of concrete containing CPA.

Table 5. Reported results for concrete and mortar containing corn cob ash, coconut shell ash and cassava peel/pulp ash.

Ash	Study	Replacement studied	Strength	Durability and other properties	Carbon footprint
CCA	Fadele and Otieno [30]	15 and 30% (mortar)	90-day: 36 MPa (700 °C ash), 44 MPa (800 °C ash)	Mostly crystalline; acts mainly as a filler	n.r.
CCA	Hasan et al. [81]	10% CCA + 1% corn husk fibre	+7.54% compressive	n.r.	−2.5% CO_2 (fibre)
CCA	Bheel et al. [79]	5–20% CCA + jute fibre (roller-compacted concrete)	32.88 MPa compressive, 5.3 MPa flexural (10% CCA + 0.50% fibre)	n.r.	Lower embodied carbon than control
CCA	Šupić et al. [29]	50% by volume (masonry mortar)	≈ −48% (7.97 → 4.11 MPa)	Flow 175 → 140 mm; cost ≈ −22%	256.85 → 166.54 kg CO_2/t (≈ −35%)
CCA	Șerbănoiu et al. [82]	2.5 and 5% by volume	Best at 2.5%	Better freeze–thaw resistance; HCl resistance 30–47% better	n.r.
CCA	Bheel et al. [83]	30% CCA as fine aggregate (± 10% GGBFS)	29.58 MPa (+11.62%); +16.98% with GGBFS	Water absorption fell	−0.3 to −0.8% (CCA alone); 329.3 → 274.70 kg CO_2/m^3 with GGBFS
CCA	Bagcal and Baccay [84]	0–20%	Strength fell; optimum 6.43% for 25 MPa	n.r.	n.r.
CSA	Maheswari et al. [85]	5–20%	29.50 / 26.50 / 24.80 / 22.67 MPa	Workability fell above 10%	n.r.
CSA	Bheel et al. [86]	CSA + metakaolin + calcined clay (80 MPa)	≈ +10.7% at ≈ 9% calcined clay	n.r.	≈ −11.8% embodied carbon
CSA	Ranatunga et al. [31]	15–30% (w/b 0.55)	27.31 / 26.94 / 25.60 / 21.40 MPa vs 27.05 MPa (control)	Slump 140 → 20 mm at 30%	397 → 343 / 325 / 306 / 288 kg CO_2-eq/m^3
CSA	Shanmuga Priya and Padmanaban [63]	M20, optimum 12.5%	23.65 → 30.19 MPa (+27.65%)	Water absorption 3.25 → 2.26%; RCPT 2850 → 1876 C	n.r.

Ash	Study	Replacement studied	Strength	Durability and other properties	Carbon footprint
CSA	Bheel et al. [87]	CSA + groundnut shell ash, 10–20%	+11.62% compressive at 10%	n.r.	≈ −16% embodied carbon at 20%
CSA	Bheel et al. [34]	0–20%	+12% compressive, +10% tensile, +9% flexural at 10%	n.r.	≈ −15% embodied carbon at 20%
CSA	Joshua et al. [33]	15–20%	SAI 92% at 20%	Final setting 350 → 375 min at 15%	n.r.
CPA	Adeniji and Ayegbusi [28]	0–20% cassava pulp ash (self-compacting concrete, w/b 0.50)	21.3 MPa at 20% (28 d); 25.5 MPa with 20% corn sheath ash, ≈ 29.1 MPa with 20% GBFS	Slump flow 755 → 645 mm at 20%; up to 10–15% recommended	n.r.
CPA	Adagba [39] (review)	5–15%	Typical 28-day loss 15–30%	Delayed setting	n.r.
CPA	Rauf et al. [80]	5–20% (mortar)	22.92 → 15.63 MPa at 20%; with superplasticiser 26.04 vs 27.08 MPa at 5%	n.r.	n.r.
CPA	Awolusi et al. [65]	CPA in bamboo-reinforced beams	Optimum 3%: flexural strength 11.85 MPa	n.r.	n.r.
CPA	Abdulwahab and Uche [37]	5–25% (self-compacting concrete)	Optimum 5% (grade 35)	Better H_2SO_4 and $MgSO_4$ resistance; lower water absorption; worse at high temperature	n.r.
CPA	Obute et al. [64]	5% CPA + RHA (20–30% total)	28.7 → 24.12 MPa at 20% total ash	Water absorption 5.59 → 3.25%	n.r.

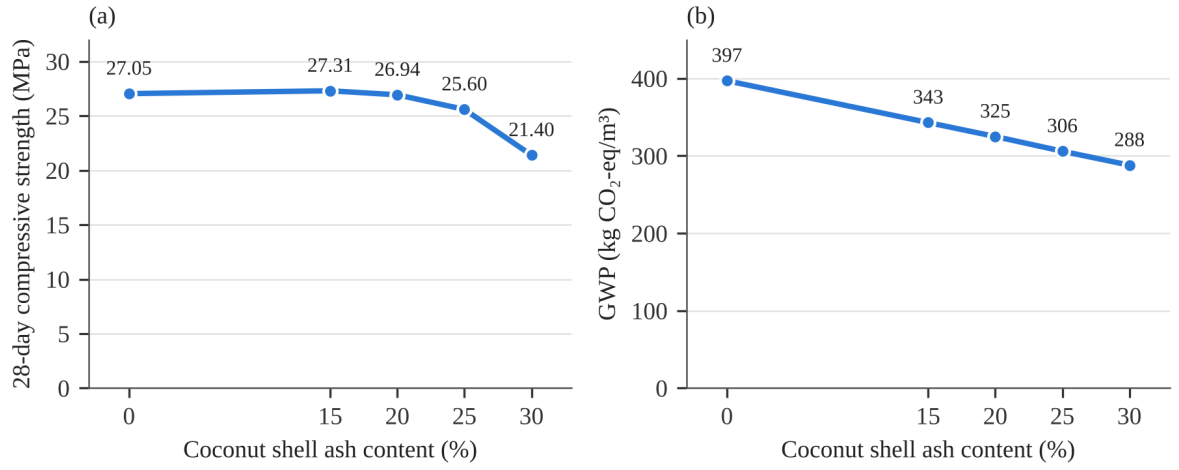


Figure 2. Effect of coconut shell ash content on (a) the 28-day compressive strength and (b) the GWP of concrete (data from [31]).

5.2 Recycled and alternative aggregates

5.2.1 Recycled concrete aggregate

In a meta-analysis of 42 papers, Piccinali et al. [8] reported that when RCA was used to substitute natural coarse aggregate, the compressive strength decreased by less than 10% at a substitution rate of 50% and by approximately 13% when the aggregate was fully substituted, while the tensile strength was around 5% lower than that of conventional concrete at 100% substitution. The modulus of elasticity was reduced more, with reductions of 12.5–38.7% observed at 100% RCA [9], and it was suggested that the use of RCA should be limited to below 30% substitution [88].

Replacing natural coarse aggregate with RCA alone reduced carbon emissions by only 0–9% per cubic metre. If more cement was needed to meet strength requirements, or if the RCA had to be transported further, emissions could increase instead. Using RCA reduces the waste sent to landfill and the use of natural aggregate, and combining RCA with cement replacement reduces carbon emissions more significantly [2, 3]. Selected results are shown in Table 6.

