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Utilization of Agricultural Waste as Aggregates and Pozzolans in Lightweight Concrete – A Review

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Abstract

Agricultural wastes are increasingly being investigated as sustainable substitutes for conventional aggregates and supplementary cementitious materials in lightweight concrete. This review synthesizes studies on rice husk ash, coconut shell, palm kernel shell, cassava peel ash, sawdust ash, groundnut shell ash, corn cob ash, and related agro-wastes, focusing on their effects on density, strength, durability, thermal performance, and microstructure. The reviewed studies show that these materials can reduce concrete density to about 800 to 2100 kg/m³, while compressive strength commonly ranges from below 10 MPa for highly porous insulation mixes to about 30 to 40 MPa for optimized structural or semi-structural lightweight concrete mixes. Optimal cement replacement levels are generally around 5 to 20 percent for ashes such as rice husk ash, cassava peel ash, sawdust ash, and groundnut shell ash, while aggregate replacement levels of 10 to 25 percent are often more suitable for coconut shell and palm kernel shell concretes. Properly processed agro-wastes can also improve water absorption resistance, shrinkage control, thermal insulation, and, in some cases, sulfate and chloride resistance, although excessive replacement usually reduces strength and workability. What distinguishes this review from earlier ones is its combined focus on both aggregates and pozzolans in lightweight concrete, its comparison of performance trends across different agricultural wastes as well as its identification of application-specific optimum ranges rather than a purely descriptive summary. It also highlights the limited number of studies on self-compacting, high-performance and field-scale lightweight concrete as well as the scarcity of standardized mix design procedures, long-term durability data and lifecycle assessment frameworks. Overall, agricultural wastes offer a practical route to lower-cost, lower-carbon lightweight concrete but broader adoption will depend on standardization, durability verification, and performance-based mix design.

Keywords

Agricultural waste; Lightweight concrete; Pozzolans; Mechanical properties; Durability; Microstructural properties

Introduction

Lightweight concrete is a specialized construction material that incorporates lightweight coarse aggregates, and occasionally lightweight fine aggregates, as substitutes for conventional aggregates (Rashid et al., 2023). This results in a material with a significantly reduced density, typically ranging between 90 to 115 lb/ft³ (1440 to 1840 kg/m³), compared to standard concrete's 140 to 150 lb/ft³ (2240 to 2400 kg/m³). For structural applications, it must achieve a compressive strength exceeding 2500 psi (17.0 MPa). The production of structural lightweight concrete often involves expanded shale, clay, or slate aggregates, which are fired in rotary kilns to create a porous structure. Alternative materials like air-cooled blast furnace slag are also employed. Non-structural variants with even lower densities are produced using different aggregates and increased air voids in the cement matrix, such as in cellular concrete (Chiadighikaobi et al., 2022).

Lightweight concrete can be categorized by production method into three primary types. Lightweight aggregate concrete uses porous aggregates with a specific gravity below 2.6. Aerated concrete contains intentionally created voids, achieved through foam aeration or air entrainment techniques (Ali et al., 2021). No-fines concrete eliminates fine aggregates altogether, resulting in a matrix with numerous interstitial voids while typically using standard coarse aggregates (Tunio et al., 2019). Additionally, classification by application includes structural lightweight concrete (meeting ASTM C 330-82a standards), masonry unit concrete (ASTM C 331-81), and insulating concrete (ASTM C 332-83), with structural types requiring specific strength criteria.

The development of artificial lightweight aggregates in the mid-20th century expanded structural applications. Notable aggregates include pumice (used in German industrial roof slabs), foamed slag (a UK innovation for reinforced concrete), and expanded clays/shales (suitable for prestressed concrete). Aerated concrete stands out for its extremely low density and workability similar to wood, often being steam-cured and prefabricated for building components. No-fines concrete, with its unique composition, serves well in various wall and flooring applications.

Concrete is the most widely used construction material globally, renowned for its versatility, strength, and durability. Cement, water, fine aggregates (sand), and coarse aggregates (gravel or crushed stone) are the traditional ingredients of concrete (Burroughs et al., 2017). However, the widespread use and exploitation of natural aggregates have led to serious environmental issues, such as habitat damage, resource depletion, and rising carbon emissions. The building industry has been investigating sustainable substitutes for traditional aggregates in response to these issues. Using agricultural waste resources to make concrete instead of aggregates is one promising strategy. (Kassim & Rohim, 2017).

Large amounts of waste materials, including rice husks, wheat straw, corncobs, and coffee husks, are produced by agricultural activities. These leftovers have historically been thrown away, burned, or allowed to break down, which has increased greenhouse gas emissions and environmental degradation. Recent studies, however, have shown that a large number of these agricultural wastes have chemical and physical characteristics that make them appropriate for use as aggregates in concrete. For example, it has been successfully utilized to substitute some of the sand in concrete mixtures with rice husk ash, which is produced by burning rice husks, improving specific performance aspects of the final product (Unnikrishnan, 2022; Kishore & Gupta, 2019).

There are several financial and environmental advantages to using farm waste in concrete. In terms of the environment, it lessens dependency on natural aggregates, protecting natural resources and reducing the ecological disturbance brought on by quarrying operations. Reusing agricultural waste also lessens the carbon footprint related to the manufacture of concrete and mitigates waste disposal problems. In areas with a lot of agricultural activity, using locally accessible agricultural byproducts can economically reduce material prices and encourage sustainable development (Kumar et al., 2022; Iswarya & Beulah, 2021).

The effectiveness of concrete that contains different types of agricultural waste has been examined in a number of studies. For instance, studies have demonstrated that adding pyrolyzed coffee husks to concrete in place of some sand can boost its strength and durability by 30% (Powell, 2025). In a similar vein, research has investigated the use of wood ash, corncob granules, and wheat straw, with results suggesting possible improvements in concrete's workability, compressive strength, and resistance to chemical attacks. (Ramos et al., 2013a).

