Review article

Utilization of Corn Cobs Ash as Cementitious and Binary Cementitious Materials in Concrete and Cement-based Composites: A Review

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ABSTRACT

This paper reviews the utilization of corn cobs ash (CCA) as pozzolanic, cementitious, and binary cementitious materials in concrete. CCA is the grey-to-brown, inorganic or heterogeneous residual material derived from the high-temperature incineration or combustion of corn cobs (CC). Despite the typical problematic nature of biomass ash, the chemical composition of CCA renders it a potential pozzolanic material. Therefore, numerous studies have critically examined the process technologies and operational conditions for CCA production and its application as a partial replacement for cement in concrete. Other studies have extensively characterized the physicochemical, morphological, microstructure, and thermal properties of CCA through various analytical techniques. Potential pozzolanic materials must meet the condition: $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 \geq 70\%$, according to ASTM C618, to which CCA complies satisfactorily. Hence, the use of CCA as a replacement for cement has been investigated over the years. Findings indicate that the partial replacement of cement with CCA decreases compressive strength, thermal conductivity, ultrasonic pulse velocity, and density of the hardened concrete at normal temperatures. Nevertheless, the thermal treatment (calcination) of CCA and extended curing enhances compressive strength owing to higher silica content and extended surface area. Besides, the partial replacement of cement with CCA enhances the insulation properties of mortar, which improves thermal comfort, costs and energy savings in buildings. Hence, the partial replacement of cement with CCA provides an environmentally friendly, low cost, and sustainable approach for valorizing CC residues whilst addressing CO₂ emissions in construction.

Keywords: CCA ash, Concrete, Corn Cobs, CO₂, Pozzolanic, ASTM

1. Introduction

Corn, otherwise known as Maize (*Zea mays* L.), is a tall cereal plant or annual grass characterized by a stout, erect, solid, and internodal stem that grows up to heights ranging from 3–13 m (or 10–43 ft) (von Cossel *et al.*, 2017; Wasaya *et al.*, 2017). The plant is considered a short day and facultative cultigen. Its leaves are large but narrow with curly margins that are spaced interchangeably on reverse sides of the stem. The male flowers formed on the tassel, which terminate at the major base on the stem, are developed based on the selected day of growing degrees in a specifically adapted environment (Hung *et al.*, 2012; Karl, 2002). In contrast, the female flowers that eventually become the ears are characteristically thick axis spikes or pair of spikelets that eventually become rows of grain (Saldivar, 2016; Young *et al.*, 2004).

Leaf-bearing stems of the corn plant generate distinct pollen and ovuliferous inflorescences that yield numerous seeds or kernels, which grow on cone-shaped structures called cobs or ears. Each ear or cob comprises around 200-400 seeds of variable color (e.g., white, blue-grey, red, black, and yellowish), with dimensions ranging in length from 100 to 250 mm, according to the variety (NWE, 2020). In principle, the ears are clusters of female flowers, enclosed and protected by numerous ~~sheets of~~ leaves that remain hidden until the pale-yellow silks emerge during growth and development (Freeling *et al.*, 2013). Nonetheless, the flowers can undergo transformations (typically known as ts4 and ts6 mutations) into hermaphrodite (or male to female flowers in a tassel) that can hamper stamen development as opposed to the pistil (Chuck *et al.*, 2007; Irish, 1997). The plant is scientifically classified on the taxonomic basis as Magnoliophyta, Liliopsida, Poales, Poaceae, and *Zea*, which correspond to its division, class, order, family, and genus, respectively. Corn is typically regarded as one of the first genetically modified food crops known to mankind, which has resulted over the years in numerous drought-resistant, insect and disease-resistant varieties, otherwise termed hybrid cultivars (Iken *et al.*, 2004; Yadav *et al.*, 2015). Historical records indicate that the plant was originally domesticated around 3,500 B.C. from the annual teosinte, *Zea mays* ssp. *parviglumis*, native to central and southern Mexico (Ali *et al.*, 2020). Due to its Native American origin corn is often also described as Indian corn or simply as *maize* by the Arawak tribes of Native America, whereas others report that the word maize is derived from Spanish, based on the indigenous Taino word for the plant, *mahiz* (Herbst *et al.*, 2007; NWE, 2020).

Cultivation and processing of corn have spread widely over the years from its ancestral epoch in Mesoamerica to become an important globalized food crop (Shiferaw *et al.*, 2011). According to the United Nations Food and

Agricultural Organization (UN-FAO), the total global production of corn was 1.5 billion tons in 2018 but has declined to 1.07 billion in 2020 (FAOSTAT, 2020; Knoema, 2020). The largest global producers (i.e., top 5) of corn, namely the United States, China, Brazil, Argentina, and Ukraine account for over 75% of global production. Furthermore, corn is cultivated on almost 100 million hectares of land located in most developing countries. Consequently, corn is considered the leading grain and most cultivated cereal crop in the world (Saldivar *et al.*, 2016; Shiferaw *et al.*, 2011). The high acreage, cultivation, and tonnage of global corn stocks are particularly ascribed to advances in genetic engineering along with the plant's high adaptability, diversity, and demand (Hardeman, 1999; Saldivar, 2016). The UN-FAO states that large quantities of corn are cultivated and processed for numerous applications, such as direct human consumption (13.8%), food production (19%), livestock feeds (54%), biofuels (14%), chemicals, pharmaceuticals, and building materials, among other uses worldwide (Saldivar *et al.*, 2016). According to analysts, the global demand and production of corn, particularly in developing countries, are projected to double by the year 2050, owing to demographic dynamics such as population growth, higher living standards, and urban drifts (Shiferaw *et al.*, 2011).