Cement accounts for around 87–96% of the GWP of conventional concrete [2]. Replacing 100% of the natural coarse aggregate with RCA decreased the GWP by about 8–9%, from 362 to 331 kg CO_2-eq/m^3 for modules A1–A3, while replacing natural fine aggregate with RCA showed no significant reduction [2]. Ben Fraj and Idir [89] showed that the use of low-quality recycled aggregate increased the amount of cement required to reach the same strength by 16%, whereas high-quality recycled aggregate increased it by only 3%. Presaturating the aggregates decreased this additional amount of cement by 35%.

The transport distance of RCA may determine whether it is beneficial. In Portugal, recycled aggregate was shown to have a lower GWP than natural aggregate unless it travelled more than 500 km further [43]. In Paris, concrete produced with 50% recycled aggregate was shown to have a lower impact on global warming if the natural aggregate had to travel more than 50 km [89]. Research conducted in Switzerland found that recycled concrete had only 1% lower GHG emissions than normal concrete, which was not a significant difference, and the authors recommended transport distances of less than 25 km [90].

As previously mentioned, RCA can be combined with cement replacement to further lower the impact of concrete. Replacing 30% and 60% of cement with fly ash decreased the GWP to 269 and 176 kg CO_2-eq/m^3, reductions of 26% and 51% respectively [2]. Using 50% uncarbonated RCA with 25% fly ash produced the lowest CO_2 intensity, 4.1 kg CO_2/m^3 per MPa, with RCA improving carbonation resistance and fly ash improving chloride resistance [91]. Although these studies used fly ash, the same approach of combining RCA with a cement replacement can be applied to agro-waste ashes, as discussed in Section V-C.

Table 6. Reported results for concrete containing recycled concrete aggregate.

Study	Replacement studied	Strength	Durability and other properties	Carbon footprint
Wang et al. [9] (review)	100% RCA	Modulus −12.5 to −38.7%	Pozzolans improve durability	n.r.
Lei et al. [92]	RAC (China)	n.r.	n.r.	Raw materials 80.92–85.62% of emissions; critical transport distance 331.7 km

Study	Replacement studied	Strength	Durability and other properties	Carbon footprint
Piccinali et al. [8] (meta-analysis)	50–100% coarse RCA	< 10% loss at 50%; ≈ 13% at 100%; tensile ≈ 5% lower at 100%	n.r.	n.r.
Dias et al. [43]	Coarse recycled aggregate (Portugal)	n.r.	Cheaper only if haul ≥ 53 km shorter	2.45 vs 28.6 kg CO_2-eq/t; lower unless > 500 km further
Etxeberria [91]	50% RCA + 25% fly ash	n.r.	Better carbonation (RCA) and chloride (fly ash) resistance	4.1 kg CO_2/m^3 per MPa (lowest)
Plaza et al. [93]	Up to 100% coarse and fine RCA	Compressive and tensile ≤ 17% loss; flexural < 15% loss	n.r.	Eco-efficiency improved
Sabău et al. [94]	50 and 100% RA; 100% RA + 25% fly ash	n.r.	n.r.	NAC 323–332 kg CO_2-eq/m^3; +0.3 to +3.4% (50% RA); 100% RA + fly ash below NAC
Visintin et al. [95]	624 mixes from 61 studies	n.r.	n.r.	Similar average to NAC, wider range
Kurda et al. [2]	100% coarse RCA; 30 and 60% fly ash	n.r.	n.r.	362 → 331 kg CO_2-eq/m^3 (−8 to −9%); 269 (−26%) and 176 (−51%) with fly ash
Ben Fraj and Idir [89]	50% RA (Paris)	Extra cement: +16% (low grade), +3% (high grade)	Presaturation cut extra cement by 35%	Lower GW when natural aggregate haul > 50 km
Kleijer et al. [90]	Recycled concrete (Switzerland)	n.r.	Transport below 25 km recommended	GHG −1% (not significant)
Marinković et al. [96]	Five mixes of equal strength	n.r.	n.r.	High-volume fly ash + RA best; RAC with plain cement worst

5.2.2 *Steel slag and ironstone aggregates*

Most studies showed that the use of steel slag aggregate resulted in higher-strength concrete (Table 7). Adeniji et al. [11] achieved compressive strengths of 15.63, 17.07, 18.30 and 19.10 N/mm^2 when 15%, 30%, 45% and 60% of the coarse aggregate was replaced with steel slag. The flexural strength reached a maximum of 4.45 N/mm^2 at 45% replacement and decreased to 3.85 N/mm^2 at 60%, so 45% was recommended as the optimum replacement level. Few studies have calculated the carbon footprint of concrete produced with steel slag. Using 50% steel slag in roller-compacted concrete pavement reduced CO_2 emissions by 11%, energy consumption by 7% and costs by up to 16% [97]. Concrete in which slag replaced gravel had up to a 7% lower environmental impact, and the slag was found to remain advantageous for transport distances of up to approximately 102 km [98]. Only one study was found that investigated ironstone. Adeniji et al. [12] found that the mix with 25% ironstone, 25% gravel and 50% granite achieved more than 90% of the strength of the control mix made with granite only. No study was found that calculated the carbon footprint of ironstone aggregate.

Table 7. Reported results for concrete containing steel slag and ironstone aggregates.

Aggregate	Study	Replacement studied	Strength	Other findings	Carbon footprint
Steel slag	Adeniji et al. [11]	0–60% of coarse aggregate (1:2:4, w/c 0.50)	15.63 / 17.07 / 18.30 / 19.10 N/mm^2 at 15 / 30 / 45 / 60%; flexural max 4.45 N/mm^2 at 45%	Optimum 45%; random forest R^2 = 0.85	n.r.
Steel slag	Raj and Selvam [97]	25–75% (roller-compacted pavement)	+16 to +21% at 25–50%; lower at ≥ 75%	Cost up to −16% at 50%	−11% CO_2, −7% energy at 50%
Steel slag	Mekonen et al. [99]	25–100%	+6.2 / +26.3 / +9.5 / +6.2% at 25 / 50 / 75 / 100%; flexural +13.1% at 50%	Reinforced concrete beams	n.r.
Steel slag	Adedokun and Anifowose [45]	Ife slag replacing granite	Optimum 28.85% (w/c 0.47)	Response surface methodology	n.r.
Steel slag	Miah et al. [100]	0–100% (replacing brick aggregate)	22.24 → 34.98 MPa (28 d); tensile 1.98 → 3.38 MPa	Porosity ≈ −39%; expansion 0.017% at 90 d	n.r.
Steel slag	Václavík et al. [98]	Slag replacing gravel fractions	90-day: 47.0 (reference), 48.5, 49.0, 46.0 MPa	Modulus +27% (4/8 mm fraction)	Impact up to −7%; beneficial up to ≈ 102 km
Ironstone	Adeniji et al. [12]	Ironstone + gravel replacing 0–100% granite	18.35 MPa; 91.8% compressive and 94.3% tensile of control (25% ironstone, 25% gravel, 50% granite)	Workability improved; granite use halved	n.r.

