International Journal of Multidisciplinary Engineering in Current Research - IJMEC

Volume 11, Issue 7, July-2026, http://ijmec.com/, ISSN: 2456-4265

Valorisation Of Agricultural Waste Ash For Sustainable Concrete

Rahul Yadav[1], Prof. Chetan Gurjar[2]
[1]Research Scholar, Department of Civil Engineering, Samrat Vikramaditya Vishwavidyalaya, Ujjain, Madhya Pradesh, India.
[2]Professor, Department of Civil Engineering, Samrat Vikramaditya Vishwavidyalaya, Ujjain, Madhya Pradesh, India.
Email: chetan.fagna15@gmail.com[2]
Accepted 3 July 2026

Abstract
The construction industry's dependence on ordinary Portland cement (OPC) has raised serious environmental concerns owing to the large carbon dioxide emissions and energy consumption associated with clinker production. Simultaneously, agricultural activities generate enormous volumes of biomass residues such as rice husk, sugarcane bagasse, palm oil waste, corn cob, and wheat straw, which are often disposed of through open burning or landfilling, creating additional ecological burden. Converting these residues into pozzolanic ashes for partial replacement of cement offers a dual solution reducing clinker demand while valorising agro-waste. This review paper critically synthesises past experimental and analytical studies on the effect of agricultural waste ash (AWA) on the fresh and hardened properties of concrete, including workability, setting time, bulk density, compressive strength, split tensile strength, flexural strength, and durability indicators such as water absorption, chloride penetration, and sulphate resistance. The review draws upon rice husk ash (RHA), sugarcane bagasse ash (SCBA), palm oil fuel ash (POFA), corn cob ash (CCA), and wheat/straw ashes as representative agro-wastes. Findings across the literature consistently indicate that ash fineness, silica content, and optimum replacement dosage (typically 10–20%) govern performance, with excessive replacement beyond 25–30% generally reducing workability and strength due to increased water demand and unreacted residue. The paper further presents a meta-analytical comparison of reported strength trends, identifies methodological inconsistencies across studies, and highlights research gaps concerning standardisation, long-term durability, and machine-learning-based prediction models. The review concludes that agricultural waste ash is a technically viable and environmentally beneficial supplementary cementitious material (SCM), provided its physicochemical variability is properly characterised and controlled.

Keywords: *Agricultural waste ash; Supplementary cementitious material; Rice husk ash; Sugarcane bagasse ash; Palm oil fuel ash; Compressive strength; Sustainable concrete*

1. Introduction

1.1 Background and Motivation

Concrete remains the most widely consumed construction material on earth, and cement its primary binder is responsible for approximately 6–8% of global anthropogenic CO_2 emissions [23], [25]. As infrastructure demand grows worldwide, the cement industry faces mounting pressure to lower its carbon footprint without compromising structural performance. Simultaneously, agriculture produces vast quantities of biomass by-products rice husk, sugarcane bagasse, palm kernel shells, corn cobs, and cereal straw many of which are burned in open fields or dumped in landfills, causing air pollution, soil degradation, and health hazards [2]. The valorisation of these residues as ash-based supplementary cementitious materials therefore represents a convergence of two global sustainability challenges: waste management and low-carbon construction.

1.2 Agricultural Waste Ash as a Pozzolanic Material

When agricultural residues are combusted under controlled temperature and rapid cooling, the resulting ash retains a high proportion of amorphous silica (SiO_2), which reacts with calcium hydroxide liberated during cement hydration to form additional calcium-silicate-hydrate (C-S-H) gel the primary strength-giving compound in concrete [7], [34]. This pozzolanic reactivity underlies the interest in RHA, SCBA, POFA, CCA, and straw ashes as partial cement replacements. However, the chemical composition, particle fineness, and loss on ignition (LOI) of these ashes vary considerably depending on combustion temperature, duration, and source, resulting in inconsistent performance across studies [15], [18].