The quantity of agricultural wastes in Nigeria, such as groundnut husk ash, palm kernel shell ash, and cassava peel ash, offers a significant chance for the manufacturing of sustainable concrete. Adding these ingredients to concrete not only solves waste management problems but also promotes the development of innovative building materials that are compatible with local resources (Fapohunda et al., 2021).

Although there is a lot of promise in using agricultural waste to substitute aggregate in concrete, there are still obstacles to overcome. The uniformity and functionality of the final concrete can be impacted by variations in the characteristics of agricultural wastes, which are determined by variables such as the source, processing techniques, and geographic location (Shafigh et al., 2014). Therefore, to guarantee dependability and structural integrity, consistent testing protocols and quality control techniques are crucial.

Agricultural Wastes

In recent years, several studies have shown how agricultural waste products can improve the qualities of concrete in a number of important ways. The raw, unprocessed states of the primary lignocellulosic and macro-structural biomass elements frequently evaluated in lightweight concrete applications are illustrated in the figure below.

Figure 1: Morphological overview of selected raw agricultural waste materials evaluated for lightweight concrete applications: (a) rice husk (b) wood sawdust (c) peanut (groundnut) shells (d) rice straw and (e) coconut shells. SCM components (a, b) require thermal calcination to optimize amorphous silica content prior to matrix incorporation, whereas macro-elements (c, e) undergo mechanical crushing to serve as alternative aggregates. (Shafigh et al., 2014).

The agricultural wastes displayed in Figure 1 vary widely in their physical structure, requiring distinct processing paths to function effectively within a cementitious matrix. Table 1 maps these physical transformations from raw biomass to finished concrete components.

Table 1: Structural roles, processing mechanisms and performance impacts of agro-biomass components in lightweight concrete

Material Component	Raw Physical State	Primary Processing Required	Resulting Role in Concrete	Primary Effect on Lightweight Concrete
Rice Husk	Loose, cellular flake	Controlled incineration (500-700^{0}C) and fine milling	Supplementary Cementitious Material (Pozzolan)	Densifies microstructure via secondary C-S-H gel, reduces permeability.
Sawdust	Fine, high-moisture woody shavings	Dehydration, calcination to ash, and grading	Supplementary Cementitious Material / Micro-filler	Decreases matrix density, controls micro-fissure propagation.
Peanut Shell	Brittle, highly porous pod	Washing, oven-drying, and mechanical crushing (5–15 mm)	Partial Coarse Aggregate Replacement	Drastically lowers unit weight, suitable for thermal insulation mixes.
Rice Straw	Elongated, fibrous stalks	Saturation pre-treatment, mechanical chopping, or alkali washing	Short Fiber Reinforcement / Aggregate	Enhances flexural toughness and mitigates drying shrinkage cracks.
Coconut Shell	Dense, hard woody endocarp (~4 mm thick)	Crushing, sieving to gravel sizes, and cement/lime slurry coating	Lightweight Coarse Aggregate	Produces structural-grade LWC (20–35 MPa) with 20–25% density reduction.

The processing methods for these wastes include:

1. Cleaning/Drying: Remove fines and organics (wash away dirt/leaves), then sun- or oven-dry biomass to low moisture. High-temperature heating is often applied to sterilize/dry (e.g., heating shells).
2. Crushing/Grinding: Mechanically crush or mill the dried waste to target sizes (e.g., coarse 5–20 mm fractions or powdered fines). For example, coconut and palm shells are broken in gravel-sized pieces; cobs are chipped into granules.
3. Sieving/Grading: Sieve the crushed material to obtain desired size fractions (coarse vs fine aggregate) and remove oversized particles. Typical gradation mimics natural aggregate (e.g., retaining most between 5–15 mm).
4. Surface Treatment: To improve bonding and reduce porosity, some studies coat agro-aggregates with cement slurry, lime, or silicate solutions. Cement coating on corn-cob granules notably improved adhesion and durability.
5. Optimized Substitution Rates: Studies find low replacement (5–15%) is often optimal. e.g., 5% coconut shell gave slight strength gain, up to ~10% palm-shell yields ≥structural-grade LWC.
6. Enhanced Insulation: All recent works note large gains in thermal performance. Corn and bagasse concrete consistently outperform mineral LWAs in insulation. Example: corn-cob board's conductivity expanded polystyrene; SCB mixes surpass typical concrete and brick.

7. Treatment Effects: Modern methods (coatings, additives) can mitigate weaknesses. Cement or Na–silicate coatings on cob aggregates improved bond and strength. Fly-ash replacement with cob mixes partially recovers strength.

Supplementary Cementitious Materials (SCMS)

Rice Husk Ash (RHA): The ash produced from the controlled burning of rice husks is rich in silica, which has pozzolanic qualities. More calcium silicate hydrate (C-S-H) gel may form as a result of this silica's reaction with the calcium hydroxide created during cement hydration. This procedure improves concrete's resilience to the elements and longevity.
(Saand et al., 2019).

Wheat Straw Ash (WSA)

Likewise, burning wheat straw can result in ash with a high pozzolanic activity. According to studies, WSA has a high silica content, which allows it to react with free lime in the cement matrix to improve the endurance and mechanical qualities of concrete. (Amin et al., 2019).

Corn Cob Ash (CCA)

Corn cob ash is made by burning the core of maize ears, or corn cobs. Because CCA contains alumina and silica, it can be used as a pozzolanic material. According to research, CCA can partially replace cement in concrete, with specific replacement levels showing the best results.(Olonade et al., 2017).

Saw Dust Ash (SDA)

SDA is created when sawdust, a byproduct of wood production, burns. SDA's pozzolanic qualities and potential as a partial cement substitute in concrete have been studied. According to studies, when utilized properly, SDA can help concrete build its strength. (Ogork & Ayuba, 2016).