5.3 Concrete containing both agricultural waste ash and RCA

Using both agro-waste ash and recycled concrete aggregate (RCA) in the same mix achieved greater carbon savings than using either material alone, and the ash also made up for some of the strength and durability losses caused by RCA. The four studies that quantified the carbon savings of concrete containing both materials reported reductions of around 7.6–29%, most of which came from the cement replacement rather than the aggregate [55, 101]–[102]. In addition, the use of pervious alkali-activated concrete containing bagasse ash, RCA and GGBS reduced the carbon footprint by up to 77%, from 286.39 to 66.59 kg CO_2-eq/m^3 [103]. The results are summarised in Table 8.

Castillo et al. [102] performed an LCA on 10 concrete mixes containing 0–100% RCA and 0–10% RHA. Using RHA alone decreased the global warming potential by 6.45%, while using RCA alone decreased it by only 1.12%. When both materials were used, the global warming potential decreased by 7.55%, along with a 6.09% decrease in energy demand and a 68.5% decrease in water use, while strength remained above 21 MPa. Bahar et al. [104] showed that a mix containing 20% RHA and 100% RCA reduced GWP by 18.5% and embodied energy by 18.3% compared with the control in a cradle-to-gate LCA, and this mix was ranked first in a multi-criteria evaluation.

The use of RCA can lower the strength and stiffness of concrete because of the old adhered mortar and the interfacial transition zones (ITZ). However, when agro-waste ash is added at replacement

levels of around 10–20%, strength can be regained, especially at later ages. When 50% and 100% RCA were used with 20% RHA, compressive strength dropped from 27.35 MPa in the plain control to 25.93 MPa and 22.55 MPa respectively, and stiffness was reduced at a greater rate than compressive strength [104]. A factorial study with 0–100% recycled aggregate and 0–30% RHA found that 10% RHA was the optimum replacement level, increasing strength by 4.9% in concrete containing 100% recycled aggregate but by only 0.4% in natural aggregate concrete [14]. However, the modulus of elasticity of concrete containing 100% RCA can be 12.5–38.7% lower than that of normal aggregate concrete [9]. Higher amounts of POFA reduced both compressive and bond strength, although the bond strength was similar to that of normal concrete when compared at the same compressive strength [105].

The durability benefits of agro-waste ash in RAC were more consistent than its strength benefits. Using ground bagasse ash at 20–50% decreased the water permeability and sulfate expansion of high-strength RAC [13]. Ground RHA at replacement levels of up to 50% also improved chloride and corrosion resistance [106]. RCA and RHA were found to have an interaction effect on water absorption, porosity and drying shrinkage, so their effects cannot be assumed to be simply additive [107].

The mixes with the lowest carbon emissions were not always the strongest. Increasing the amounts of RCA and ash can decrease the CO_2 emitted per m^3 of concrete, but if strength also decreases, the environmental benefit can become smaller or even reverse when emissions are normalised by strength (see (1)). When strength, toughness and environmental impact were considered together, 50% RCA with around 20% ash gave the best balance [104], while 100% RCA with 20% RHA was the cheapest mix, reducing cost by 31% [108].

Table 8. Reported results for concrete containing both agricultural waste ash and recycled concrete aggregate.

Study	Materials and replacement	Strength	Durability and other properties	Carbon footprint
Bahar et al. [104]	50 and 100% RCA + 20% RHA	25.93 and 22.55 MPa vs 27.35 MPa (control)	Stiffness fell more than strength	GWP −18.5%, embodied energy −18.3% (100% RCA + 20% RHA)
Berwal et al. [109]	0–30% RCA + 0–15% SCBA (M30)	≈ 40.1 MPa (≈ 10% SCBA + 10–20% RCA)	Slump 85 → 65 mm at 15% SCBA	n.r.
Castillo et al. [102]	0–100% RCA + 0–10% RHA	> 21 MPa	Energy −6.09%; water use −68.5%	GWP −6.45% (RHA), −1.12% (RCA), −7.55% (both)
Alharthai et al. [108]	80–100% RCA + 15–20% RHA	≈ 27 MPa (15% RHA + 80% RCA)	Cost −31% (100% RCA + 20% RHA)	n.r.
Marathe et al. [103]	Bagasse ash + RCA + GGBS (pervious alkali-activated)	n.r.	n.r.	286.39 → 66.59 kg CO_2-eq/m^3 (up to −77%)
Agrela et al. [101]	Mixed recycled aggregate + olive biomass ash	Long-term loss 1.7–10.4% (concrete)	Cost −20% (mortar), −13.8% (concrete)	CO_2 −25% (mortar), −12% (concrete)
Ma et al. [14]	0–100% RA + 0–30% RHA	Optimum 10% RHA: +4.9% (100% RA), +0.4% (NAC)	n.r.	n.r.

Study	Materials and replacement	Strength	Durability and other properties	Carbon footprint
Fernando et al. [110]	Slurry-treated RCA + RHA in binder	55.4 MPa (above NAC control)	n.r.	n.r.
Zhang et al. [111]	RAC + 10–30% RHA	20% RHA: 103.94% of control at 360 d	Slump −15.38% at 20%; freeze–thaw resistance worse	n.r.
Rattanachu et al. [106]	RAC + up to 50% ground RHA	60-day strength above plain RAC at 20%	Better chloride and corrosion resistance	n.r.
Rattanachu et al. [13]	High-strength RAC + 20–50% ground bagasse ash	n.r.	Lower water permeability and sulfate expansion	n.r.
Padhi et al. [112]	100% RCA + 0–35% RHA	10–15% RHA met design requirements	n.r.	n.r.
Rattanachu et al. [113]	High-strength RAC + 20% ground bagasse ash	Above NAC control at ≥ 90 d	n.r.	n.r.
Alnahhal et al. [55]	100% RCA + 30% RHA, POFA or palm oil clinker powder	RHA best strength efficiency at 90 d	n.r.	CO_2 ≈ −29%

5.4 Factors controlling the carbon footprint

Figure 3 compares the reductions in CO_2 emissions or GWP reported by the reviewed studies for the different materials. Table 9 summarises the main factors that affected the carbon footprint values reported in the reviewed studies. These include the amount of cement replaced, the production route of the ash, transport distances, any extra cement needed to restore strength, the curing regime, the burden allocation method, the functional unit and end-of-life carbonation.

