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Potential of Agro-Industrial Wastes to Address Environmental Challenges - A Review

Anshul Nikhade[1]†, Devendra Padole[2], Sameer Algburi[3], Monali Wagh[4], Harshal Nikhade[4], Ahmed M. Abdulhadi[5], Hasan Sh. Majdi[6], Adel Hadi Al-Baghdadi[7] and Prajakta Waghe[8]
[1]Department of Civil Engineering, Karmaveer Dadasaheb Kannamwar College of Engineering, Nagpur, India
[2]Structural Consultant, Struct Design, Nagpur, India
[3]Al-Kitab University, Kirkuk 36015, Iraq
[4]Department of Civil Engineering, Yeshwantrao Chavan College of Engineering, Nagpur, India
[5]Al-Safwa University College, Kerbala, Iraq
[6]Department of Chemical Engineering and Petroleum Industries, College of Engineering, Al-Mustaqbal University, 51001 Hillah, Babylon, Iraq
[7]Al-Mustaqbal University, 51001 Hillah, Babylon, Iraq
[8]Department of Chemistry, Yeshwantrao Chavan College of Engineering, Nagpur, 441110, India
†Corresponding author: Anshul Nikhade; anshulnikhade1986@gmail.com

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ABSTRACT

The cement industry is one of the largest contributors to global carbon emissions, accounting for a significant share of industrial greenhouse gases. In response to this challenge, researchers have increasingly explored the use of agro-industrial waste as a sustainable alternative to conventional cement-based materials. This study reviews and assesses the environmental potential of such waste-derived construction products, focusing on their ability to reduce emissions and conserve natural resources. Findings indicate that substituting traditional cement with eco-friendly, waste-based materials could achieve up to a 32% reduction in greenhouse gas emissions, thereby offering a tangible pathway toward decarbonization of the construction sector. Beyond emission reduction, these materials also address critical issues of resource scarcity by valorizing agricultural and industrial by-products that would otherwise contribute to waste streams. The integration of these innovative materials into mainstream construction practices represents a unique opportunity to simultaneously mitigate climate change, promote circular economy principles, and advance the development of environmentally responsible infrastructure.

INTRODUCTION

Over the last three decades, global issues such as population explosion, rapid urbanization, industrialization, growing consumerism, and increasing energy needs have had an exponential impact on issues such as environmental pollution, depletion of reserved fossil fuels, energy security, and mounting solid waste generation, which require sustainable attention (Venkata et al. 2018). These issues have led to an increase in carbon footprints worldwide, resulting in significant variations in climate change. The emission of anthropogenic CO_2 into the environment is a major challenge worldwide. The generation of this hazardous CO_2 is mainly due to a) the combustion of biomass and fossil fuels and b) deforestation and other land-use changes. c) Cement industry. The cement industry is the third largest source of anthropogenic CO_2 emissions after fossil fuels and land-use changes (Andrew 2018).

Cement industries are currently under scrutiny because of the large amount of anthropogenic CO_2 they emit into the atmosphere. Cement production contributes approximately 5-7 % of the global loading of anthropogenic CO_2 into the atmosphere (Chen et al. 2010). In 2019, approximately 1.6 Gt of anthropogenic

CO_2 was emitted due to the decomposition of carbonates in the production of cement clinker, while 0.9 Gt of CO_2 was emitted from the combustion of fossil fuels to produce the heat required by the global cement industry (Jackson et al. 2018). In addition, cement production is a highly energy-consuming process. For the manufacture of cement clinker, approximately 4 GJ of energy and 0.85 tonnes of CO_2 are required, as well as 3.00 kg of NO_2, 1.5 kg of SO_2, and 0.23 kg of particulate matter are released into the atmosphere (SSEF 2013). Additionally, extracting large amounts of raw materials, such as limestone, not only consumes high energy but also results in land deforestation. It is complicated to determine the exact area of land destroyed for cement production because the issue is complex, and there is a lack of precise data that distinguishes cement manufacturing from other activities, such as land development or mining. However, based on the pattern of excavation limestone, which is the main raw material in cement manufacturing, can help determine the approximate area deforested for cement manufacturing. According to the World Resources Institute, the probable estimate of all mining activities, including cement production, destroys approximately 0.5–1 million hectares of forest annually worldwide (Stanimirova et al. 2024). In India, from 2018 to 2023, 18,847 hectares of forest land have been cleared for mining activities, including limestone extraction (Pandey et al. 2023). Furthermore, the extraction of virgin non-renewable materials by the cement industry emits hazardous solid waste into the environment (Mehta 2001).