Conversely, the cultivation and processing of corn generate large quantities of solid wastes or stover comprising leaves, stems, and cobs, which account for over half the mass of the plant. These waste streams are utilized as animal feeds, mulching materials, organic manure, and cooking fuel (Jansen *et al.*, 2012). Other notable strategies for utilizing corn waste streams include landfilling, field dumping, and open combustion (Kapoor *et al.*, 2016; Santiago-De la Rosa *et al.*, 2017). Combustion of agricultural residues generates soot or particulate matter (PM) and greenhouse gases that pose a grave danger to human health, safety, and well-being. Such practices result in the loss of soil-plant nutrients and microbial obliteration, which severely affect the ecosystem (Dominguez-Escribá *et al.*, 2010; Kapoor *et al.*, 2016). Hence, the under listed strategies for exploiting these wastes are considered inefficient and unsustainable (Bhuvaneshwari *et al.*, 2019; Jain *et al.*, 2014). The ineffectiveness of the current strategies has also resulted in the underutilization of large volumes of these waste streams, which pose severe dangers to flora, fauna, and the environment at large (Ali *et al.*, 2020).

Furthermore, the poor fuel properties, namely high moisture content, low energy density, and transport and handling of corn wastes affect its utilization as biofuels for bioenergy (Meng *et al.*, 2019; Porteiro *et al.*, 2010). Likewise, several studies have shown that the ash content of biomass, such as corn cobs could pose

technical problems during combustion and gasification. Notably, the biomass ash causes bed agglomeration, fouling, sintering, and clinker formation, which lower the conversion efficiencies and operational maintenance of such biomass technologies (Lu *et al.*, 2015; Nyakuma *et al.*, 2017). Alternatively, numerous researchers have sought to utilize corn cob ash (CCA) as cementitious materials in the bid to address current challenges of waste disposal, management, and valorization of maize residues. Therefore, this paper is needed by experts in the field, as it provides an overview of the status and challenges of utilizing CCA as cementitious materials in concrete. Furthermore, it gives insights into the future use of CCA.

2. Corn Cobs: Overview and Current Uses

Corn cob (CC) is the solid cone-shaped residue generated from the threshing of the corn kernels (Bakharev *et al.*, 2020; NIIR, 2006; Yu *et al.*, 2015). The internal structure of CC is characterized by a white appearance, whereas the outermost part of the CC can range from yellow, beige, yellow to purple, depending on the variety (Ajao *et al.*, 2016; Salvador-Reyes *et al.*, 2020). It is also considered the central core of the maize ear with a residual yield of 1.42–1.53 dry tons per hectare. Consequently, corn cobs are major by-products of corn processing, which account for 20–30% (along with the outer leafy covering of corn called husks) by weight of the corn plant (Kapoor *et al.*, 2016; Samanta *et al.*, 2012). Da Silva *et al.* (2015) report that typically 180 kg of corn cob are generated from the processing of 1 ton of corn ear. This quantity amounts to over 140 million tons annually. The bulk of the CC generated annually is currently utilized for the production of fine chemicals, e.g., furfural (Zhang *et al.*, 2019; Zhang *et al.*, 2020), agrochemicals, such as pesticides and rodenticides (Jacob *et al.*, 2018; Nasser, 2018), livestock fodder (Garantjang *et al.*, 2020; Wachirapakorn *et al.*, 2016), farmhouse beddings (Kapoor *et al.*, 2016; Pallas *et al.*, 2020), biofuels, such as ethanol and charcoal (Kluska *et al.*, 2020; Li *et al.*, 2018), soil enhancers (Amoakwah *et al.*, 2017; Shen *et al.*, 2019), and adsorbents (Ji *et al.*, 2015; Nethaji *et al.*, 2013), and other applications.

The utilization of CC in the outlined applications is a result of its ultimate, proximate, and calorific properties summarized from the most cited references, published from 2011 to 2020, with details listed in Table 1. The abbreviations M, VM, FC, AS, C, H, N, S, O, and HHV stand for moisture, volatile matter, fixed carbon, ash, carbon, hydrogen, nitrogen, sulfur, and oxygen contents (all in wt.%), and higher heating value (MJ/kg) for CC.

As revealed by data in Table 1, CC contains volatile matter, fixed carbon, carbon, hydrogen, and higher heating values are typically in the range of 60.30–87.76 wt.%, 9.41–32.13 wt.%, 41.00–53.15 wt.%, 2.01–6.54 wt.%, and 16.46–18.84 MJ/kg, respectively, which enhance renewable energy recovery *via* thermochemical conversion into fuel gases by using gasification, pyrolysis, and combustion technologies. The presence of oxygen results, however, in the oxidative conversion of nitrogen and sulphur into gaseous pollutant oxides such as NO_x, SO_x, and N_xO_y along with carbon and hydrogen, released during the production of ash. As observed, the ash and mineral matter in CC is typically between 1.05–13.70 wt.%, which cause operational problems, including the formation of eutectics in the high-temperature thermochemical conversion processes, such as gasification. Nevertheless, the ash generated from the conversion of CC could be utilized as cementitious or pozzolanic materials (otherwise termed pozzolans) or as a replacement for cement in concrete, widely used in the construction industry.