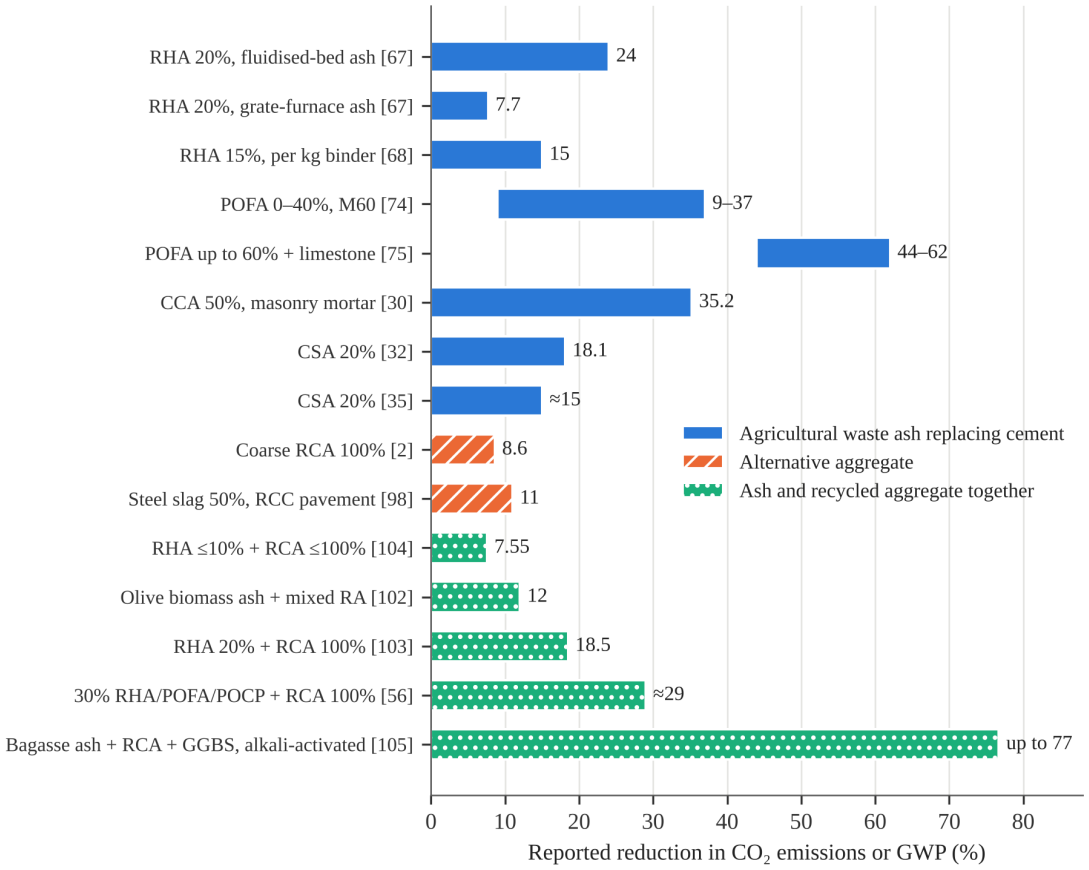


Figure 3. Reductions in CO_2 emissions or GWP reported for concrete and mortar containing agricultural waste ash, alternative aggregates or both, relative to each study's control mix.

Table 9. Factors controlling the carbon footprint of agricultural waste ash and recycled aggregate concrete.

Factor	Effect on carbon footprint	Source
Cement content and replacement level	Dominant driver; cement is 87–96% of conventional concrete GWP, so each percent of clinker replaced counts most	Xing et al. [7]; Kurda et al. [2]
Ash production route	Fluidised-bed RHA saved 24% CO_2-eq against 7.7% for grate-furnace ash at the same dosage; improved burning raises reactivity	Rigon et al. [66]; Hu et al. [71]
Transport distance	Can cancel the benefit of RCA; reported critical distances range from below 25 km to over 500 km; short SCM haul (15–25 km) maximises savings	Kleijer et al. [90]; Dias et al. [43]; Sabău et al. [94]; Lei et al. [92]
Extra cement to restore strength	Low-grade recycled aggregate needed ≈ 16% more cement (3% for high grade)	Ben Fraj and Idir [89]
Curing regime	Warm curing of SCBA mortar raised the impact reduction from 14% to 31%	Francioso et al. [77]
Burden allocation of the waste	Fly ash GWP varied by more than 400 times between no allocation and mass allocation	Kurda et al. [3]; Marinković et al. [96]
Functional unit	Per-m^3 results favour weak, low-cement mixes; strength- or durability-normalised units can reverse rankings	Xing et al. [7]; Etxeberria [91]
End-of-life carbonation	Stored recycled aggregate absorbed 5.4–12.6% of the CO_2 from its cement within months	Leemann et al. [58]

6 Conclusion

Several studies were reviewed on the carbon footprint and performance of concrete containing agricultural waste ash, recycled concrete aggregate and other aggregates such as steel slag and ironstone. From these studies, it was found that:

1. Substituting cement has a greater effect on reducing carbon emissions than substituting aggregate. Using RCA in place of natural aggregate changed the GWP by −9% to +3% per m^3 of concrete produced, while replacing 10–20% of the cement with agro-waste ash reduced it by about 8–30%, and some studies with higher ash replacement levels achieved reductions as high as 44–62%.
2. There are benefits to using agro-waste ash and RCA together. Studies that combined both materials reported reductions in GWP of about 7.6–29%. With ash replacement levels of 10–20%, most of the strength lost through RCA substitution was regained, and the ash also improved durability by reducing water permeability and improving resistance to chlorides and sulfates.
3. Transport distances, extra cement used to meet design requirements, the method used to produce the ash, curing conditions and the allocation method can all affect the results and may change which mix has the lowest carbon footprint.
4. More information is needed on mixes that use both materials. Cradle-to-grave analyses that take into account the service life of the structure should be conducted, together with more standardised procedures for processing the ash and more local data. Research in sub-Saharan Africa is especially needed, as local conditions may give different results.
5. The majority of the agricultural waste ashes met the ASTM C618 requirement for SiO_2 + Al_2O_3 + Fe_2O_3, but their composition varied depending on where the ash came from and how it was burnt. Corn cob ash had the highest variation, and cassava peel ash tended to decrease the strength of concrete.
6. When steel slag was used as an aggregate, it usually improved the strength of concrete, and around 45% was optimal in one study conducted in Nigeria. Replacing 50% of the granite with ironstone and gravel retained more than 90% of the control's strength. However, very few studies have determined the carbon footprint of these aggregates, particularly ironstone.

References

[1] Scrivener KL, John VM, Gartner EM. Eco-efficient cements: Potential economically viable solutions for a low-CO_2 cement-based materials industry. *Cement and Concrete Research*. 2018;114:2–26. https://doi.org/10.1016/j.cemconres.2018.03.015

[2] Kurda R, Silvestre JD, de Brito J. Life cycle assessment of concrete made with high volume of recycled concrete aggregates and fly ash. *Resources, Conservation and Recycling*. 2018;139:407–417. https://doi.org/10.1016/j.resconrec.2018.07.004

[3] Kurda R, Silvestre JD, de Brito J. Toxicity and environmental and economic performance of fly ash and recycled concrete aggregates use in concrete: A review. *Heliyon*. 2018;4(4):e00611. https://doi.org/10.1016/j.heliyon.2018.e00611

[4] Thomas BS, Yang J, Mo KH, Abdalla JA, Hawileh RA, Ariyachandra E. Biomass ashes from agricultural wastes as supplementary cementitious materials or aggregate replacement in cement/geopolymer concrete: A comprehensive review. *Journal of Building Engineering*. 2021;40:102332. https://doi.org/10.1016/j.jobe.2021.102332

[5] Thomas BS, et al. Sugarcane bagasse ash as supplementary cementitious material in concrete: A review. *Materials Today Sustainability*. 2021;15:100086. https://doi.org/10.1016/j.mtsust.2021.100086

[6] Pacheco J, de Brito J. Recycled aggregates produced from construction and demolition waste for structural concrete: Constituents, properties and production. *Materials*. 2021;14(19):5748. https://doi.org/10.3390/ma14195748