In developing countries like India, an increasing population, growth in urbanization, and rapidly changing technologies boost the agriculture and industrialization sectors, resulting in India being the second fastest growing economy after China in 2019. However, this booming economy leaves millions of tons of solid waste derived from agriculture and industry, causing serious environmental pollution problems. The globe is currently dealing with a shortage of natural resources (Wagh et al. 2025, Waghe et al. 2023). According to Pappu et al. (2007), 960 million tons of solid waste are generated in India every year, contributing approximately 350 million tons (MT) of organic waste from the agriculture sector and 290 MT of inorganic waste from the industrial and mining sectors (Pappu et al. 2007).

It is urgent to a) reduce the emission of anthropogenic CO_2 from cement industries and b) consume the accumulated waste generated by different agricultural and industrial activities. Carbon dioxide (CO_2) emissions caused by

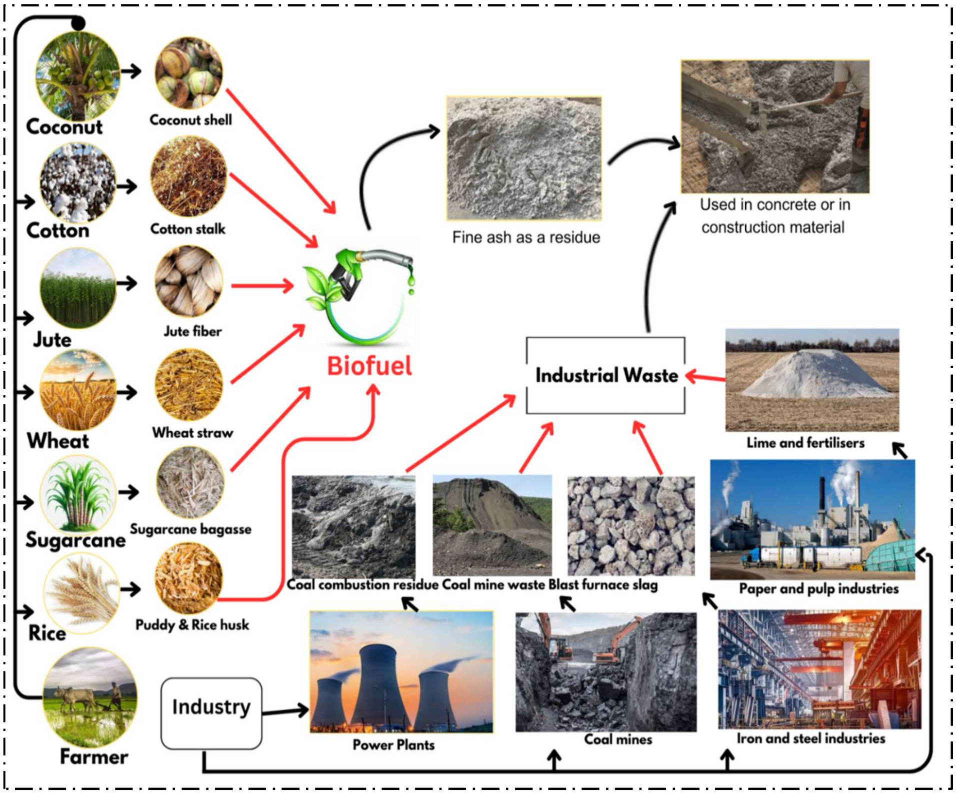

Fig. 1: Agricultural and industrial waste as supplementary cementitious materials.