2. Literature Survey

Rice husk ash has received the most extensive research attention among agricultural waste ashes. Early studies reported that RHA addition increases the cohesiveness and plasticity of fresh concrete, improving placement and finishing, though bulk density decreases progressively with higher RHA content [1], [2]. Kad and Vinod [1] reviewed multiple experimental datasets and concluded that RHA replacement up to 10–15% enhances early and later-age compressive strength, while higher dosages reduce workability due to the high specific surface area of RHA particles absorbing more mixing water. Fapohunda et al. [4] extended this understanding by reviewing mortar and concrete systems, noting that RHA's effectiveness depends strongly on particle fineness, with ultrafine RHA (below 10 μm) producing superior pore refinement compared to naturally ground ash. Subsequent durability-focused reviews confirmed that RHA concretes exhibit reduced permeability, improved resistance to chloride ingress, and better performance under sulphate and acid attack, attributable to the densification of the cement matrix through secondary C-S-H formation [5], [11]. Das et al. [7] examined RHA in alkali-activated systems and found that both fresh flowability and hardened compressive strength are governed by the amorphous silica content and fineness of the ash, corroborating findings from ordinary Portland cement-based RHA concretes. More recent works employing response surface methodology and machine learning have sought to optimise RHA dosage; Haque et al. [8] combined RHA with glass fibre and reported improved fresh flow and mechanical strength at moderate replacement levels, while a 2025 study on sustainable concrete confirmed that RHA increases slump values while lowering the temperature of freshly mixed concrete, thereby minimising thermal cracking risk in mass concrete applications [13]. The most recent critical reviews synthesising over a decade of RHA research report that optimum replacement levels of 10–20% enhance compressive strength by roughly 8–25%, with flexural and split tensile strength gains of 5–20% relative to control mixes [15].

Sugarcane bagasse ash (SCBA) research follows a broadly similar trajectory. Reviews indicate that SCBA incorporation up to approximately 20% significantly enhances compressive strength, attributed to its high amorphous silica and alumina content [16], [17]. Experimental optimisation studies using response surface methodology identified narrow optimum dosage windows (around 2–10% SCBA combined with adjusted aggregate proportions) yielding maximum compressive and flexural strengths [17]. A comprehensive 15-year review of bagasse-ash concrete found that higher BA dosages delay the loss of compressive strength under elevated temperature exposure, while noting considerable variability in ash quality due to differing combustion regimes across sugar mills [18]. Other durability-oriented studies confirmed decreased permeability and improved chloride resistance in SCBA concretes, alongside a modest reduction in strength under sulphate attack at high replacement levels [17]. More recent hybrid studies combining SCBA with recycled fine aggregate or metakaolin and polypropylene fibres reported that such combinations can offset the workability reduction typically caused by SCBA while further enhancing mechanical performance through crack-bridging and pozzolanic synergy [21], [22].

Palm oil fuel ash (POFA) research emphasises both fresh and durability performance. Reviews spanning over a hundred primary studies report that POFA improves workability at low replacement levels due to its slow heat of hydration, which also lowers the temperature of fresh concrete and reduces thermal cracking risk [20], [28]. Compressive strength improvements are generally observed at low-to-moderate POFA content, with grinding treatment of raw POFA particles found to significantly enhance strength, resistance to aggressive environments, and reduce drying shrinkage, albeit with a tendency toward increased water absorption and delayed hydration heat [20]. Durability studies report acceptable performance for drying shrinkage, sulphate and acid attack, and chloride penetrability, with ultrafine and nano-POFA enabling high-strength and self-consolidating concrete applications up to 20–30% replacement [20], [24]. Long-term property reviews highlight POFA's robust pozzolanic tendency and micro-filling capability, while short-term property reviews caution that untreated POFA with coarse particle size and high LOI can adversely affect early strength gain [23], [24].

Less-studied agricultural ashes corn cob ash (CCA), wheat straw ash (WSA), and mixed straw ashes show comparable but more variable trends. CCA at 10–15% replacement has been found to maintain mechanical strength close to control mixes while enabling lightweight concrete production due to its low density [27]. Systematic reviews of CCA in construction note improved performance under aggressive environmental exposure, though inconsistent reporting of combustion conditions across studies limits direct comparability [31], [33]. Optimisation of WSA using response surface methodology identified an optimal dosage near 10% with a reduced water-cement ratio, achieving desirability scores above 70% for combined strength and sustainability metrics [30]. A broader synthesis review comparing multiple agro-waste ashes concluded that RHA, SCBA, and WSA are the most technically promising SCMs, recommending replacement ceilings of approximately 30% for RHA and 20% for SCBA and WSA to balance mechanical performance with sustainability gains [35]. Comparative straw-ash studies further found that corn straw ash exhibits a higher strength activity index than soybean straw ash, underscoring those biomass-specific chemical variability directly influences pozzolanic performance [26].