[7] Xing W, Tam VWY, Le KN, Hao JL, Wang J. Life cycle assessment of recycled aggregate concrete on its environmental impacts: A critical review. *Construction and Building Materials*. 2022;317:125950. https://doi.org/10.1016/j.conbuildmat.2021.125950

[8] Piccinali A, Diotti A, Plizzari G, Sorlini S. Impact of recycled aggregate on the mechanical and environmental properties of concrete: A review. *Materials*. 2022;15(5):1818. https://doi.org/10.3390/ma15051818

[9] Wang D, et al. Mechanical performance of recycled aggregate concrete in green civil engineering: Review. *Case Studies in Construction Materials*. 2023;19:e02384. https://doi.org/10.1016/j.cscm.2023.e02384

[10] Ren Z, Li D. Application of steel slag as an aggregate in concrete production: A review. *Materials*. 2023;16(17):5841. https://doi.org/10.3390/ma16175841

[11] Adeniji A, Kupolati W, Burger EA, Olatunji T, Snyman J. Performance evaluation of slag modified concrete using machine learning techniques. *Kufa Journal of Engineering*. 2026;17(3):12–29. https://doi.org/10.30572/2018/kje/170302

[12] Adeniji AA, Snyman J, Burger EA. Assessment and optimisation of mechanical performance of ironstone and gravel modified concrete for sustainable construction. *Matériaux & Techniques*. 2026;114(5):502. https://doi.org/10.1051/mattech/2026022

[13] Rattanachu P, Tangchirapat W, Jaturapitakkul C. Water permeability and sulfate resistance of eco-friendly high-strength concrete composed of ground bagasse ash and recycled concrete aggregate. *Journal of Materials in Civil Engineering*. 2019;31(6). https://doi.org/10.1061/(ASCE)MT.1943-5533.0002740

[14] Ma W, Wang Y, Huang L, Yan L, Kasal B. Natural and recycled aggregate concrete containing rice husk ash as replacement of cement: Mechanical properties, microstructure, strength model and statistical analysis. *Journal of Building Engineering*. 2023;66:105917. https://doi.org/10.1016/j.jobe.2023.105917

[15] Xu Q, Ji T, Gao SJ, Yang Z, Wu N. Characteristics and applications of sugar cane bagasse ash waste in cementitious materials. *Materials*. 2019;12(1):39. https://doi.org/10.3390/ma12010039

[16] Amran M, et al. Rice husk ash-based concrete composites: A critical review of their properties and applications. *Crystals*. 2021;11(2):168. https://doi.org/10.3390/cryst11020168

[17] Endale SA, Taffese WZ, Vo DH, Yehualaw MD. Rice husk ash in concrete. *Sustainability*. 2023;15(1):137. https://doi.org/10.3390/su15010137

[18] Standard specification for coal ash and raw or calcined natural pozzolan for use in concrete (ASTM C618-25), ASTM International, West Conshohocken, PA, 2025. [Online]. Available: https://store.astm.org/c0618-25.html

[19] Abiodun YO, Jimoh AA. Microstructural characterisation, physical and chemical properties of rice husk ash as viable pozzolan in building material: A case study of some Nigerian grown rice varieties. *Nigerian Journal of Technology*. 2018;37(1):71–77. https://doi.org/10.4314/njt.v37i1.10

[20] Amran M, Murali G, Fediuk R, Vatin N, Vasilev Y, Abdelgader H. Palm oil fuel ash-based eco-efficient concrete: A critical review of the short-term properties. *Materials*. 2021;14(2):332. https://doi.org/10.3390/ma14020332

[21] Hamada HM, Al-attar AA, Yahaya FM, Muthusamy K, Tayeh BA, Humada AM. Effect of high-volume ultrafine palm oil fuel ash on the engineering and transport properties of concrete. *Case Studies in Construction Materials*. 2020;12:e00318. https://doi.org/10.1016/j.cscm.2019.e00318

[22] Alsubari B, Shafigh P, Ibrahim Z, Jumaat MZ. Heat-treated palm oil fuel ash as an effective supplementary cementitious material originating from agriculture waste. *Construction and Building Materials*. 2018;167:44–54. https://doi.org/10.1016/j.conbuildmat.2018.01.134

[23] Amran M, et al. Palm oil fuel ash-based eco-friendly concrete composite: A critical review of the long-term properties. *Materials*. 2021;14(22):7074. https://doi.org/10.3390/ma14227074

[24] Prabhath N, et al. A review on the optimization of the mechanical properties of sugarcane-bagasse-ash-integrated concretes. *Journal of Composites Science*. 2022;6(10):283. https://doi.org/10.3390/jcs6100283

[25] Olopade S, Ngene E. Performance evaluation of untreated sugarcane bagasse ash as partial replacement of cement on setting time and compressive strength of M15 concrete. *Journal of Applied Research and Technology*. 2024;22(5):654–661. https://doi.org/10.22201/icat.24486736e.2024.22.5.2236

[26] Seyoum R, Tesfamariam BB, Andoshe DM, Algahtani A, Ahmed GMS, Tirth V. Investigation on control burned of bagasse ash on the properties of bagasse ash-blended mortars. *Materials*. 2021;14(17):4991. https://doi.org/10.3390/ma14174991

[27] Otitolaiye VO, et al. Thermal and kinetic analyses of maize cob combustion under non-isothermal and multiple heating rate thermogravimetric conditions. *Petroleum and Coal*. 2021;63(3):694–703. https://www.vurup.sk/na_stiahnutie/thermal-and-kinetic-analyses-of-maize-cob-combustion-under-non-isothermal-and-multiple-heating-rate-thermogravimetric-conditions/

[28] Adeniji AA, Ayegbusi OA. Chemical classification of corn sheath ash, cassava pulp ash, and granulated blast furnace slag as supplementary cementitious materials using X-ray fluorescence analysis. *International Journal of Latest Technology in Engineering, Management & Applied Science*. 2025;14(12):1485–1494. https://www.ijltemas.in/submission/online/article/download/3855/5113/13922

[29] Šupić S, et al. Environmentally friendly masonry mortar blended with fly ash, corn cob ash or ceramic waste powder. *Materials*. 2023;16(20):6725. https://doi.org/10.3390/ma16206725

[30] Fadele OA, Otieno MB. Properties of corn cob ash and effect on hydration kinetics in PC-blended cementitious systems. *Discover Civil Engineering*. 2026;3:67. https://doi.org/10.1007/s44290-026-00462-6

[31] Ranatunga KS, del Rey Castillo E, Toma CL. Evaluation of the optimal concrete mix design with coconut shell ash as a partial cement replacement. *Construction and Building Materials*. 2023;401:132978. https://doi.org/10.1016/j.conbuildmat.2023.132978

[32] Adeniji A, et al. Assessment of chloride ion penetration of coconut shell and rice husk ash modified concrete. *Kufa Journal of Engineering*. 2026;17(2):401–416. https://doi.org/10.30572/2018/KJE/170224

[33] Joshua O, et al. Data on the pozzolanic activity in coconut shell ash (CSA) for use in sustainable construction. *Data in Brief*. 2018;18:1142–1145. https://doi.org/10.1016/j.dib.2018.03.125

[34] Bheel N, Mahro SK, Adesina A. Influence of coconut shell ash on workability, mechanical properties, and embodied carbon of concrete. *Environmental Science and Pollution Research*. 2021;28(5):5682–5692. https://doi.org/10.1007/s11356-020-10882-1