Over the years, the quest for sustainability in the building and construction sector has stimulated the search for alternatives to cement. Studies have shown that cement accounts for 3–7% of the global CO₂ emissions from the construction industry (Hanle *et al.*, 2004). Typically, it is estimated that 0.9 tons of CO₂ are released while producing 1 ton of cement (Benhelal *et al.*, 2013). According to the study by Andrew (2018), the global emissions from the cement production process are 1.45±0.20 Gigatons of CO₂ in the year 2016, which is equal to about 4% of fossil fuel-based emissions. However, the cumulative CO₂ emissions for the sector amounts to 39.3±2.4 Gigatons from 1928 to 2016. As a result, the cement industry is considered one of the largest sources of anthropogenic CO₂ or emissions after the fossil-based fuels and land use changes (Andrew, 2018; Mikulčić *et al.*, 2012; Zhang *et al.*, 2014). Carbon dioxide emissions are largely ascribed to the calcination reactions of raw materials and the combustion of process fuels required during cement production (Zhang *et al.*, 2014). Hence, there is a growing global call for the development and deployment of strategies that can mitigate CO₂ emissions originating from the cement industry (Benhelal *et al.*, 2013; Deja *et al.*, 2010). For example, the European Union has called for the ratification and implementation of the “Best Available Techniques (BAT)” in industrial cement and lime production (Schorcht *et al.*, 2013; Valderrama *et al.*, 2012). The reference document proposes reduced fuel consumption, low organic raw materials selection, and the utilization of low carbon heating values to replace coal (Giner-Santonja *et al.*, 2019; Schorcht *et al.*, 2013).

Table 1. Ultimate, Proximate and Calorific Properties of Corn Cobs

References	M	VM	FC	AS	C	H	N	S	O	HHV
Aboyade <i>et al.</i> (2011)	6.50	80.20	16.70	3.10	49.00	6.00	0.30	0.08	44.70	17.20
Wang <i>et al.</i> (2012)	0.00	79.65	17.75	2.61	47.26	6.39	0.54	0.10	43.11	18.84
Song <i>et al.</i> (2013)	5.93	75.22	18.95	5.83	46.53	5.91	0.94	0.14	36.72	**
Biagini <i>et al.</i> (2014)	10.10	80.06	17.82	2.12	47.60	6.10	0.52	**	45.78	18.56
Barontini <i>et al.</i> (2015)	0.00	80.10	17.80	2.10	47.60	6.10	0.50	0.00	45.80	17.30
Shariff <i>et al.</i> (2016)	7.14	87.76	11.19	1.05	43.81	6.54	0.77	0.69	48.19	16.46
Munir <i>et al.</i> (2017)	4.01	79.02	14.77	2.02	43.63	6.07	0.00	0.19	44.08	17.61
Dutta <i>et al.</i> (2018)	2.21	64.24	32.13	1.42	53.15	2.01	0.12	**	23.73	**
Dai <i>et al.</i> (2019)	0.00	85.72	9.41	4.87	44.31	6.38	0.36	0.00	44.44	18.66
Sattar <i>et al.</i> (2020)	7.30	60.30	18.70	13.70	41.00	6.10	1.50	0.40	30.00	17.10

Other notable schemes, such as the Best available techniques (BAT) Emission levels associated with the best available techniques (BAT-AELs), Industrial Emissions Directive (IED) and the Industrial Pollution Prevention and Control Directive (IPPCD) are also aimed to curb emissions from the cement industry (Calvo *et al.*, 2021). Largely, these initiatives propose the deployment of the three-pronged process-energy-materials approach, which involves carbon sequestration, energy-saving, and the use of alternative materials (Benhelal *et al.*, 2013; Calvo *et al.*, 2021). According to the authors, the transition from the wet to dry calcination process could reduce energy utilization by 50%, while reducing CO₂ emissions from cement production by up to 20%. Unfortunately, techno-economic challenges and prohibitive costs of carbon capture storage (CSS) have prevented thus far large-scale implementation. Lastly, the materials aspect involves the partial replacement or complete utilization of alternative materials, including agricultural wastes for cement production. All the above are considered efficient measures for limiting CO₂ emissions in the industry (Benhelal *et al.*, 2013; Deja *et al.*, 2010; Zhang *et al.*, 2014). The most notable examples of such agricultural wastes include the lignocellulosic residues and secondary materials generated from global cultivation, processing, and valorization of corn globally. The next section of the paper presents details on corn cob ash (CCA) and its utilization as cementitious materials in concrete.

3. Corn Cob Ash (CCA)

Corn cob ash (or CCA) is defined as the grey-to-brown residues or materials obtained from incineration or combustion of corn cob (CC) residues. The high-temperature process of CCA production involves the thermal degradation of lignocellulosic components of CC into a heterogeneous mix of inorganic materials or

mineral matter. Figure 1 displays the CCA produced from the CC combustion process.

Figure 1. Corn Cobs and CCA (Memon *et al.*, 2019)

The reaction pathway, thermal degradation mechanism, and mass/energy balance of the CCA production are presented in Figure 2. Mass and energy balances were computed based on the average high heating value of CC is 17.72 MJ/kg, whereas in Table 1 ash and moisture contents are 3.882 wt.% and 4.319 wt.%, respectively. Typically, the process begins with the heating of CC from ambient temperatures to 105±5 °C where drying occurs, surface-bound water being eliminated. Next, dried CC undergoes devolatilization, which thermally degrades volatile organic matter content (see Table 1) along with depolymerizing and decarbonizing hemicellulose, cellulose, and lignin to high-carbon content char. This second stage termed pyrolysis or carbonization, is typically conducted at temperatures from 105 °C to 600 °C, yielding char and releasing fuel gases; hydrogen (H₂), carbon monoxide (CO), methane (CH₄), and carbon dioxide (CO₂) along with tar or bio-oil. The third stage involves the oxidation or combustion of char at high temperatures (typically 600 °C to 1000 °C) to ash, mineral matter, and flue gases comprising primarily (CO₂, CO, NO_x, and SO_x).