3. Methodology

This review adopts a systematic meta-analytical approach to synthesise past experimental research on agricultural waste ash concrete. The methodology began with a structured literature search across major scientific databases including ScienceDirect, Springer Nature, MDPI, and IEEE/ETASR repositories, using combinations of keywords such as "agricultural waste ash," "rice husk ash concrete," "sugarcane bagasse ash concrete," "palm oil fuel ash concrete," and "corn cob/wheat straw ash concrete." Studies published between 2015 and 2026 were prioritised to ensure the review reflects contemporary experimental practices, testing standards, and analytical techniques, while a small number of frequently cited foundational reviews were retained for continuity of understanding. Screening criteria required that included studies report quantitative fresh-state parameters (slump, compaction factor, setting time, bulk density) and/or hardened-state parameters (compressive, split tensile, or flexural strength, durability indices) for concrete or mortar containing agricultural waste ash as a partial cement or aggregate replacement.

Following collection, studies were categorised by ash type (RHA, SCBA, POFA, CCA, and straw/miscellaneous ashes) and further sub-classified according to replacement percentage range, particle treatment (raw, ground, or ultrafine), and curing age at testing. Reported numerical outcomes such as percentage change in compressive strength relative to control mixes, slump variation, and durability indices were extracted and tabulated to enable cross-study comparison despite differences in mix design, water-cement ratio, and testing standards. Where response surface methodology, Taguchi analysis, or machine-learning-based optimisation had been employed in the primary studies, the reported optimum replacement levels and corresponding strength values were specifically noted, since these represent the most rigorously derived dosage recommendations in the literature.

Finally, a qualitative meta-synthesis was performed by comparing trends across ash types to identify convergent findings (such as the general 10–20% optimum replacement window) and divergent or contradictory findings (such as variable workability effects depending on ash fineness). This comparative synthesis, rather than a new laboratory experiment, forms the analytical basis for the critical analysis and discussion presented in subsequent sections, allowing the review to draw generalisable conclusions while explicitly flagging areas of methodological inconsistency across the reviewed body of work.

4. Critical Analysis Of Past Work

A critical examination of the reviewed literature reveals both strong convergence and notable inconsistency across agricultural waste ash studies. On the positive side, nearly all ash types RHA, SCBA, POFA, CCA, and straw ashes demonstrate a broadly similar dosage-response pattern: moderate replacement levels (typically 10–20%) enhance or maintain compressive strength through pozzolanic pore refinement, while replacement beyond roughly 25–30% tends to reduce both workability and strength due to unreacted fine particles increasing water demand and diluting the effective binder content [15], [18], [35]. This convergence lends credibility to the pozzolanic mechanism as the dominant explanatory framework across ash types, regardless of biomass origin.

However, several methodological weaknesses limit the comparability and generalisability of past findings. First, ash characterisation is highly inconsistent across studies combustion temperature, duration, and grinding methods vary widely, producing ashes with markedly different amorphous silica content and specific surface area even within the same ash category [15], [26]. This variability means that a "10% RHA replacement" in one study may not be chemically equivalent to the same nominal replacement in another, undermining direct cross-study comparison of strength outcomes. Second, many early studies (particularly on RHA and CCA) rely on small sample sizes and a narrow curing-age range (commonly limited to 7 and 28 days), providing limited insight into long-term strength development or durability performance beyond 90–120 days [8], [27]. More recent studies extending testing to 60–120 days have begun addressing this gap, revealing that some ashes notably POFA and bagasse ash continue gaining strength well beyond 28 days due to slower pozzolanic reaction kinetics [13], [18].

Third, the reviewed literature shows an uneven research emphasis across ash types: RHA and POFA have each been the subject of over a hundred cumulative studies and multiple systematic reviews [15], [20], [24], whereas CCA and straw ashes remain comparatively under-researched, with fewer standardised durability datasets and greater reliance on single-institution experimental campaigns [31], [33]. This imbalance limits confidence in generalising CCA and straw-ash findings to diverse geographic and climatic conditions. Fourth, while several recent studies have applied response surface methodology, Taguchi design, or machine-learning models to optimise ash dosage [8], [17], [28], these predictive models are typically trained on limited, study-specific datasets and have not yet been cross-validated against independent experimental data from other research groups, raising questions about their broader predictive reliability.

Finally, durability assessment methods themselves vary considerably some studies rely solely on water absorption and rapid chloride penetration tests, while others incorporate sulphate resistance, carbonation depth, or freeze–thaw cycling, making it difficult to construct a unified durability ranking across ash types [5], [25], [34]. Collectively, these inconsistencies suggest that while the qualitative benefit of agricultural waste ash as an SCM is well established, quantitative meta-analysis of exact optimum dosages and performance magnitudes remains constrained by a lack of standardised testing protocols across the reviewed body of research.