Cassava Peel Ash (CPA)

This product is made by burning cassava peels, which are a waste product from manufacturing cassava. According to research, CPA may improve the qualities of concrete at specific replacement levels when used as an additional cementitious material (Abdulwahab et al., 2024). The ash must be calcined for 90 minutes at 700°C to make it pozzolanic, making sure that the silica, alumina, and ferric oxide content is greater than 70% (Ikponmwosa & Olonade, 2017). About 6.8 million tons of cassava peels are produced each year, with estimates that this number would rise to 12 million tons by 2020. Peels account for 20–35% of the weight of the tuber, particularly when they are manually peeled (Adesanya et al., 2008).

Palm Kernel Shell Ash (PKSA)

Made by burning the shells of palm kernels, which are a byproduct of making palm oil. The pozzolanic activity of PKSA and its impact on concrete when used as a partial cement substitute have been investigated. (Hassan et al., 2023).

Peanut husks

Also known as groundnut husk ash (GHA), can be made by burning the peanut shells. Studies on GHA's potential as a pozzolanic material in concrete have revealed that the replacement amount has a different impact on the material's characteristics. (Ikumapayi et al., 2021).

Table 2: Comparative performance of agricultural waste supplementary cementitious materials

Material	Waste source	Main pozzolanic feature	Reported optimum replacement level	Compressive strength trend	Durability trend	Key remarks
Rice Husk Ash (RHA)	Burned rice husks	High silica content, strong pozzolanic reactivity	5–15%	Often improves or maintains strength at low replacement; decline beyond optimum	Reduced permeability, improved resistance to aggressive media	Strongly influenced by calcination temperature and fineness
Wheat Straw Ash (WSA)	Burned wheat straw	High silica content	5–10%	Improved strength at low dosage; higher replacement may reduce strength	Lower water absorption and improved durability in some mixes	Quality depends on burning control
Corn Cob Ash (CCA)	Burned corn cobs	Silica and alumina content	5–15%	Moderate improvement at optimum dosage	Some resistance to chemical attack and permeability reduction	Useful as partial cement replacement
Saw Dust Ash (SDA)	Burned sawdust	Pozzolanic ash from wood waste	5–20%	Can improve strength at low to moderate levels	Improved resistance to deterioration in selected mixes	Fineness and carbon content affect performance
Cassava Peel Ash (CPA)	Burned cassava peels	Silica, alumina, ferric oxide	1–10%	Comparable or improved strength at low replacement	Reduced water absorption in some studies	Requires proper calcination for pozzolanic activity
Palm Kernel Shell Ash (PKSA)	Burned palm kernel shells	Reactive ash from palm waste	5–15%	Variable, but optimum at low replacement	Can improve durability when well processed	Performance depends on combustion quality
Groundnut Husk Ash (GHA)	Burned groundnut husks	Siliceous ash	5–20%	Usually decreases at high replacement but acceptable at low dosage	May improve resistance to chemical attack	Optimum dosage varies across studies
Coffee Husk Ash (CHA)	Pyrolyzed coffee husks	Fine reactive ash	5–10%	Can improve strength at lower dosage	Potential reduction in permeability	Limited number of studies available
Sugarcane Bagasse Ash (SCBA)	Burned sugarcane residue	Silica-rich ash	5–15%	Often improves strength at moderate dosage	Better durability and matrix densification	Promising sustainable binder material

Coffee Husk Ash

Pyrolyzed coffee husks can be used in place of some sand in concrete, according to research, giving the material more strength and longevity. Coffee grinds are heated in order to create a substance that improves the structural qualities of concrete.
(Biswas et al., 2024).

Wheat Straw Ash (WSA)

This a byproduct of agriculture that can be made by burning wheat straw. The presence of silica in WSA contributes to its pozzolanic qualities. Research has indicated that adding WSA to cement mortar can improve compressive strength, with particular replacement amounts showing the best results. (Sun et al., 2023).

Sugarcane Bagasse Ash (SCBA)

Sugarcane bagasse ash is made by burning the fibrous residue left behind after sugarcane is processed. SCBA has shown promise in improving concrete's qualities and promoting sustainability in construction when used as a partial substitute for cement.

Cement-Based Reinforcement Materials

Sisal Fibers: Thin cement-based laminates have successfully used long, aligned sisal fibers as reinforcement. Their addition improves the composites' toughness and tensile strength, which qualifies them for a range of structural uses (Naraganti, 2021).

Bamboo Fibers: Within the cement matrix, bamboo fibers are renowned for their exceptional endurance and tensile strength. Their application as reinforcing materials aids in the creation of robust and sustainable building materials. (Mohanty et al., 2005).

Partial Replacement of Aggregates

The partial replacement of conventional aggregates with agricultural waste has been widely investigated as a strategy for producing lightweight concrete (LWC) while addressing solid waste disposal challenges. Since aggregates constitute approximately 60–80% of the volume of concrete, the successful use of agricultural solid wastes as whole or partial replacements of conventional aggregates contributes to energy saving, conservation of natural resources, and a reduction in construction material costs. Among the most extensively studied materials, coconut shell (CS) and oil palm shell (OPS) have demonstrated the strongest structural potential. OPS can reduce concrete density by 20–25% compared to normal weight concrete, with compressive strengths in the range of 20–35 MPa suitable for structural applications, though its 24-hour water absorption of 21–33% is significantly higher than conventional aggregates. Similarly, coconut shell brick aggregate concrete possesses satisfactory mechanical properties, with density and modulus of elasticity decreasing as coconut shell content increases, and strong correlations observed between most mechanical properties. Palm kernel shell (PKS) concrete has yielded densities between 1447 and 1714 kg/m³ at varying replacement levels, comfortably within LWC classifications (Danso & Appiah-Agyei, 2020). For fine aggregate substitution, sugarcane bagasse ash (SCBA), produced from combustion of fibrous bagasse at 600–800°C, contains significant amorphous silica and has been identified as a viable substitute material for both cement and natural fine aggregate in concrete. Corn cob and raw rice husk have been characterised for non-structural and thermally insulating applications, with corn cob concrete achieving compressive strengths of 10–12.4 MPa alongside favourable thermal insulation properties. Across all materials, workability consistently declines with increasing agro-waste content due to elevated water absorption, and durability remains a common limitation. However, pre-soaking, surface treatment and integration with supplementary cementitious materials have been shown to effectively mitigate these drawbacks (Alengaram et al., 2015; Aziz et al., 2022).