Figure 2. Process Flow, Reaction Pathway and Mass/Energy Balance of CCA production.

In practice, various research groups have investigated the conversion of CC into CCA using different reaction parameters, reactors, obtaining dissimilar yields and distribution of the products. Numerous reaction

parameters and process conditions employed during the CCA production process are summarized in Table 2. CCA production typically occurs through either controlled or uncontrolled burning or combustion of CC. The most common reactor used is the muffle furnace, owing to its capacity to ensure safe, secure, and controlled combustion of CC into CCA. Other reactors reported in the literature include rotary drums, fabricated chambers, charcoal-fired ovens, and open-air burning, as well. Analysis of reaction parameters revealed that the combustion of CC to CCA normally takes place at temperatures from 450 to 750 °C, although some studies mentioned temperatures above 1000 °C, and reaction times ranging from 2 to 10 h. According to Suwanmaneechot *et al.* (2015), the selection of optimal combustion temperature and thermal treatment processes, such as calcination is critical to the quality of the ash and the cement-based composites produced. Typically, optimal values and high temperatures produce amorphous silica at high yield, large surface area and porosity. The amorphous silica possesses favorable engineering properties, because of high SiO₂, Al₂O₃, and Fe₂O₃ content (Bessenouci *et al.*, 2011; Suwanmaneechot *et al.*, 2015). Comprehensive characterization of CCA is done using advanced techniques, to evaluate the physicochemical properties, chemical composition, and mineral matter. Hence, scanning electron microscopy (SEM) is used to examine the morphology and microstructure of CCA, whereas X-ray fluorescence (XRF) determines the chemical composition and mineral matter for potential applications. Table 3 lists the metal oxides compositions of CCA determined by XRF.

As observed in Table 3, the major metal oxides typically found in the CCA are SiO₂, Al₂O₃, Fe₂O₃, CaO, and MgO as reported in the literature. For SiO₂ the values typically range from 38.80 wt.% to 67.41 wt.% (or 62.22 wt.% on average), whereas the Al₂O₃ range from 5.80 wt.% to 17.57 wt.% (or 9.16 wt.% on average) and Fe₂O₃ is from 1.97 wt.% to 9.07 wt.% (or 5.09 wt.% on average). In contrast, the values of CaO and MgO typically range from 1.80 wt.% to 12.00 wt.% (8.60 wt.% on average) and 0.98 wt.% to 4.56 wt.% (or 2.47 wt.% on average), respectively. Combined contents of SiO₂, Al₂O₃, Fe₂O₃, CaO, and MgO in CCA exceed 70%, which indicates it could be potentially utilized as a substitute or partial replacement for cement in concrete during the construction of buildings.

According to the ASTM standard C618, the requirement for the use of alternate substances such as CCA as pozzolanic or supplementary cementing materials is that the combined sum of SiO₂, Al₂O₃, and Fe₂O₃ is 70% or above (Adesanya *et al.*, 2010; Adesanya, D.A. *et al.*, 2009).

Table 2. Reaction parameters and reaction conditions for CCA production

References	Method	Selected Reactor	Reaction Temperature (°C)	Ashing Time (h)	Particle size of CCA (µm)
Udoeyo <i>et al.</i> (2003)	Uncontrolled Open Burning	Open Air Burner	**	**	600
Owoyale <i>et al.</i> (2008)	Semi controlled Combustion	Rotary Drum Oven	750	**	75
Adesanya, D.A. <i>et al.</i> (2009)	Controlled combustion	Blacksmith Furnace	650	8	**
Wang <i>et al.</i> (2012)	Controlled combustion	Muffle furnace oven	550	6	1000
Ettu <i>et al.</i> (2013)	Controlled combustion	Fabricated combustion chamber	650	**	650
Jimoh <i>et al.</i> (2013)	Uncontrolled Open burning/ Controlled combustion	Open Air Pile/Muffle Furnace	590-650	10	**
Oluborode <i>et al.</i> (2015)	Controlled combustion	Muffle Furnace Oven	600	2	75
Akinwumi <i>et al.</i> (2015)	Uncontrolled Burning	Open Air Burner	560	10	75
Kamau <i>et al.</i> (2016a)	Uncontrolled Burning	Open Air Charcoal-Fired Burner	650	8	**
Apampa (2019)	Uncontrolled Burning	Open Heap Burning	650	5	212
Adigun <i>et al.</i> (2019)	Controlled combustion	Muffle Furnace Oven	450	8	250
Bheel <i>et al.</i> (2020)	Controlled combustion	Muffle Furnace Oven	600	10	75

Table 3: Metal oxides and mineral compositions of CCA determined by XRF

References	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	Na ₂ O	K ₂ O	Mn ₂ O ₃	P ₂ O ₅	TiO ₂
Adesanya, D.A. <i>et al.</i> (2009)	67.33	7.34	3.74	10.29	1.82	1.11	0.39	4.20	**	**	**
Adesanya <i>et al.</i> (2010)	66.38	7.48	4.44	11.57	2.06	1.07	0.41	4.92	**	**	**
Raheem <i>et al.</i> (2011)	65.39	9.14	5.61	11.53	2.33	1.10	0.48	4.92	**	**	**
Jimoh <i>et al.</i> (2013)	65.40	5.80	2.97	3.70	2.30	1.10	0.48	8.39	0.06	2.45	0.61
Mujedu <i>et al.</i> (2014)	67.41	8.39	5.00	10.87	2.27	1.59	**	**	**	**	**
Oluborode <i>et al.</i> (2015)	56.39	17.57	9.07	11.47	0.98	0.55	1.91	1.98	**	**	**
Kamau <i>et al.</i> (2016a)	38.80	7.90	7.40	1.80	2.10	0.59	0.90	23.50	**	**	**
Singh <i>et al.</i> (2018)	64.56	9.42	5.12	12.00	3.01	**	**	**	**	**	**
Memon <i>et al.</i> (2018)	61.80	6.31	1.97	4.01	3.24	1.17	0.19	5.81	**	4.04	0.05
Memon <i>et al.</i> (2019)	63.73	15.08	5.32	6.56	4.56	**	0.10	2.05	**	2.50	0.06
Bheel <i>et al.</i> (2020)	67.23	6.34	5.33	10.75	**	1.04	0.37	**	**	**	**