[35] Bheel N, Mangi SA, Meghwar SL. Coconut shell ash as cementitious material in concrete: A review. *Jurnal Kejuruteraan*. 2021;33(1):27–38. https://doi.org/10.17576/jkukm-2020-33(1)-03

[36] Otekunrin OA. Cassava (Manihot esculenta Crantz): A global scientific footprint – production, trade, and bibliometric insights. *Discover Agriculture*. 2024;2:1–20. https://doi.org/10.1007/s44279-024-00121-3

[37] Abdulwahab MT, Uche OAU. Durability properties of self-compacting concrete (SCC) incorporating cassava peel ash (CPA). *Nigerian Journal of Technology*. 2021;40(4):584–590. https://www.nijotech.com/index.php/nijotech/article/view/2704

[38] Oghenejoboh KM, Orugba HO, Oghenejoboh UM, Agarry SE. Value added cassava waste management and environmental sustainability in Nigeria: A review. *Environmental Challenges*. 2021;4:100127. https://doi.org/10.1016/j.envc.2021.100127

[39] Adagba T. The potential of cassava peel ash (CPA) as a cement replacement material for sustainable concrete production: A review. *Recent Progress in Materials*. 2026;8(3):006. https://doi.org/10.21926/rpm.2603006

[40] Adeniji AA, Ayegbusi OA. Performance assessment of sustainable self-compacting concrete incorporating GBFS, CPA, and CSA as cement replacement materials. *International Journal of Research and Innovation in Applied Science*. 2026;11(13):1–7. https://doi.org/10.51584/IJRIAS.2026.110130001

[41] Ferdous W, et al. Recycling of landfill wastes (tyres, plastics and glass) in construction – A review on global waste generation, performance, application and future opportunities. *Resources, Conservation and Recycling*. 2021;173:105745. https://doi.org/10.1016/j.resconrec.2021.105745

[42] Aboginije A, Aigbavboa C, Thwala W. A holistic assessment of construction and demolition waste management in the Nigerian construction projects. *Sustainability*. 2021;13(11):6241. https://doi.org/10.3390/su13116241

[43] Dias AB, Pacheco JN, Silvestre JD, Martins IM, de Brito J. Environmental and economic life cycle assessment of recycled coarse aggregates: A Portuguese case study. *Materials*. 2021;14(18):5452. https://doi.org/10.3390/ma14185452

[44] Han S, Zhao S, Lu D, Wang D. Performance improvement of recycled concrete aggregates and their potential applications in infrastructure: A review. *Buildings*. 2023;13(6):1411. https://doi.org/10.3390/buildings13061411

[45] Adedokun SI, Anifowose MA. Optimal replacement of granite modified with Ife iron and steel slag on strength properties of concrete. *International Journal of Engineering Research in Africa*. 2022;58:183–190. https://www.scientific.net/JERA.58.183

[46] Standard test method for potential expansion of aggregates from hydration reactions (ASTM D4792/D4792M-13, reapproved 2025), ASTM International, West Conshohocken, PA, 2025. [Online]. Available: https://store.astm.org/d4792_d4792m-13r25.html

[47] Ofoegbu SU. Characterization studies on Agbaja iron ore: A high-phosphorus content ore. *SN Applied Sciences*. 2019;1:204. https://doi.org/10.1007/s42452-019-0218-9

[48] Habert G, et al. Environmental impacts and decarbonization strategies in the cement and concrete industries. *Nature Reviews Earth & Environment*. 2020;1(11):559–573. https://doi.org/10.1038/s43017-020-0093-3

[49] Yetano Roche M. Built for net-zero: Analysis of long-term greenhouse gas emission pathways for the Nigerian cement sector. *Journal of Cleaner Production*. 2023;383:135446. https://doi.org/10.1016/j.jclepro.2022.135446

[50] Etim MA, Babaremu K, Lazarus J, Omole D. Health risk and environmental assessment of cement production in Nigeria. *Atmosphere*. 2021;12(9):1111. https://doi.org/10.3390/atmos12091111

[51] Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification, ISO 14067:2018, International Organization for Standardization, Geneva, 2018. [Online]. Available: https://www.iso.org/standard/71206.html

[52] Imtiaz L, et al. Life cycle impact assessment of recycled aggregate concrete, geopolymer concrete, and recycled aggregate-based geopolymer concrete. *Sustainability*. 2021;13(24):13515. https://doi.org/10.3390/su132413515

[53] Marinković S, Josa I, Braymand S, Tošić N. Sustainability assessment of recycled aggregate concrete structures: A critical view on the current state-of-knowledge and practice. *Structural Concrete*. 2023;24(2):1956–1979. https://doi.org/10.1002/suco.202201245

[54] Izaola B, Akizu-Gardoki O, Oregi X. Setting baselines of the embodied, operational and whole life carbon emissions of the average Spanish residential building. *Sustainable Production and Consumption*. 2023;40:252–264. https://doi.org/10.1016/j.spc.2023.07.001

[55] Alnahhal MF, Alengaram UJ, Jumaat MZ, Abutaha F, Alqedra MA, Nayaka RR. Assessment on engineering properties and CO_2 emissions of recycled aggregate concrete incorporating waste products as supplements to Portland cement. *Journal of Cleaner Production*. 2018;203:822–835. https://doi.org/10.1016/j.jclepro.2018.08.292

[56] Öztürk E, Ince C, Derogar S, Ball R. Factors affecting the CO_2 emissions, cost efficiency and eco-strength efficiency of concrete containing rice husk ash: A database study. *Construction and Building Materials*. 2022;326:126905. https://doi.org/10.1016/j.conbuildmat.2022.126905

[57] Guo R, et al. Global CO_2 uptake by cement from 1930 to 2019. *Earth System Science Data*. 2021;13(4):1791–1805. https://doi.org/10.5194/essd-13-1791-2021

[58] Leemann A, Münch B, Wyrzykowski M. CO_2 absorption of recycled concrete aggregates in natural conditions. *Materials Today Communications*. 2023;36:106569. https://doi.org/10.1016/j.mtcomm.2023.106569

[59] Ikumapayi CM, Adeniji AA, Obisesan AA, Odeyemi O, Ajayi JA. Effects of carbonation on the properties of concrete. *Scientific Review*. 2019;5(12):205–214. https://doi.org/10.32861/sr.512.205.214

[60] Almutlaqah A, Maddalena R, Kulasegaram S. Optimising thermo-mechanical treatments of residual rice husk ash for cement blending. *Case Studies in Construction Materials*. 2025;22:e04103. https://doi.org/10.1016/j.cscm.2024.e04103

[61] Wi K, Lee HS, Lim S, Ismail MA, Hussin MW. Effect of using micropalm oil fuel ash as partial replacement of cement on the properties of cement mortar. *Advances in Materials Science and Engineering*. 2018;2018:5164030. https://doi.org/10.1155/2018/5164030

[62] Akeke GA, Inem PEU, Alaneme GU, Nyah EE. Experimental investigation and modelling of the mechanical properties of palm oil fuel ash concrete using Scheffe's method. *Scientific Reports*. 2023;13:18583. https://doi.org/10.1038/s41598-023-45987-3