Mechanical Properties of Concrete Agricultural Waste as Aggregates and Pozzolans
Properties of concrete with agricultural waste as aggregates
Coconut shells

The hard, woody endocarp that surrounds the seed of the coconut fruit (Cocos nucifera) is known as a coconut shell. The shell acts as a protective coat for the seed and is located between the fibrous husk (mesocarp) and the edible white flesh (endosperm). It usually has three germination holes, often known as the "eyes" of the coconut, and is around 4 millimeters thick (Ramachandrudu, 2012). In order to measure the effects of substituting coconut shell for traditional coarse aggregate, Kanojia & Jain (2017) focused on compressive strength and density. According to the results, concrete's compressive strength dropped by 62.6% in 7 days, 21.5% in 28 days, and 7.47% in weight when 40% coconut shell was substituted. For a concrete mix design with a typical strength of 20 $N/mm^{2,}$ only 3.6% more cement was needed for 10% replacement and none at all for 5% replacement.

Kumar & Kumar (2014) examined the viability of partially substituting coconut shells for coarse particles in concrete. Both compressive and flexural strengths were observed to decrease as the percentage of coconut shell substitution increased. In particular, the corresponding flexural strengths were 4.44, 4.15, 3.85, and 3.70 N/mm^2, and the 28-day compressive strengths for 2.5%, 5%, 7.5%, and 10% replacements were 36.44, 36.00, 35.11, and 34.67 N/mm^2, respectively. According to these findings, coconut shell concrete may be used in non-load-bearing situations where it is preferable to use lightweight concrete.

Aziz et al. (2022) explored the use of coconut shell (CS) as a partial replacement for natural coarse aggregates (NWA) in concrete, aiming to develop a cost-effective, sustainable, and durable lightweight structural material. The findings indicated that incorporating CS improved the workability of the concrete mixes. The 28-day compressive strengths ranged from 30 to 39 MPa, with oven-dried densities between 1856 and 2103 kg/m^3. Notably, the mix containing 50% CS and 25% BA exhibited an 18% reduction in drying shrinkage compared to coconut shell concrete (CSC) and was approximately 14% higher than conventional normal weight concrete (NWC). In a study by Anwar et al. (2016) where M20 grade concrete was produced by replacing NWA with CS at 0%, 5%, 10%, 20%, 30%, 40%, and 50% by weight, sixty-three cubes were cast to evaluate compressive strength at 7, 14, and 28 days The findings showed that the concrete's compressive strength dropped as the proportion of CS replacement rose. In particular, for every 20% increase in CS replacement, the compressive strength at 28 days decreased by about 24%. Concrete mixtures with up to 10% CS substitution, however, showed compressive strengths appropriate for non-structural uses.

Oyster shells

One of the most important marine biological resources for mankind, oysters are the most extensively farmed shellfish in the world. An estimated 200,000 tons of oyster shell debris are produced globally each year. These shells are a useful raw material since they contain more than 90% calcium carbonate ($CaCO_3$). It may be possible to use oyster shells as coarse aggregates when making concrete. However, because of the increased air content, utilizing them in large quantities might negatively impact the concrete's long-term strength and elastic modulus (Wang et al., 2021). For example, Martínez-García et al. (2017) said mussel shell replacement should be limited to 25% of fine or coarse aggregates, or 12.5% of both fine and coarse aggregates. With these percentages, the NSC and the SC will display correct behavior.

Eo & Yi (2015) investigated the utilization of waste oyster shells (OS) as concrete aggregate to mitigate environmental pollution and promote resource recycling. The research analyzed the physicochemical characteristics of OS and assessed the material and mechanical properties of both fresh and hardened concrete incorporating OS. The findings revealed no occurrence of new chemical reactions or formation of abnormal substances due to the inclusion of OS. Although an increased OS replacement rate posed challenges related to strength and workability, these issues were addressed through the use of admixtures and stone powder. The optimal particle size range for OS as coarse aggregate was determined to be 10–13 mm. Furthermore, hollow concrete blocks exhibited satisfactory quality even with a 50% substitution of fine aggregate with OS, indicating the feasibility of utilizing OS in concrete production.

Palm kernel

Palm kernel shells (PKS) are the hard outer shells of palm kernel fruits, a by-product of palm oil production, and are used as a renewable energy source and in various other applications. Oluwasola et al. (2020) investigated the impact of various curing methods on the compressive strength of concrete incorporating Palm Kernel Shell (PKS) as aggregate. Materials were sourced from Ede, Osun State, Nigeria. The slump test indicated that the 1:1½:3 mix ratio provided a better slump. Compressive strengths of the cubes ranged from 2.244 to 3.852 N/mm^2. The findings highlight that curing methods significantly influence the compressive strength of PKS aggregate concrete.

Monika et al. (2021) investigated the effect of replacing coarse aggregate with palm kernel shell (PKS) waste on concrete properties. PKS was used to replace 40%, 50%, and 60% of the coarse aggregate volume. The results indicated that the highest compressive and tensile strengths under sealed oven, moist, and air curing methods occurred with a 60% PKS replacement. However, water curing yielded the highest compressive strength at a 40% PKS replacement and the highest tensile strength without any PKS replacement.