Morphology and microstructure of CCA have been comprehensively characterized in the literature. Figure 3 exhibits the SEM micrograph of CCA recorded by Olafusi *et al.* (2018). The micrograph reveals that CCA is characterized by polygonal-shaped and agglomerated

particles with potential for utilization in concrete composites. Also, the agglomeration potential of CCA could enhance hardening when mixed in concrete composite mixtures. Hence, various researchers have extensively investigated the use of CCA as pozzolanic

materials for the partial replacement of cement in concrete.

Cement concrete is considered one of the most extensively used construction material worldwide. Typically, the construction of buildings and other infrastructure depends significantly on concrete derived from Ordinary Portland Cement (OPC). The use of concrete cement provides a cost-effective, satisfactory strength and structural performance in building infrastructures worldwide (Adole *et al.*, 2011; Scrivener, 2014; Turner *et al.*, 2013).

Figure 3. SEM Micrographs of CCA (Olafusi *et al.*, 2018)

An undesired effect of cement production and utilization in the construction industry is the emission of large quantities of carbon dioxide. It is estimated that the cement industry accounts for 5–8% of anthropogenic CO₂ emitted globally, although this could soar

significantly over the years (Scrivener, 2014; Turner *et al.*, 2013).

Life cycle analysis of concrete performed by (Sjunnesson, 2005) found that the production of 1 t of concrete aggregate generates approximately 5.4 kg (2.75 m³) of CO₂. According to Ma *et al.* (2016), concrete accounts for 20% and 12% of energy and CO₂ emissions, respectively, in the United States. Other researchers have reported that the use of cement accounts for about 80% of CO₂ emission attributed to concrete (Latawiec *et al.*, 2018; Turner *et al.*, 2013). Due to the high carbon footprint of cement in concrete, numerous scientists have examined the use of pozzolanic or cementitious materials such as CCA as a replacement for cement, as highlighted in Section 4 of this review paper.

4. CCA as Cementitious Materials

Use of CCA as pozzolanic or cementitious materials has been examined in many papers. These studies report on comprehensive findings of the production of CCA from CA through combustion/incineration technologies. Also described is the characterization of the pozzolanic properties. Lastly, these studies examine the physical, chemical, thermal, and mechanical properties of the concrete or cement-based composites, derived from CCA and OPC. Table 4 provides more detailed findings of the CCA studies reviewed in this paper.

Adesanya, D. *et al.* (2009) investigated the mechanical properties of corn cob ash (CCA) blended cement concrete.

Table 4. Summary of findings on CCA utilization as Pozzolanic materials

References	Objective of the Study	Parameters/ Reaction Conditions	Findings/Conclusions
Adesanya, D. <i>et al.</i> (2009)	To test the workability and compressive strength characteristics of CCA blended cement concrete.	<ul style="list-style-type: none"> • Nine samples of CCA-blended cement • CCA content from 0-25% • Mix proportions of cement / sand / granite are 1:1½:3, 1:2:4, and 1:3:6 with 0.5, 0.6, and 0.7 water-to-cement ratios, respectively. • Curing age: 3, 7, 28, 60, 120, and 180 da 	<ul style="list-style-type: none"> • Concrete slump and compacting factor reduced with increasing CCA content. • Concrete was less workable (stiff) at a higher CCA percentage. • Compressive strength of CCA-blended cement concrete was lower than the control • Optimum compressive strength ranged from 28.07-57.10 N/mm² • 8% CCA replacement suitable for blended cement and application in structural concrete