[63] Shanmuga Priya S, Padmanaban I. Effect of coconut shell ash as an additive on the properties of green concrete. *Global NEST Journal*. 2024;26(1):1–9. https://doi.org/10.30955/gnj.005413

[64] Obute JO, Akin OO, Amartey YD, Ejeh SP. Effects of the partial replacement of cement with cassava peel ash and rice husk ash on concrete. *Covenant Journal of Engineering Technology*. 2021;5(1):20–28. https://journals.covenantuniversity.edu.ng/index.php/cjet/article/download/2594/1273/4873

[65] Awolusi TF, Aladegboye OJ, Babalola OE, Ayo EK, Azab M, Deifalla AF. Optimizing the flexural behavior of bamboo reinforced concrete beams containing cassava peel ash using response surface methodology. *Civil Engineering Journal*. 2023;9(8):1971–1990. https://doi.org/10.28991/CEJ-2023-09-08-011

[66] Rigon MR, Modolo RCE, Zortea RB, Mancio M, Moraes CAM. CO_2 emission assessment for rice husk ash in concrete on environmental approach. *Revista AIDIS de Ingeniería y Ciencias Ambientales*. 2021;14(1):246–265. https://doi.org/10.22201/iingen.0718378xe.2021.14.1.70340

[67] Ro JW, Cunningham PR, Miller SA, Kendall A, Harvey J. Technical, economic, and environmental feasibility of rice hull ash from electricity generation as a mineral additive to concrete. *Scientific Reports*. 2024;14:9158. https://doi.org/10.1038/s41598-024-59615-1

[68] Suárez Silgado SS, Calderón Valdiviezo L, Betancourt Quiroga C. Life cycle analysis and economic evaluation of cement and concrete mixes with rice husk ash: application to the Colombian context. *Materiales de Construcción*. 2024;74(353):e335. https://doi.org/10.3989/mc.2024.350723

[69] Xi B, et al. Optimization of rice husk ash concrete design towards economic and environmental assessment. *Environmental Impact Assessment Review*. 2023;103:107229. https://doi.org/10.1016/j.eiar.2023.107229

[70] Fernando S, Gunasekara C, Law DW, Nasvi MCM, Setunge S, Dissanayake R. Life cycle assessment and cost analysis of fly ash–rice husk ash blended alkali-activated concrete. *Journal of Environmental Management*. 2021;295:113140. https://doi.org/10.1016/j.jenvman.2021.113140

[71] Hu L, He Z, Zhang S. Sustainable use of rice husk ash in cement-based materials: Environmental evaluation and performance improvement. *Journal of Cleaner Production*. 2020;264:121744. https://doi.org/10.1016/j.jclepro.2020.121744

[72] Passuello A, et al. Evaluation of the potential improvement in the environmental footprint of geopolymers using waste-derived activators. *Journal of Cleaner Production*. 2017;166:680–689. https://doi.org/10.1016/j.jclepro.2017.08.007

[73] Menaka K, Bhuvaneshwari M. Sustainable concrete development using RSM-optimised palm oil fuel ash: strength, energy and carbon reduction benefits. *European Journal of Environmental and Civil Engineering*. 2025;30(1):1–41. https://doi.org/10.1080/19648189.2025.2584889

[74] Sanit-in P, et al. An investigation of palm oil fuel ash and limestone powder for use in sustainable high strength concrete construction. *Materiales de Construcción*. 2024;74(355):e351. https://doi.org/10.3989/mc.2024.372324

[75] Umer M, Zada NS, Awoyera PO, Khan MB, Ahmed W, Fadugba OG. Synergistic effects and optimization of palm oil fuel ash and jute fiber in sustainable concrete. *Scientific Reports*. 2026;16:259. https://doi.org/10.1038/s41598-025-27579-5

[76] Ullah MF, Tang HS, Ullah A, Tóth Z, Ahmad M, Alzlfawi A. Mechanical and environmental performance of sugarcane bagasse ash from Khyber Pakhtunkhwa in sustainable concrete. *Scientific Reports*. 2025;15. https://doi.org/10.1038/s41598-025-10383-6

[77] Francioso V, Lopez-Arias M, Moro C, Jung N, Velay-Lizancos M. Impact of curing temperature on the life cycle assessment of sugarcane bagasse ash as a partial replacement of cement in mortars. *Sustainability*. 2023;15(1):142. https://doi.org/10.3390/su15010142

[78] Sakib N, Hasan R, Mutalib AA, Jamil M, Raman SN, Kaish ABMA. Utilization of sugar mill waste ash as pozzolanic material in structural mortar. *Minerals*. 2023;13(3):324. https://doi.org/10.3390/min13030324

[79] Bheel N, et al. Combined effect of jute fiber and corn cob ash on sustainability assessment and mechanical properties of roller compacted concrete using RSM modelling. *Scientific Reports*. 2024;14. https://doi.org/10.1038/s41598-024-81345-7

[80] Rauf AT, Akintoye OO, Chukwuemeka EG, Okolo I. Compressive and flexural strength of cement mortar blended with cassava peel ash and high-range water-reducing admixtures. *Engineering Today*. 2024;3(3):29–35. https://doi.org/10.5937/engtoday2400011R

[81] Hasan NMS, Murshed NHMM, Al Noman MA, Miah MJ, Sobuz MHR, Kabbo MKI. Performance of fiber reinforced low-carbon concrete: role of corn cob ash and corn husk fiber. *Journal of Sustainable Cement-Based Materials*. 2025;15(3):786–806. https://doi.org/10.1080/21650373.2025.2580424

[82] Șerbănoiu AA, Grădinaru CM, Muntean R, Cimpoeșu N, Șerbănoiu BV. Corn cob ash versus sunflower stalk ash, two sustainable raw materials in an analysis of their effects on the concrete properties. *Materials*. 2022;15(3):868. https://doi.org/10.3390/ma15030868

[83] Bheel N, et al. Utilization of corn cob ash as fine aggregate and ground granulated blast furnace slag as cementitious material in concrete. *Buildings*. 2021;11(9):422. https://doi.org/10.3390/buildings11090422

[84] Bagcal OR, Baccay MA. Effect of maize cob ash as supplementary cementitious material on the mechanical properties of concrete. *International Journal of Materials Engineering Innovation*. 2019;10(2):83–97. https://www.inderscience.com/filter.php?aid=99788

[85] Maheswari E, Suresh Babu S, Neelamegam P, Karthick R. Development of environmentally friendly fibre reinforced concrete using agricultural byproduct as a cement substitute to reduce the ecological footprint of cement. *Advances in Civil and Architectural Engineering*. 2025;16(31):1–13. https://doi.org/10.13167/2025.31.1

[86] Bheel N, et al. Synergistic effect of recycling waste coconut shell ash, metakaolin, and calcined clay as supplementary cementitious material on hardened properties and embodied carbon of high strength concrete. *Case Studies in Construction Materials*. 2024;20:e02980. https://doi.org/10.1016/j.cscm.2024.e02980

[87] Bheel N, Aluko OG, Khoso AR. Synergistic and sustainable utilization of coconut shell ash and groundnut shell ash in ternary blended concrete. *Environmental Science and Pollution Research*. 2022;29(18):27399–27410. https://doi.org/10.1007/s11356-021-18455-6