Padavala et al. (2024) examined the strength characteristics of lightweight concrete by replacing cement with fly ash (FA) and coarse aggregate (CA) with palm kernel shells (PKS). The concrete grade considered was M30. In the first phase, cement was partially replaced with FA in proportions of 5%, 10%, 15%, 20%, 25%, and 30%. In the second phase, with the optimal FA content fixed, CA was partially replaced with PKS in proportions of 5%, 10%, and 15%. Additionally, the effect of hybrid fibers was studied. The results indicated that replacing 25% of cement with FA and 10% of CA with PKS, along with adding 1.2% hybrid fibers, yielded the optimum strength.

Yiwo et al. (2023) investigated the use of untreated dura-Palm Kernel Shells (PKS) as coarse aggregates in previous lightweight concrete, aiming to assess their suitability for flood mitigation applications. The findings indicate that a 100% replacement with dura-PKS led to increased porosity and permeability but significantly reduced mechanical strengths. In contrast, a 25% replacement of limestone with dura-PKS achieved optimal water permeability, flexural strength, and compressive strength.

Ezeanokwasa (2019) evaluated the effects of recycled tyre steel fibers and palm kernel shells on the mechanical properties of structural lightweight concrete. Recycled tyre steel fibers were incorporated at 0.25%, 0.50%, and 0.75% by volume, with aspect ratios of 80 and 100, to determine optimal fiber content and aspect ratio. The results indicated that recycled tyre steel fibers can enhance the compressive and splitting tensile strengths of normal-weight concrete. When combined with palm kernel shells replacing 25% of coarse aggregates, the concrete achieved maximum compressive and splitting tensile strengths at a fiber content of 0.50% and an aspect ratio of 80. Flexural strength values were higher in normal-weight concrete compared to lightweight concrete with optimal fiber and shell content. Beams with 25% and 50% palm kernel shell content, optimal fiber content, and aspect ratios met the criteria for structural lightweight concrete.

Properties of concrete with agricultural waste as pozzolan

Biswas et al. (2024) investigated the use of waste coffee husk (WCH) as a partial replacement for sand in alkali-activated bricks composed of ground granulated blast furnace slag (GGBFS), fly ash (FA), and sodium silicate solution (SS). WCH was substituted at volumes of 0%, 5%, 10%, 15%, 20%, and 30%. The findings indicate that incorporating WCH enhances the compressive strength, achieving a peak of 15.7 MPa, and reduces the density to a minimum of 1509 kg/m³ at a 30% replacement rate.

Gedefaw et al. (2022) evaluated the effects of replacing Ordinary Portland Cement (OPC) with Coffee Husk Ash (CHA) on the properties of C-25 concrete. Concrete mixtures were prepared with CHA substitutions of 0%, 5%, 10%, and 20% by weight, maintaining a constant water-to-cement ratio of 0.5. The workability, setting times, compressive strength, water absorption, sulfate resistance, and microstructural characteristics of the concrete were assessed. Results indicated that increasing CHA content decreased workability, with slump flow values ranging from 15 to 35 mm, and extended setting times. Compressive strength decreased with higher CHA levels, with 28-day strengths ranging from 35.1 MPa at 5% CHA to 22.7 MPa at 20% CHA. The study concluded that up to 10% CHA replacement maintains concrete strength, suggesting CHA's potential as a sustainable partial cement substitute.

Njagi et al. (2022) investigated the use of Rice Husk Ash (RHA) as a partial replacement for Ordinary Portland Cement (OPC) in concrete production, focusing on its effects on concrete's chemical composition, workability, density, compressive strength, and tensile strength. RHA, obtained from Mwea, Kirinyaga County, Kenya, was calcined to produce white ash and analyzed for pozzolanic properties. Concrete mixes replaced OPC with RHA at 0%, 5%, 10%, 15%, 20%, and 30% by weight, maintaining a constant water-cement ratio of 0.6. The results indicated that incorporating up to 10% RHA improved workability and tensile strength, with a slight decrease in compressive strength compared to pure OPC concrete. Microstructural analyses confirmed effective geopolymerization, suggesting that up to 10% RHA can be used as a sustainable alternative without significantly compromising concrete performance.

Abdulwahab et al. (2024) investigated the use of cassava peel ash (CPA) as a partial cement substitute in concrete. Various percentages of CPA were incorporated into the M20 concrete mix, following a mix ratio of 1:1.5:3. The batched concrete samples were cast in molds and cured for different durations. Slab tests were performed on the fresh concrete mixtures to assess split tensile and compressive strengths. The results indicated that increasing the CPA replacement percentage enhanced the workability of the mixture. At 1% CPA replacement, the optimal compressive strength and split tensile strength values were 32.9 N/mm² and 3.9 N/mm², respectively, which were comparable to the control mix. This research highlighted the potential suitability of CPA as a cement substitute in concrete.

Omolola et al. (2023) examined the strength properties of geopolymer concrete incorporating CCA and metakaolin. Concrete mixes with 0%, 10%, 20%, 30%, and 40% CCA were evaluated. The study found that a 10% CCA replacement resulted in a compressive strength of 28.6 N/mm² at 28 days, comparable to the control mix, suggesting that CCA can be effectively used in geopolymer concrete. Adole et al. (2011) examined the impact of chemicals on the properties of concrete with cement partially replaced with Groundnut Husk Ash (GHA). The compressive strength of Ordinary Portland Cement (OPC) and OPC/GHA concrete was measured after curing in three chemical solutions ($MgSO_4$, NaCl, H_2SO_4) for 14, 21, and 28 days. The results showed that OPC/GHA concrete performed best in most solutions, with values of 21.05N/mm^2 in $MgSO_4$ and 22.55N/mm^2 in NaCl.