References	Objective of the Study	Parameters/ Reaction Conditions	Findings/Conclusions
Adesanya <i>et al.</i> (2010)	To examine the permeability and impact of acid attack on CCA blended cements.	<ul style="list-style-type: none"> Permeability and chemical attack using HCl and H₂SO₄. Nine CCA blended cements used and CCA ranged 0-25%. 0% CCA replacement represents ordinary Portland cement (OPC) or the control. Water absorption used blended cement concrete with mix proportions 1:1½:3, 1:2:4, and 1:3:6. Water-to-binder (W/B) ratios 0.5-0.7. Chemical attack test used 50×50×15 mm mortar samples with mix proportions 1:1, 1:2, and 1:3 and W/B ratio 0.26-0.29. 	<ul style="list-style-type: none"> CCA blended cement reduced water absorption. Optimal reduction was at 10% and 15% CCA replacement at 1:1½:3 and 1:2:4 mix proportions, respectively. Resistance to chemical attack was enhanced by adding 15% CCA but decreased permeability and reduced weight loss.
Raheem <i>et al.</i> (2011)	To examine the thermal conductivity (TC) of CCA blended cement mortar	<ul style="list-style-type: none"> Thermal conductivity decreased with increasing CCA percentage. For the mix proportion 1:1, the TC reduced from 1.80 to 0.69 W/m °C with an increase in CCA from 2 to 25% TC of control (0% CCA) was 2.40 W/m °C. CCA blended cements improve the insulation potential of the mortar. 	<ul style="list-style-type: none"> Integration of CCA into the blended cement mortar lowers TC Addition of CCA enhances the insulation properties of blended cements Application of CCA blended cements could enhance thermal comfort of building occupants and save cooling and promote energy conservation.
Olafusi <i>et al.</i> (2012)	To examine the strength characteristics of CCA based concrete	<ul style="list-style-type: none"> Physicomechanical properties of changing CCA percentage in cement concrete 72 concrete cubes of CCA to Portland cement ratio 0:100, 10:90, and 20:80 were examined. Physicomechanical properties tested after casting 35 MPa high strength concrete was designed using CCA for fractional substitution for cement A total of 32 concrete cubes (16 samples for 0% and 10% partial replacements) 8 concrete cylinders (4 samples each of 0% and 10% partial replacements). 	<ul style="list-style-type: none"> Replacement of cement with 10% CCA showed satisfactory performance without effects on compressive strength. The specific gravity of the CCA was 1.15, Ratios of concrete mix of 1:2:4 at 7 days did not meet the standard strength at 14, 21, and 28 days. Split tensile test showed concrete tensile strength is 11-12 times lower than its compressive strength. Use of CCA as a partial replacement for cement in concrete promotes waste to wealth innovation. CCA concrete takes a longer time to attain desired strength and requires a W/B ratio below 0.40.
Ettu <i>et al.</i> (2013)	To examine the strength of CCA based binary blended cement composites.	<ul style="list-style-type: none"> 105 concrete and sandcrete cubes used. Dimensions of cubes: 150×150×150 mm Percentage CCA for OPC replacement was 5-25% Samples were ground to attain compressive strengths Curing Age/Days 3, 7, 14, 21, 28, 50, and 90. 	<ul style="list-style-type: none"> Strength of OPC-CCA binary blended cement concrete was higher than the control at 90 days of curing, for 5-15% replacement. OPC-CCA binary blended cement sandcrete exhibited lower strength compared to the control at early ages up to 28 days. Strength increases significantly thereafter and becomes greater than the control after 50 days. OPC-CCA binary blended cement sandcrete has potential applications in civil engineering.

References	Objective of the Study	Parameters/ Reaction Conditions	Findings/Conclusions
Price <i>et al.</i> (2014)	To investigate the role of CCA on the mechanical properties (i.e., compressive strength and workability) and thermal performance of concrete	<ul style="list-style-type: none"> CCA served as the major blending agent with OPC. Screening tests to determine the suitable percentage of CCA for replacement of cement that complies with specific standards Compressive strength, workability and thermal performance CCA blended cements examined. 	<ul style="list-style-type: none"> 10% CCA replacement suitable for replacement of cement or concrete production Ratio can enhance the process with no impact on the structural integrity of OPC CCA addition to concrete mixtures enhanced compressive strength and workability 10% CCA substantially reduced the thermal conductivity of the concrete mixtures examined.
Suwanmanee chot <i>et al.</i> (2015)	To develop, characterize and improve the utilization potential of CCA as cement replacement materials or cementitious-based materials.	<ul style="list-style-type: none"> The effects of heat treatment on the chemical properties of CCA examined. CCA was calcined from 200 to 600 °C for 4 h Composition and physical properties XRF, XRD, SEM, and PSA (Particle Size Analysis) of the treated CCA were determined. Mechanical and engineering properties of the treated CCA were examined. CCA percentage used for replacement tests were 0-20% by weight (5% additions). Curing time 7, 14, 28, and 56 days. 	<ul style="list-style-type: none"> Results indicate CCA treated at 600 °C for 4 h has the highest fraction of $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 \sim 72\%$ CCA-600 is a Class N calcined natural pozzolan based on ASTM C618. XRD revealed a high content of amorphous silica phase, which was enhanced at increased calcination temperatures. Water requirement, as well as the initial and final setting times, increased with increasing CCA percentage. CCA-600 °C effectively enhanced the compressive and splitting tensile strengths of the concrete as compared to the control.
Kamau <i>et al.</i> (2016b)	To examine the feasibility of utilizing CCA as pozzolanic material in concrete	<ul style="list-style-type: none"> CCA percentages of 5, 7.5, 10, 15, and 20% examined as a replacement for cement. Mixes were determined by weight in concrete as required in the application. Results compared to the control (0% CCA or 100% OPC). Durability tests were performed through sulfate elongation by immersing specimens in 5% Na_2SO_4. 	<ul style="list-style-type: none"> The entire replacements attained significant compressive strengths appropriate for application in structures. Tests for sulfate elongation demonstrated CCA is applicable in destructive settings containing Na_2SO_4 which is an alkali-based activator. High repeatability highlighted the prospects of CCA for effective utilization as pozzolanic material in concrete.
Singh <i>et al.</i> (2018)	To investigate the impacts of high temperatures on CCA as a replacement for cement in concrete	<ul style="list-style-type: none"> The influence of high temperatures (150-600 °C, $\Delta 150$ °C) on mechanical properties such as compressive strength was examined. Cube samples characterized for 2 h duration in a muffle furnace. Grade M25 concrete and CCA percentages of 0%, 5-20% ($\Delta 5\%$) were used for replacing cement examined. Water/Binder (W/B) ratio was maintained at 0.45. 	<ul style="list-style-type: none"> Compressive strength of the concrete decreases with increasing CCA percentage at normal temperature. Trend reversed when the calcination temperature increased to 300 °C for the all mixes and the control. Optimum CCA percentage and calcination temperature for replacing cement in concrete is 10% and 300 °C, respectively.