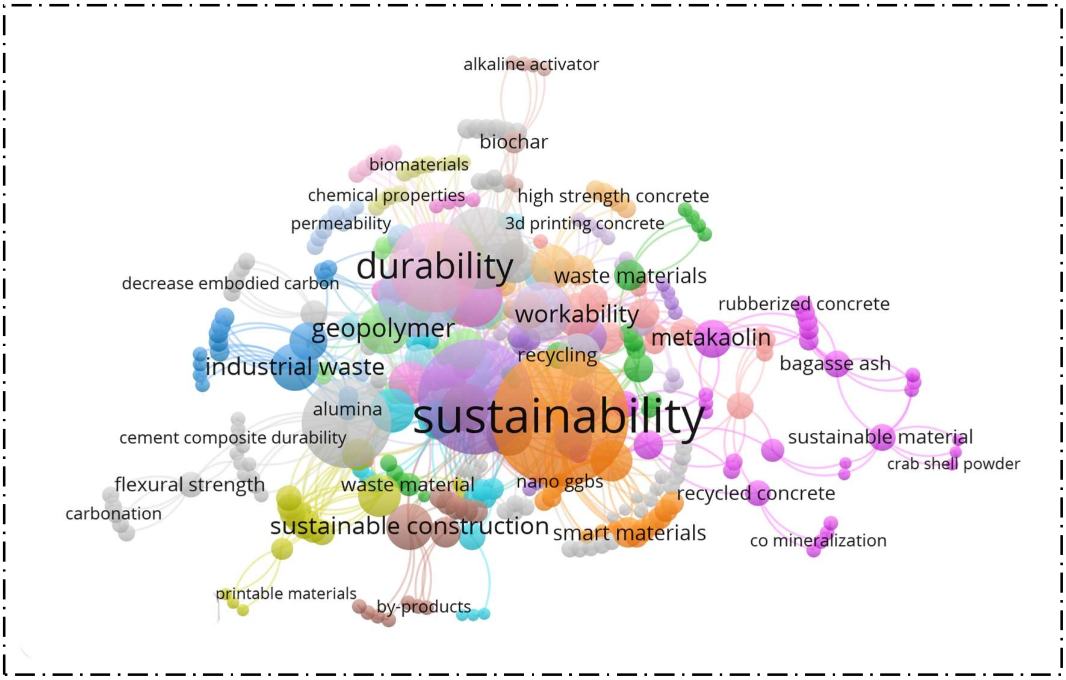

Fig. 2: Cluster network visualisation produced with study article keywords.

human activities are termed anthropogenic CO_2 emissions. Anthropogenic CO_2 emissions from the cement industry contribute approximately 7–8% of global CO_2 emissions, making it the largest contributor to greenhouse gas emissions. These emissions originate from the energy and chemical processes used in cement manufacturing (Zhang 2024). **Fig. 1** shows the various agricultural and industrial wastes used as supplementary cementitious materials. Efforts are being made to utilize these unwanted solid wastes as usable raw materials for various sustainable uses. Many researchers have successfully developed value-added products using these solid wastes. This helps resolve environmental and solid waste management problems and reduces dependency on crude non-renewable resources, which are dwindling day-by-day. This paper reviews studies that have been published to compensate for both issues and come together into novel, eco-friendly, sustainable construction products. Fig. 2 shows the cluster network visualisation produced with study article keywords.

CEMENT DEMAND

Global Cement Demand

Cement has become an important commodity produced by more than 150 countries worldwide (Sharma 2017). Generally, the economic growth of a country is predicted by the growth of cement consumption in that country, and with the development of the economy, cement production and consumption increase every year. After 1990, global cement consumption accelerated drastically owing to the rapid development of China (Andrew 2018). The demand for cement in the top ten countries (China, India, the United States, Vietnam, Indonesia, Iran, Turkey, Russia, Brazil, and Egypt) was studied and graphically represented. It was observed that 65–70% of the global cement was produced in China. The compound annual growth rate (CAGR) of global cement demand increased by 5% from 2002 to 2019. The global cement demand in 2019 is almost two times greater than the demand in 2002 and four times greater than the demand in 1990 (Armstrong 2018). The demand for cement is forecasted to reach 18000 Mt by 2050 (Aprianti et al. 2015). Fig. 3 shows the worldwide cement demand. Fig. 4 displays the demand for cement by the top 10 countries. The demand for cement in 2019 in China, India, and the rest of the world is depicted in Fig. 5.