Raheem et al. (2013) evaluated concrete where cement was partially replaced with groundnut shell ash (GSA) at various percentages. The study focused on compressive strength development over time. Findings indicated that while the strength decreased with higher GSA content, a 10% replacement level achieved a compressive strength of 20.68 N/mm² at 28 days, suggesting its viability for certain structural applications.

Tyagher et al. (2013) investigated the strength of concrete using groundnut shell ash (GSA) mixed with 45% slaked lime. The ash was sieved and used to partially replace ordinary Portland cement (OPC) in various proportions. The design mix used was 1:2:4, with water-cement ratios of 0.45, 0.55, and 0.65 by weight. Nine cubes of side 150mm were cast for each proportion and water-cement ratio, and three cubes were tested for density and strength at different ages. The study concluded that for a 1:2:4 mix, up to 20% GSA/lime proportion provided a 28-day minimum strength of 20N/mm^2 at a water-cement ratio of 0.65, making it recommended for use as structural concrete.

Research by James & Daniel (2018) indicated that substituting 5% of cement with SDA can lead to a compressive strength of approximately 34.11 N/mm² after 28 days of curing. This strength surpasses the typical design strength of 30 N/mm² for standard concrete, suggesting that such a replacement level is feasible for structural applications. A study by Adebola and Aluko (2022) showed the viability of successfully incorporating SDA as a partial replacement of OPC and laterite soil to replace the conventional fine aggregate. An acceptable slump and compressive strength can be achieved using 10% SDA and 45% laterite as partial replacement of OPC and river sand, respectively.

Table 3: Summary of past findings

Author(s) (Year)	Waste Type (Aggregate)	Study Description	Key Findings
Bari et al. (2021)	Coconut shells (coarse, partial replacement of brick agg.)	Produced concrete mixes replacing 0–15% brick aggregate by crushed coconut shell; measured workability, densities, 28d strength and microstructure (SEM).	- Air content ↑ and density/28d compressive strength ↓ as shell content ↑. Fissures formed at the shell–cement interface grew with more shell; fissure width reduced over time, improving strength.
de Souza et al. (2023)	Sugarcane bagasse (fibers as aggregate in blocks)	Fabricated cementitious composites using 100% raw sugarcane bagasse as the sole aggregate, with aerial lime or soil binder.	- SCB+soil: 2.6 MPa compressive, 2.1 MPa flexural. SCB+lime: 1.76/1.7 MPa. Better thermal insulation & water resistance; high water absorption → waterproofing needed.
Danso & Appiah-Agyei (2021)	Palm kernel shells (coarse; 25% of coarse agg.)	Investigated concrete with 25% of coarse aggregate replaced by palm kernel shells (sizes 6, 8, 10, 12 mm).	- All dry densities <2000 kg/m³. 12 mm PKS mix had best 28d compressive (10.2 MPa) and flexural (2.85 MPa) strengths. A high Ca/Si ratio showed good hydration. Recommended 12 mm PKS.
Polat (2021)	Corn cobs (ground, coarse aggregate)	Used ground corn cob as 100% aggregate in lightweight concrete.	- Unit weight: ~800–1520 kg/m³; thermal conductivity: ~0.19–0.35 kcal/m·h·°C; 28d compressive strength: 0.14–5.5 MPa. Lightweight, but low strength.
Chabi et al. (2024)	Rice husks (untreated, fine	Developed mixes fully replacing sand with rice husks.	- 28d compressive strength: 0.56–5.41 MPa. Thermal conductivity:

	aggregate replacement)	Tested compressive strength and thermal conductivity.	~0.070–0.129 W/m·K. High porosity suited for insulation or low-rise walls.
Thongchua et al. (2023)	Rice straw (waste) as aggregate in blocks	Produced cold-pressed blocks with saturated/as-received straw as partial aggregate.	- Saturated straw gave better strength. Optimum (2% straw) mix: 6.43 MPa at 28d, suitable for non-structural use.
Palh et al. (2021)	Date-palm seeds (dried pits, coarse aggregate)	Replaced 0–4% coarse agg. in 1:2:4 mix. Tested slump, density, and 28-day strength.	- Seeds' ↓ workability, ↓ density (SG ~0.84). 2–3% replacement acceptable; higher % weakened concrete.
Choosakul et al. (2021)	Banana peels (mashed, fine; sand replacement)	Mixed mortar with 0–3% banana peel. Measured strength, density, and water absorption.	- Density ↓, absorption ↑ (~5% per 1% peel), strength ↓ (~10% per 1%). 1% peel: 6.75 MPa. Met Thai lightweight standard.
Astutiningsih et al. (2024)	Oil-palm empty fruit bunch (fibers; fine aggregate)	Replaced 1–3% of fine quartz sand with untreated OPEFB in mortar.	- 1–3% OPEFB ↓ density, compressive strength, ↑ flexural strength (1%), ↓ drying shrinkage. Good insulation/crack resistance, limited strength.
Gradinaru et al. (2021)	Sunflower stalks and corn cobs	Developed 10 microconcretes replacing 20–80% natural agg. Measured strength, durability, and thermal conductivity.	- >50% replacement = lightweight. Sunflower mixes > corn cob in strength/durability. All had low thermal conductivity.
Tong & Namasivayam (2023)	Peanut (groundnut) shells	Replaced 0.5 -- 2% coarse agg. with peanut shells. Evaluated strength and durability.	- Up to 2%: acceptable strength and durability. Cost-effective but limited to non-structural use.
Lee et al. (2023)	Spent coffee grounds (SCGs)	Added wet SCGs as partial agg. in mortar. Measured strength, thermal conductivity.	- Optimal SCG ↑ strength; too little/too much ↓ of it. Thermal conductivity ↓ with more SCG. Good insulator.
Cemalgil et al. (2023)	Fruit pits (grape, cherry seeds)	Replaced 100% of coarse/fine agg. with pits (untreated/NaOH-treated).	- Density ↓ drastically, thermal insulation ↑ and compressive strength ↓ significantly. Suitable only for non-structural insulation.