References	Objective of the Study	Parameters/ Reaction Conditions	Findings/Conclusions
Memon <i>et al.</i> (2019)	To investigate the eco-friendly use of CCA as a partial replacement for sand in concrete.	<ul style="list-style-type: none"> CCA with percentages of 0, 5, 10, 15, and 20% was used as fine aggregate in eco-friendly concrete mixes. Characterization and pozzolan potential were done by physical, thermal, chemical, morphology, and microstructure analyses. Mechanical properties of CCA concrete and blends were examined <i>via</i> shrinkage, slump, compressive strength, and slump tests. Water absorption, ultrasonic pulse velocity, and density tests were also performed. Curing age of CCA concrete and blends; 7, 28, 56, and 90 days. 	<ul style="list-style-type: none"> CCA is amorphous, highly porous adequately graded, and devoid of organic contaminations. TGA thermal and chemical analyses revealed that CCA exhibits pozzolanic properties for potential application as a partial replacement in concrete. Morphology analysis revealed micropores, perforations, and tubules. Mechanical properties such as slump and shrinkage increased, whereas the density of fresh concrete declined with increasing CCA percentage. The increase in CCA percentage adversely impacted the compressive strength, ultrasonic pulse velocity, and density of the hardened concrete. Water absorption also decreased with the curing/testing age. Compressive strength of 10% CCA concrete was 22 MPa after curing age/ time of 28 days.
Bheel <i>et al.</i> (2020)	To investigate the impact of CCA and Glass Powder as binary cementitious materials (BCM) for applications in Concrete	<ul style="list-style-type: none"> Five mixtures were designed based on equal proportions of CCA and glass powder (GP) for application as BCM to replace the Portland cement (PC) 10-20% CCA and control (0BCM i.e., only PC) used as a binder. Water to Binder (W/B) ratio was kept constant at 0.50. Total of 75 samples comprising 30 cylinder-shaped and 45 cubes were made. Mechanical properties: slump values, compressive and split tensile strengths of the mixtures were examined. Curing age varied from 7 to 28 days. Sustainability analysis of embodied energy and carbon footprint of BCM mixtures were also examined. 	<ul style="list-style-type: none"> Integration of BCM decreased the slump value of concrete. 10% BCM observed as the optimum based on the enhancement of mechanical properties, namely compressive and split tensile strengths. BCM is considered a suitable alternative and sustainable material for reducing the embodied energy and carbon footprint of concrete mixtures. Compressive and split tensile strengths of blends with 10% BCM OPC replacement was enhanced by 8.4% and 4.9%, respectively. BCM utilization in concrete enhances sustainability. The blends of concrete with 5-20% BCM partial replacement for OPC have 4.3-16.8% lower embodied carbon control compared to non-BCM variants. BCM use in mixtures reduced concrete embodied energy by about 21%.

Synthesized CCA-blended cements were examined for compressive strength and workability, using slump and compacting factor tests. Findings indicated that higher CCA content negatively impacted the compacting factor and concrete slump, which revealed that the concrete composite became stiff (i.e., lower or reduced workability). However, the compressive strength of the CCA-blended cement concretes was significantly affected by curing age with improvements observed after 120 days. A separate study by (Adesanya *et al.*, 2010), examined the durability and permeability of CCA-blended cement concrete along with the susceptibility of the composites to acid attack. Results showed that the water absorption property of concrete decreased with the addition of CCA-blended cement. Nevertheless, the resistance to chemical attack was improved, particularly upon adding 15% CCA, although this was accompanied

by a simultaneous reduction in the permeability and reduction in weight loss. The lower permeability and weight loss was ascribed to the reaction of the specimens with the acids. Raheem *et al.* (2011) examined the thermal conductivity of CCA-blended cement-based mortar. Their data showed that the addition of CCA to concrete decreased the thermal conductivity of the blended cement composites, which indicates an increase in the insulation potential of the concrete. Various studies have demonstrated that the addition of pozzolanic materials to concrete composites lowered their thermal conductivity (Stefanidou *et al.*, 2010; Wongkeo *et al.*, 2012). This observation could be ascribed to their high silica content (Raheem *et al.*, 2011) and the high porosity of the concrete upon addition of CCA (Bessenouci *et al.*, 2011). Overall, the study by Raheem *et al.* (2011) concluded that adding

CCA-blended cements to concrete could potentially enhance the thermal comfort of building occupants, reduce energy costs, and potential emissions.

Olafusi *et al.* (2012) investigated the strength properties of CCA based concrete. Results of the study revealed that the increase of CCA percentage added as a partial replacement for cement lowered the compressive strength of the CCA based concrete composite. Authors also noted that as observed with pozzolans, the compressive strength and density increased the curing age. Similarly, Ettu *et al.* (2013) examined the strength of binary CCA-blended cement composites through empirical and mathematical modelling. Authors revealed that the comprehensive strength of CCA-based composites decreased in the first instance but increased with the curing age. Oluborode *et al.* (2015) investigated the strength of CCA blended with OPC through several mechanical tests (e.g., specific gravity, aggregate absorption, and particle size distribution) and chemical analysis. The addition of up to 30% CCA was beneficial to the concrete. Price *et al.* (2014) examined the effect of CCA on the mechanical properties (i.e., compressive strength and workability) and thermal performance of concrete. Results showed that the compressive strength and workability decreased with the addition of 10% CCA to concrete blends, whereas the insulation characteristics were improved.