Cement Demand in India

India is the second largest cement producer in the world, after China (Bahurudeen et al. 2017, Balogun et al. 2016, Rajya Sabha 2011). The immense geographical size and population demand in India require more infrastructure and industrial development, pushing the production of cement more effectively every year. Hence, after agriculture, construction is the second largest industry in India (Kulkarni 2012). The

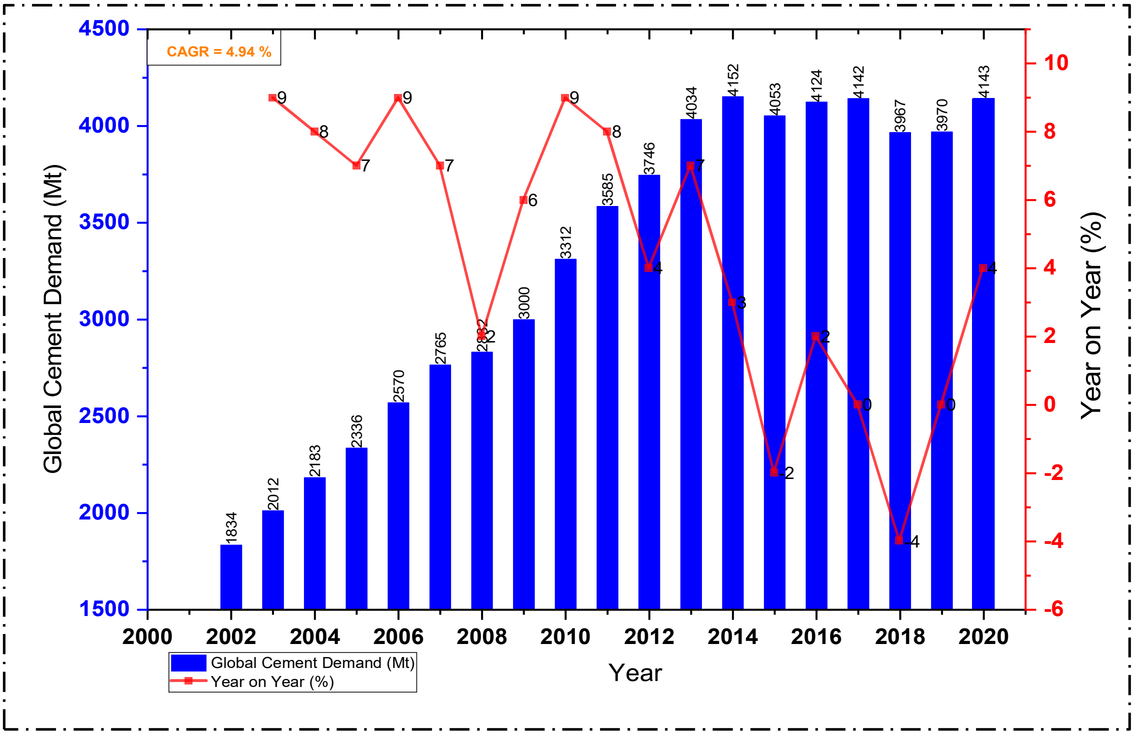

Fig. 3: Global Cement demand (Sharma 2017, Armstrong 2018, IBEF 2019, 2020, Hargreaves 2013).