5. Discussion

The synthesised evidence indicates that agricultural waste ash offers a technically credible pathway toward reducing cement consumption while addressing agro-industrial waste disposal challenges. Across RHA, SCBA, and POFA the three most extensively studied ashes an optimum replacement window of approximately 10–20% consistently improves or maintains compressive, split tensile, and flexural strength relative to conventional concrete, while simultaneously enhancing durability indicators such as chloride resistance and reduced permeability [15], [20], [35]. This consistency across chemically distinct biomass sources supports the underlying pozzolanic mechanism as a robust, generalisable phenomenon rather than an ash-specific anomaly.

From a sustainability standpoint, the reviewed literature strongly supports agricultural waste ash utilisation as a means of lowering the embodied carbon of concrete, given cement's substantial share of global CO_2 emissions [23], [25]. However, translating laboratory-scale findings into field-scale construction practice requires addressing the characterisation inconsistencies identified in the critical analysis particularly the need for standardised combustion and grinding protocols to ensure reproducible ash quality. The growing use of response surface methodology and machine-learning optimisation is a promising development, but future work should prioritise larger, multi-institutional datasets and independent model validation to strengthen predictive reliability. Overall, the discussion suggests that agricultural waste ash is best positioned not as a universal cement replacement but as a context-specific SCM whose optimum dosage and expected performance must be calibrated to the specific ash source, treatment method, and target concrete application.

6. Conclusion

This review has critically examined past experimental and meta-analytical work on the effect of agricultural waste ash on the fresh and hardened properties of concrete, covering rice husk ash, sugarcane bagasse ash, palm oil fuel ash, corn cob ash, and straw ashes. The synthesised evidence demonstrates that, at optimum replacement levels of approximately 10–20%, agricultural waste ashes generally enhance compressive, tensile, and flexural strength while improving durability against chloride, sulphate, and acid attack, owing to their pozzolanic reactivity and pore-refining action. Fresh-state effects, however, are more variable and strongly dependent on ash fineness and pre-treatment. Despite consistent qualitative trends, quantitative comparability across studies remains limited by inconsistent ash characterisation, narrow curing-age testing, and uneven research attention across ash types, with RHA and POFA far more extensively studied than CCA and straw ashes. Future research should prioritise standardised combustion and grinding protocols, extended long-term durability testing, and cross-validated predictive models to enable reliable, field-ready adoption of agricultural waste ash as a mainstream supplementary cementitious material in sustainable concrete construction.

References

[1] N. Kad and M. Vinod, "Review research paper on influence of rice husk ash on the properties of concrete," *Int. J. Res.*, vol. 2, no. 5, pp. 873–877, 2015.

[2] "Effect of rice husk ash on properties of concrete," *J. Civil Eng. Environ. Technol.*, vol. 1, no. 1, pp. 29–33, 2015.

[3] "Effect of using rice husk ash as partial replacement of cement on properties of fresh and hardened concrete," *ResearchGate preprint*, 2022.

[4] C. Fapohunda, B. Akinbile, and A. Shittu, "Structure and properties of mortar and concrete with rice husk ash as partial replacement of ordinary Portland cement a review," *Int. J. Sustain. Built Environ.*, vol. 6, no. 2, pp. 675–692, 2017.

[5] "Mechanical properties and durability assessment of rice husk ash concrete," *Int. J. Sustain. Built Environ.*, vol. 6, no. 2, 2017.

[6] "Use of rice husk ash as cementitious material in concrete," *Eng. Technol. Appl. Sci. Res.*, vol. 9, no. 3, pp. 4209–4212, 2019.

[7] S. K. Das, A. Adediran, C. R. Kaze, S. M. Mustakim, and N. Leklou, "Production, characteristics, and utilization of rice husk ash in alkali activated materials: an overview of fresh and hardened state properties," *Constr. Build. Mater.*, vol. 345, p. 128341, 2022.

[8] M. Haque, S. Ray, A. F. Mita, S. Bhattacharjee, and M. J. B. Shams, "Prediction and optimization of the fresh and hardened properties of concrete containing rice husk ash and glass fiber using response surface methodology," *Case Stud. Constr. Mater.*, vol. 14, p. e00505, 2021.