Suwanmaneechot *et al.* (2015) examined the potential of CCA as supplementary materials for cement in concrete. The authors observed that the higher the composition of CCA used to replace cement, the higher the water requirement was. Original and final setting times were required for the concrete composites. Thermal treatments such as calcination of CCA significantly impacts the content of the pozzolanic oxide (SiO_2 , Al_2O_3 , Fe_2O_3 , and amorphous silica) and provides high specific surface area, which all enhance the suitable engineering properties of concrete. Similarly, Kamau *et al.* (2016b) investigated the pozzolanic potential of CCA for application in concrete. They found that replacing cement with fractions of OPC yielded composite blends with satisfactory compressive strengths that could be potentially applied in concrete structures. Tests for sulfate elongation revealed that CCA could also be advantageously applied in destructive settings that contain sodium sulphate. According to Donatello *et al.* (2013), Na_2SO_4 is a salt-based source of alkali used to activate pozzolanic materials with little impact on the hydration of cement clinker. The authors also demonstrated that the addition of sodium sulfate lowered the setting times, induction times, as well as enhanced the hydration and compressive strength.

Singh *et al.* (2018) examined the effect of temperature on the pozzolanic performance and mechanical properties of CCA in concrete. They reported that an

increase of CCA content in concrete lowered the compressive strength at normal temperatures; a reverse trend was observed at higher temperatures. This could be ascribed to the higher SiO_2 content, which is available to react with calcium oxide generated during cement hydration. Consequently, the compressive strength of the concrete produced with CCA was like the one observed in the literature (Suwanmaneechot *et al.*, 2015). Studies by Memon *et al.* (2018) and Memon *et al.* (2019) examined the eco-friendly use of CCA as fractional replacement of sand in cement-based concrete composites. Authors revealed that CCA contains numerous micropores, perforations, and tubules suitable for application as pozzolanic materials. Besides, the increase in the percentage of CCA in the composites resulted in higher shrinkage and slump values, whereas the ultrasonic pulse velocity, compressive strength, and density of the hardened concrete declined accordingly. Overall, the studies demonstrated that CCA is a useful raw material for the replacement of cement in concrete and an environmentally friendly approach for waste disposal and management. In a recent paper, Bheel *et al.* (2020) addressed the effects of CCA and glass powder, as binary cementitious material (BCM) for the fractional replacement of cement in concrete. Results indicated that CCA addition reduced the slump values of CCA blended concretes. Optimization showed that 10% BCM enhanced the compressive strength and the split tensile strength. Furthermore, the BCM used to replace OPC, even at 20%, did not negatively impact the mechanical properties of the concrete.

In general, most authors observed that with the increase in the demand and utilization of OPC, the sustainability of the building construction industry is critically at risk of exacerbating global warming and climate change. Hence, alternative materials are required to reduce sector-related greenhouse gas emissions.

5. Conclusions

Our paper presents an overview of the utilization of corn cobs ash (CCA) as cementitious and binary cementitious materials (BCM) in concrete. The basic theories, history, and background on the cultivation, processing, products, and waste streams derived from Corn (*Zea mays* L.) were described in the first part of the paper. Subsequently, the yield and distribution of solid lignocellulosic wastes, such as corn cobs (CC), were highlighted.

Our literature review indicates that the effective disposal, management, and valorization of CC remains a major challenge, considering the residue to crop ratio of corn. Current strategies for valorization include the manufacture of chemicals, fuels, livestock feeds, farmhouse beddings, and soil enhancers. Utilization of CC for the outlined processes and products is ascribed to

its high elemental, proximate, and heating value properties, such as carbon, volatile matter, fixed carbon, and ash. Although numerous reports have highlighted the problematic nature of the ash content in CC, its chemical composition indicates it as a possible valuable resource for potential utilization as cementitious or binary cementitious materials (BCM). Hence, numerous studies have critically examined the various processing technologies, operational conditions, and selected reactors for the valorization of CC in corn cob ash (CCA). CCA is suitable for being applied in the construction industry as a partial replacement for cement in concrete, mortar, or other cement-based composites. Before its application as a cement replacement material, CCA is subjected to extensive characterization to elucidate its particle size distribution, chemical, morphological, microstructure, and thermal properties. For analysis, a variety of instrumental methods are used, including X-ray fluorescence (XRF), X-ray diffraction (XRD), Scanning electron microscope (SEM), energy dispersive X-ray (EDX), thermogravimetric analysis (TGA), and others. Based on ASTM C618, potential pozzolanic materials are required to meet the condition; $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 = 70\%$, or greater. Our literature review indicates that CCA typically meets this requirement, which has prompted numerous utilizations of CCA as a replacement for cement. Addition of 10% CCA to concrete results in compressive strength values ranging from 18-22 MPa after curing age/time of 28 days. It is also observed that the partial replacement of cement with CCA decreases compressive strength, thermal conductivity ultrasonic pulse velocity, and density of the hardened concrete at normal temperatures. Nonetheless, the thermal treatment or calcination of CCA particularly at high temperatures from 300 to 600 °C along with higher curing age enhances compressive strength owing to the high availability of silica, extended surface area, and porosity. Overall, the findings indicate that CCA is a low cost, environmentally friendly, and sustainable material for effective application as a pozzolan. Hence, its partial replacement for cement or combination with other materials as BCM could address the twin challenges of greenhouse gas emissions and sustainability of the building construction industry through lower costs and decreased energy demand. Future studies could extend the knowledge on and applicability of CCA by examining its synergistic combination or blending with other waste streams, such as clinker, or spent bleaching earth. Future studies should examine the effect of other parameters, such as calcination temperature (above 600 °C), particle sizes, and moisture content.

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