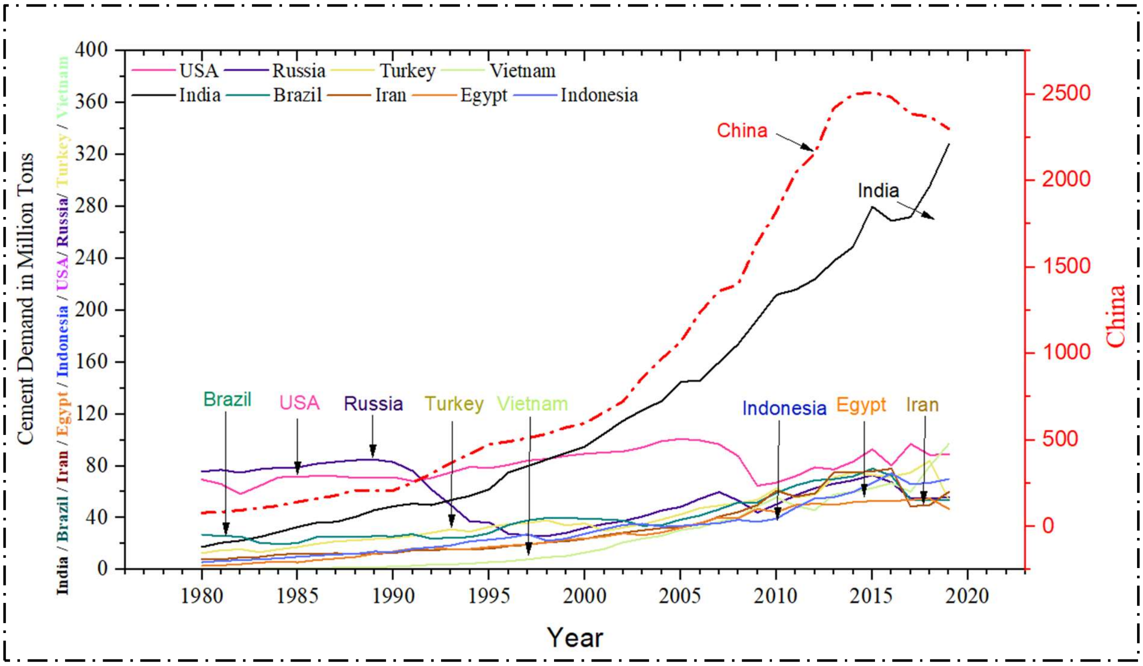

Fig. 4: Cement demand by top 10 Countries (Sharma 2017, Armstrong 2018, IBEF 2020, Hargreaves 2013).

demand for cement in India increased from 146 million tons to 375 million tons from the financial year 2006 to 2023, with a CGAR of 5.7 percent. It is forecasted that the demand will reach 400 million tons by 2025 and 700 million tons

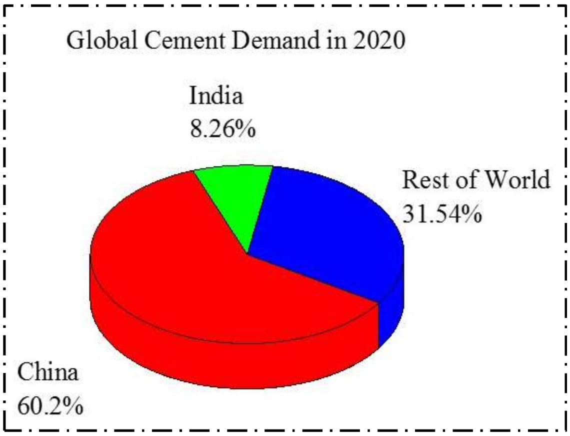

Fig. 5: Demand of cement by China, India and the rest of the world in the year 2019 (Sharma 2017, Armstrong 2018, IBEF 2020, Hargreaves 2013).