Durability Performance of Concrete with Pozzolans

Research has demonstrated that incorporating sawdust ash (SDA) as a partial replacement for cement in concrete can enhance various durability properties. For instance, Ayuba et al. (2022) reported water absorption values below 10% for SDA replacements up to 30%, aligning with Neville's (2011) criterion for good quality concrete. Cheah and Ramli (2013) observed that specimens with up to 15% SDA exhibited favorable shrinkage properties and reduced carbonation depths, indicating improved resistance to carbonation. Ramos et al. (2013b) found that alkali-aggregate reactions were mitigated with SDA replacements up to 20%. Bahri et al. (2018) said that material with 20% ground RHA as partial cement replacement in HPC of Grade 50 could be used without any reduction in the mechanical and durability properties.

Awolusi et al. (2024) noted that the addition of CPA slightly reduced the compressive strength of CPAC cubes, with values of 23.4 N/mm², 22.2 N/mm², and 21.4 N/mm² observed for 0%, 10%, and 20% CPA replacement levels, respectively. However, incorporating CPA had a positive effect by reducing water absorption and narrowing the flexural crack width in BRC-CPA beams. Gedefaw et al. (2022) said that water absorption increased with CHA content due to its porous nature. Microstructural analyses confirmed effective geo-polymerization and thermal stability up to 575 °C in CHA-modified bricks.

In another study, Ogirigbo and Odibi (2023) examined ternary blends of Portland limestone cement (PLC) with rice husk ash (RHA) and SDA. They observed increased consistency and setting times due to the hygroscopic nature and high surface area of the ashes. However, compressive strengths of the blends were lower than the plain mix at all ages, and water absorption was higher, indicating inferior performance compared to the control. Performance declined as RHA content decreased. Ewa et al. (2023) optimized the compressive strength of previous concrete incorporating SDA and quarry dust using Scheffe's simplex lattice method. They reported that the inclusion of SDA influenced the compressive strength, with optimization techniques aiding in achieving desirable strength characteristics. Onyeka et al. (2023) focused on concrete kerbs for pavement construction, partially replacing cement with SDA up to 20%. Their findings indicated that a 5% SDA replacement achieved maximum strength gain, suggesting its suitability for kerb production.

Chloride ion penetration resistance is a critical indicator of concrete's permeability and is commonly assessed to evaluate the electrical conductance of cementitious materials with partial replacements. Studies have demonstrated that incorporating agro-waste ashes, such as rice husk ash (RHA) and palm oil fuel ash (POFA), significantly enhances concrete durability by reducing chloride ion permeability. For instance, concrete mixes containing POFA have shown a decrease in chloride penetration, with optimal results observed at replacement levels up to 35% by weight of the binder (Chalee et al., 2023). Water absorption and permeability tests further support these findings. Research indicates that the inclusion of RHA in concrete can lead to reductions in water absorption and permeability by as much as 26% and 78%, respectively, compared to control samples. These improvements are attributed to the pozzolanic reaction between the silica in agro-waste ashes and calcium hydroxide from cement hydration, resulting in a denser and less permeable concrete matrix (Chalee et al., 2023).

Microstructural Properties

Agricultural waste materials when utilized as supplementary cementitious materials (SCMs) in concrete (often referred to as agro-cements) exhibit pozzolanic properties that significantly enhance the mechanical performance of concrete. The lignin and cellulose found in these materials are rich in organic chemicals that, when burned, produce ashes that are high in silica, which actively contribute to pozzolanic reactions in the cement matrix.

The silica from the agro-waste ash combines with the calcium hydroxide (lime) generated during cement hydration when agro-cement and Portland cement are mixed (Padma et al., 2023; Yousheng et al., 2023). Additional calcium silicate hydrate (C-S-H) gel, the main substance that gives concrete its strength and durability, is created by this reaction. A denser and more durable cementitious matrix results from the development of more C-S-H gel, which lowers the amount of free lime in the mixture. By expanding the nucleation sites for C-S-H gel formation and improving the microstructure of the cured concrete, research has shown that adding agro-cement to concrete can increase its compressive strength (Padma et al., 2023; Zhang et al., 2025).

The cement matrix's porosity is decreased in part by the fine agro-cement particles. These particles create a denser, less permeable structure by efficiently filling micropores. By reducing the entry of dangerous materials, this micro-filling effect not only increases the concrete's compressive strength but also its overall longevity. Additionally, agro-cement particles' mesoporous structure helps lower the cementitious matrix's effective water–binder ratio, which is crucial for increasing strength and durability (Van et al., 2014).

It has been demonstrated that using agro-cement in place of some of the Portland cement enhances the concrete's long-term performance. Strength and durability gradually grow over time as a result of the continuous pozzolanic processes. Furthermore, agro-cement's high silica content increases the possibility of subsequent hydration processes, which helps to further establish a strong microstructure.(Sudarsan et al., 2023a). A more intricate and linked pore structure results from the C-S-H gel that forms around aggregate particles, which also affects the pore size distribution. There are several advantages of adding agro-cement to concrete mixtures, such as better durability, decreased porosity, and increased mechanical qualities. The main cause of these enhancements is the pozzolanic activity of the silica obtained from agricultural wastes, which encourages the production of more C-S-H gel and improves the cement matrix's microstructure (Zhao et al., 2024). This sustainable approach not only addresses waste management issues but also contributes to the development of high-performance concrete.