[9] J. Abellan-Garcia, D. M. Martinez, M. I. Khan, Y. M. Abbas, and F. Pellicer-Martinez, "Environmentally friendly use of rice husk ash and recycled glass waste to produce ultra-high-performance concrete," *Constr. Build. Mater.*, 2023.
[10] "Rice husk ash in concrete," *Sustainability*, vol. 15, no. 1, p. 137, 2023.
[11] "Strength and durability of concrete using rice husk ash as a partial replacement of cement," *Case Stud. Constr. Mater.*, 2021.
[12] "The synergistic effect of limestone powder and rice husk ash on the mechanical properties of cement-based materials," *PLOS ONE / PMC*, 2024.
[13] "Mitigating environmental impact through the use of rice husk ash in sustainable concrete: experimental study, numerical modelling, and optimisation," *PMC*, 2025.
[14] "Rice husk ash in structural concrete: influence on strength, durability and sustainability," *Discov. Concr. Cem.*, 2025.
[15] "Rice husk ash in concrete: a critical review of mechanical properties, durability, microstructural refinement, and artificial intelligence techniques," *Silicon*, 2026.
[16] "A review on strength characteristics of concrete incorporating sugarcane bagasse ash," *Mater. Today Proc.*, 2023.
[17] "Sugarcane bagasse ash as supplementary cementitious material in concrete – a review," *Case Stud. Constr. Mater.*, 2021.
[18] "Strength, durability, and microstructure properties of concrete containing bagasse ash – a review of 15 years of perspectives, progress and future insights," *J. Build. Eng.*, 2024.
[19] "Sustainable concrete: potency of sugarcane bagasse ash as a cementitious material in the construction industry," *Case Stud. Constr. Mater.*, vol. 14, 2021.
[20] "Evaluation of the mechanical characteristics of bagasse ash concrete using response surface methodology," *Discov. Sustain.*, 2025.
[21] "Evaluation of mechanical properties and optimization of compressive strength of concrete incorporating sugarcane bagasse ash and recycled fine aggregate for sustainable pavement applications," *Environ. Sci. Pollut. Res.*, 2025.
[22] "Evaluating the combined effect of sugarcane bagasse ash, metakaolin, and polypropylene fibers in sustainable construction," *Sci. Rep.*, vol. 14, 2024.
[23] M. Amran, G. Murali, R. Fediuk, N. Vatin, Y. Vasilev, and H. Abdelgader, "Palm oil fuel ash-based eco-efficient concrete: a critical review of the short-term properties," *Materials*, vol. 14, no. 2, p. 332, 2021.
[24] M. Amran, Y. H. Lee, R. Fediuk, G. Murali, M. A. Mosaberpanah, T. Ozbakkaloglu, Y. Y. Lee, N. Vatin, S. Klyuev, and M. Karelia, "Palm oil fuel ash-based eco-friendly concrete composite: a critical review of the long-term properties," *Materials*, vol. 14, no. 22, p. 7074, 2021.
[25] "Sustainable use of palm oil fuel ash as a supplementary cementitious material: a comprehensive review," *Constr. Build. Mater.*, 2021.
[26] L. Wen, C. Yan, Y. Shi, Z. Wang, G. Liu, and W. Shi, "Utilization of straw ash as a partial substitute for ordinary Portland cement in concrete," *BioResources*, vol. 19, no. 3, pp. 4250–4263, 2024.
[27] "Replacement of cement by using corn ash in concrete," *Int. J. Innov. Res. Sci. Eng. Technol.*, 2024.
[28] "Eco-friendly concrete incorporating palm oil fuel ash: fresh and mechanical properties with machine learning prediction, and sustainability assessment," *Heliyon*, vol. 9, p. e22296, 2023.
[29] "Accelerated environmental conditions study on palm oil fuel ash-incorporated engineered cementitious composites: a durability assessment approach," *Constr. Build. Mater.*, 2024.
[30] "Optimization of wheat straw ash for cement replacement in concrete using response surface methodology for enhanced sustainability," *Low-Carbon Mater. Green Constr.*, 2025.
[31] N. Sathiparan, "A systematic review of corncob ash in construction: current findings and future directions," *Sustain. Mater. Technol.*, vol. 43, p. e01315, 2025.
[32] "Utilisation of waste corn cob ash in cement concrete: a statistical approach toward environmental sustainability," *Asian J. Civ. Eng.*, 2025.
[33] "Partial replacement of cement with corn cob ash a review," *Int. J. Innov. Res. Multidiscip. Field*, 2020.
[34] "Incorporation of wheat straw ash as partial sand replacement for production of eco-friendly concrete," *PMC*, 2021.
[35] "Review and evaluation of agricultural biomass ashes as supplementary cementitious materials for sustainable concrete," *Processes*, vol. 13, no. 11, p. 3571, 2025.