[88] Joseph HS, et al. A comprehensive review on recycling of construction demolition waste in concrete. *Sustainability*. 2023;15(6):4932. https://doi.org/10.3390/su15064932

[89] Ben Fraj A, Idir R. Concrete based on recycled aggregates – Recycling and environmental analysis: A case study of Paris' region. *Construction and Building Materials*. 2017;157:952–964. https://doi.org/10.1016/j.conbuildmat.2017.09.059

[90] Kleijer AL, Lasvaux S, Citherlet S, Viviani M. Product-specific life cycle assessment of ready mix concrete: Comparison between a recycled and an ordinary concrete. *Resources, Conservation and Recycling*. 2017;122:210–218. https://doi.org/10.1016/j.resconrec.2017.02.004

[91] Etxeberria M. Evaluation of eco-efficient concretes produced with fly ash and uncarbonated recycled aggregates. *Materials*. 2021;14(24):7499. https://doi.org/10.3390/ma14247499

[92] Lei B, Yu L, Chen Z, Yang W, Deng C, Tang Z. Carbon emission evaluation of recycled fine aggregate concrete based on life cycle assessment. *Sustainability*. 2022;14(21):14448. https://doi.org/10.3390/su142114448

[93] Plaza P, Sáez del Bosque IF, Frías M, Sánchez de Rojas MI, Medina C. Use of recycled coarse and fine aggregates in structural eco-concretes. Physical and mechanical properties and CO_2 emissions. *Construction and Building Materials*. 2021;285:122926. https://doi.org/10.1016/j.conbuildmat.2021.122926

[94] Sabău M, Bompa DV, Silva LFO. Comparative carbon emission assessments of recycled and natural aggregate concrete: Environmental influence of cement content. *Geoscience Frontiers*. 2021;12(6):101235. https://doi.org/10.1016/j.gsf.2021.101235

[95] Visintin P, Xie T, Bennett B. A large-scale life-cycle assessment of recycled aggregate concrete: The influence of functional unit, emissions allocation and carbon dioxide uptake. *Journal of Cleaner Production*. 2020;248:119243. https://doi.org/10.1016/j.jclepro.2019.119243

[96] Marinković S, Dragaš J, Ignjatović I, Tošić N. Environmental assessment of green concretes for structural use. *Journal of Cleaner Production*. 2017;154:633–649. https://doi.org/10.1016/j.jclepro.2017.04.015

[97] Raj A, Selvam M. *Performance, economic, and environmental assessment of steel slag aggregate in roller compacted concrete pavement*. Transportation Research Record: Journal of the Transportation Research Board, early access. 2026. https://doi.org/10.1177/03611981261425970

[98] Václavík V, Ondová M, Dvorský T, Eštoková A, Fabiánová M, Gola L. Sustainability potential evaluation of concrete with steel slag aggregates by the LCA method. *Sustainability*. 2020;12(23):9873. https://doi.org/10.3390/su12239873

[99] Mekonen TB, Alene TE, Alem YA, Nebiyu WM. Influence of steel slag as a partial replacement of aggregate on performance of reinforced concrete beam. *International Journal of Concrete Structures and Materials*. 2024;18(1):56. https://doi.org/10.1186/s40069-024-00698-5

[100] Miah MJ, Patoary MMH, Paul SC, Babafemi AJ, Panda B. Enhancement of mechanical properties and porosity of concrete using steel slag coarse aggregate. *Materials*. 2020;13(12):2865. https://doi.org/10.3390/ma13122865

[101] Agrela F, Rosales M, López Alonso M, Ordóñez García BJ, Cuenca Moyano GM. Life-cycle assessment and environmental costs of cement-based materials manufactured with mixed recycled aggregate and biomass ashes. *Materials*. 2024;17:4357. https://doi.org/10.3390/ma17174357

[102] Castillo NIS, Aragoncillo AMM, Magadia BT, Migo-Sumagang MV, Laurio MVO. Life cycle assessment of low carbon concrete using recycled concrete aggregate and rice husk ash. *Carbon Footprints*. 2026;5(3):44. https://doi.org/10.20517/cf.2026.71

[103] Marathe S, Sheshadri A, Nikolaiev V. Life cycle assessment of sustainable air-cured alkali-activated concrete for permeable pavements using agro-industrial wastes. *Scientific Reports*. 2025;15:22012. https://doi.org/10.1038/s41598-025-04783-x

[104] Bahar A, Tjaronge MW, Irmawaty R. Mechanical performance and life-cycle environmental impact of sustainable concrete incorporating rice husk ash and recycled coarse aggregate. *Ecological Engineering & Environmental Technology*. 2026;27(7). https://doi.org/10.12912/27197050/224680

[105] Sripan T, et al. Assessment of bonding strength of steel bar in recycled aggregate concrete containing ground palm oil fuel ash. *Innovative Infrastructure Solutions*. 2024;9:59. https://doi.org/10.1007/s41062-023-01360-x

[106] Rattanachu P, Toolkasikorn P, Tangchirapat W, Chindaprasirt P, Jaturapitakkul C. Performance of recycled aggregate concrete with rice husk ash as cement binder. *Cement and Concrete Composites*. 2020;108:103533. https://doi.org/10.1016/j.cemconcomp.2020.103533

[107] Cecconello V, Sartori BRC, Kulakowski MP, Kazmierczak CS, Mancio M. Shrinkage and porosity in concretes produced with recycled concrete aggregate and rice husk ash. *Revista IBRACON de Estruturas e Materiais*. 2019;12(3):694–704. https://doi.org/10.1590/S1983-41952019000300013

[108] Alharthai M, et al. Enhancing concrete strength and durability through incorporation of rice husk ash and high recycled aggregate. *Case Studies in Construction Materials*. 2025;22:e04152. https://doi.org/10.1016/j.cscm.2024.e04152

[109] Berwal P, Ali ABM, Aljumaily MM, Khishe M. Assessing the performance of sugarcane bagasse ash and recycled aggregates in concrete through experimental and statistical approaches. *Hybrid Advances*. 2026;14:100693. https://doi.org/10.1016/j.hybadv.2026.100693

[110] Fernando A, Selvaranjan K, Srikanth G, Gamage JCPH. Development of high strength recycled aggregate concrete: composite effects of fly ash, silica fume and rice husk ash as pozzolans. *Materials and Structures*. 2022;55(7):185. https://doi.org/10.1617/s11527-022-02026-3

[111] Zhang W, Liu H, Liu C. Impact of rice husk ash on the mechanical characteristics and freeze–thaw resistance of recycled aggregate concrete. *Applied Sciences*. 2022;12(23):12238. https://doi.org/10.3390/app122312238

[112] Padhi RS, Patra RK, Mukharjee BB, Dey T. Influence of incorporation of rice husk ash and coarse recycled concrete aggregates on properties of concrete. *Construction and Building Materials*. 2018;173:289–297. https://doi.org/10.1016/j.conbuildmat.2018.03.270

[113] Rattanachu P, Karntong I, Tangchirapat W, Jaturapitakkul C, Chindaprasirt P. Influence of bagasse ash and recycled concrete aggregate on hardened properties of high-strength concrete. *Materiales de Construcción*. 2018;68(330):e158. https://doi.org/10.3989/mc.2018.04717