Sustainability and Environmental Benefits

The use of agricultural waste pozzolans in concrete offers several environmental and practical benefits. Firstly, it contributes to the reduction of greenhouse gas emissions, as the cement industry is responsible for up to 8% of global anthropogenic CO_2 emissions; partially replacing Portland cement with agricultural waste materials lowers the demand for cement production and its associated emissions (Favier et al., 2018). Secondly, this practice supports waste minimization and resource conservation by diverting agricultural byproducts from landfills and transforming them into valuable construction materials, promoting circular economy principles (Thomas et al., 2021). Thirdly, the conservation of natural aggregates is achieved through the use of pozzolans such as rice husk ash (RHA) and bamboo leaf ash (BSA), which reduces the pressure on natural aggregate sources and mitigates the environmental impact of quarrying activities (Zhang & Malhotra, 1996). Additionally, incorporating these materials into concrete enhances its durability and reduces maintenance needs, offering increased resistance to chemical attack and decreased permeability, thus extending the service life of structures and reducing long-term resource and energy consumption (Chindaprasirt et al., 2007). Moreover, this substitution results in energy savings and further emission reductions, as cement manufacturing is highly energy-intensive, and lowering cement content directly reduces energy use and CO_2 output (Sudarsan et al., 2023b). Lastly, the approach improves agricultural waste management by offering an eco-friendly alternative to the traditional disposal methods, such as burning or landfilling, which helps in reducing air pollution and conserving landfill space (Siddiqua et al., 2022).

Research Gap

Although numerous studies have demonstrated the feasibility of using agricultural waste as aggregates and pozzolans in lightweight concrete, significant gaps limit their standardization and widespread adoption. Most research investigates individual wastes such as rice husk ash, coconut shell, or palm oil clinker in isolation using disparate mix designs and testing protocols. There is a critical lack of systematic comparative studies evaluating multiple agricultural wastes under uniform conditions, making it difficult to identify optimal materials for specific performance objectives like strength, durability, or sustainability.

No universally accepted methodology exists for determining optimal replacement rates, and robust performance prediction models correlating waste properties (particle size, silica content, water absorption, pozzolanic reactivity) with concrete performance metrics are absent. Furthermore, major standardization bodies (ASTM, BS, EN) have not established qualification guidelines for agricultural wastes as supplementary cementitious materials or lightweight aggregates, hindering regulatory acceptance.

The overwhelming majority of studies focus on short-term mechanical properties at 7–28 days, with minimal attention to long-term durability. Critical parameters including chloride penetration, sulfate resistance, freeze-thaw cycling, carbonation depth, alkali-silica reaction potential, and strength gain beyond 90 days remain largely unexplored. Accelerated aging tests and real-time monitoring studies spanning 6 months to 5+ years are urgently needed for structural applications with 50-year service life expectations. Research remains confined to laboratory-scale trials, with minimal field applications or pilot-scale construction projects. The absence of documented case studies in buildings, pavements, or precast elements creates uncertainty among engineers and regulators regarding on-site workability and in-service behavior. Full-scale field trials are essential to validate laboratory findings and build industry confidence.

While environmental benefits are frequently cited, rigorous lifecycle assessment studies following ISO 14040/14044 standards are scarce. Comprehensive cradle-to-grave analyses quantifying embodied carbon, embodied energy, and waste diversion rates are lacking, as are detailed cost-benefit analyses considering processing, transportation, and lifecycle maintenance costs. This impedes evidence-based decision-making for policymakers and construction firms. Most investigations target normal-strength lightweight concrete (20–40 MPa) with conventional compaction. There is limited research on self-compacting or high-performance lightweight concrete (>50 MPa) incorporating agricultural wastes with modern admixtures (superplasticizers, viscosity-modifying agents) or alkaline activators. Key challenges include achieving adequate rheology, optimizing particle packing density, and maintaining strength while reducing density.

Finally, research on synergistic effects of combining natural fibers (sisal, bamboo, coir) with agricultural waste pozzolans is notably absent. The potential of hybrid fiber-waste composites to enhance tensile strength, flexural toughness, crack control, and permeability reduction remains unexplored.

Conclusion

The synthesis of the literature establishes that the strategic utilization of agricultural waste materials as either supplementary cementitious materials (SCMs) or alternative aggregates provides a technically viable pathway toward lower-cost, lower-carbon lightweight concrete (LWC). The engineering performance of these green concretes is governed by distinct operational thresholds: optimal cement replacement levels are consistently restricted to a 5–20% window for silica-rich ashes (such as rice husk ash, cassava peel ash, and sawdust ash) to exploit pozzolanic matrix densification via secondary C-S-H gel formation without compromising early strength. Conversely, structural and semi-structural lightweight applications utilizing woody macro-elements like coconut shells and palm kernel shells achieve optimal performance within a 10–25% substitution range, balancing a targeted oven-dry density reduction (800 to 2100 kg/m^3) against localized interfacial microcracking and high water absorption inherent to agro-aggregates.

Despite these clear environmental and density benefits, transition from laboratory empirical trials to widespread industry standard adoption remains heavily constrained. The critical synthesis of current research exposes a fragmented landscape lacking standardized performance-based mix design methodologies and universal quality control protocols to neutralize the geographic and processing variability of biomass byproducts. Furthermore, long-term durability metrics under realistic aggressive exposures (specifically deep-matrix carbonation, cyclic freeze-thaw behavior, and structural degradation beyond 90 days) remain profoundly under-documented.

To transition agro-waste concrete into mainstream structural and non-structural engineering, future research must move beyond isolated descriptive studies. Priority must be placed on uniform comparative frameworks, advanced multi-scale microstructural modeling and rigorous "cradle-to-grave" life-cycle assessments (ISO 14040/14044) that balance real-world processing penalties against carbon-reduction metrics. Ultimately, establishing qualification guidelines within major regulatory frameworks (ASTM, BS, EN) alongside field-scale pilot projects will be the definitive steps required to convert these abundant agricultural secondary resources into predictable, durable and commercially scalable structural materials.

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