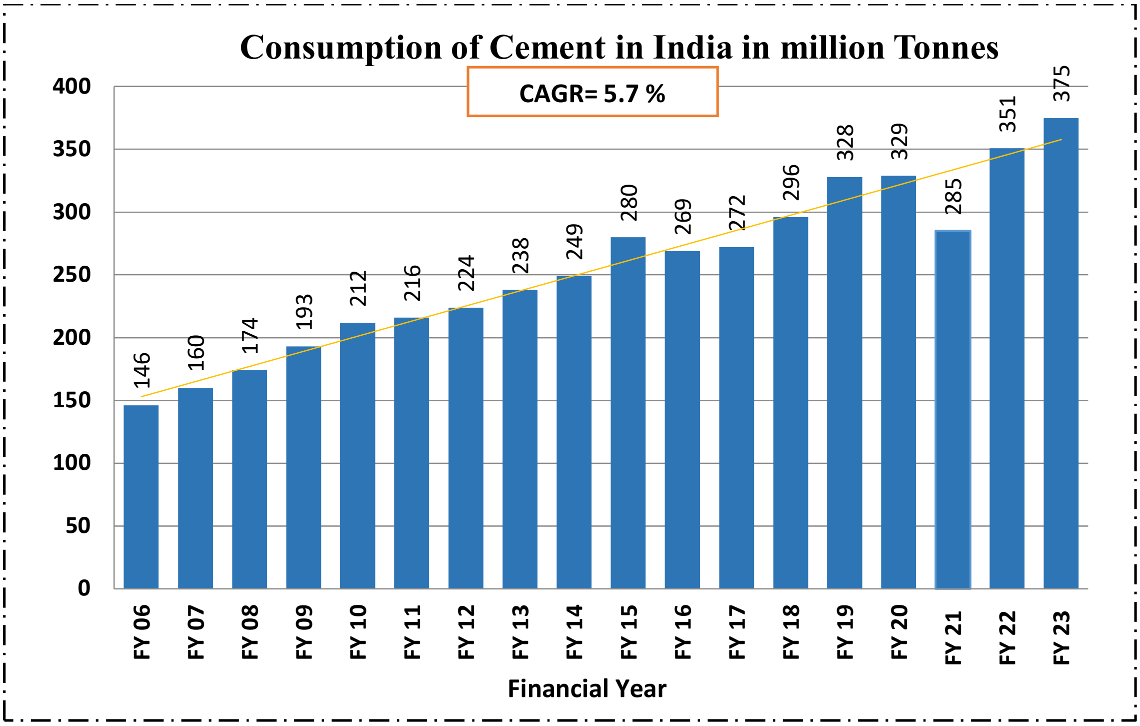

Fig. 6: Demand of Cement in India (Sharma 2017, Armstrong 2018, IBEF 2020, Hargreaves 2013).

by 2050. The current cement production capacity of India is approximately 500 million tons per annum, and it is predicted that it may increase to 50 million tons by 2025 to meet the domestic growth of the country (Armstrong 2012, IBEF 2019). The serious issue behind increasing consumption is the unrestricted growth of the population, the modernization of industrial development, and unrestricted consumption of natural resources, and secondly, due to a lack of awareness to adopt sustainable practices in the country. Fig. 6 illustrates the cement demand in India.

The cement industry is the third largest source of anthropogenic carbon dioxide emissions, after the oxidation of fossil fuels and deforestation (Andrew 2018). Cement production accounts for approximately 5–7% of the global anthropogenic CO_2 loading into the atmosphere (Chen et al. 2010). In 2019, approximately 2.5 Gt of anthropogenic CO_2 was emitted, of which 1.6 Gt was emitted due to the decomposition of carbonates during the production of cement clinker, while 0.9 Gt of CO_2 was emitted from the combustion of fossil fuels to produce the heat required (Jackson et al.

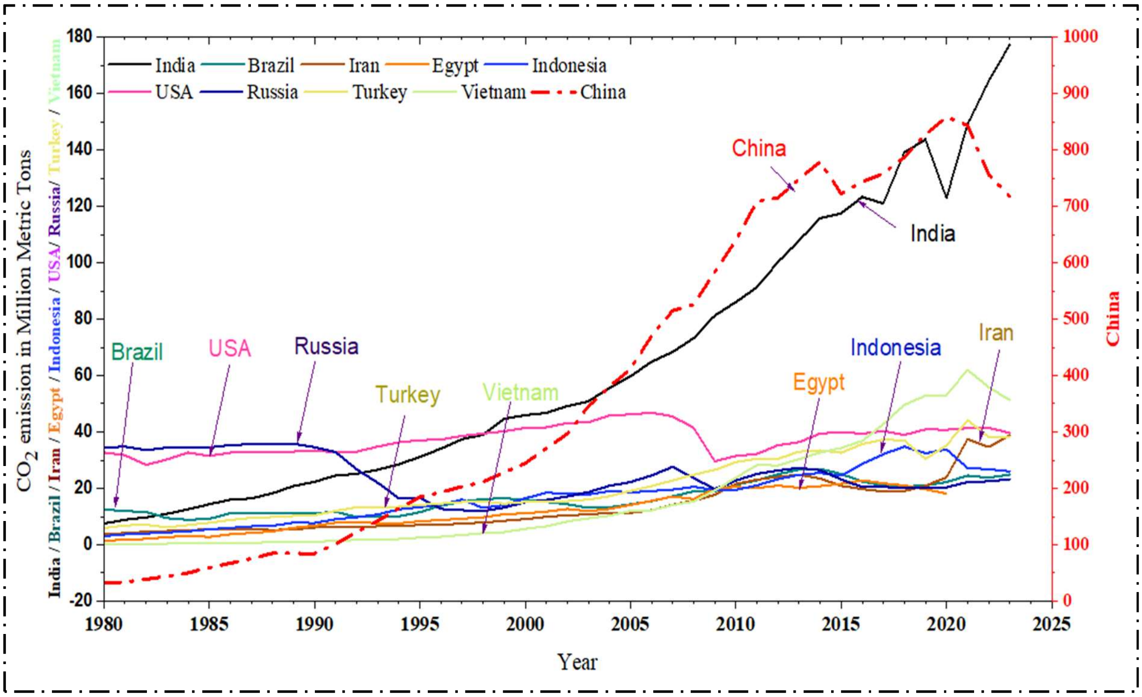

Fig. 7: CO_2 emission by cement industries by the top 10 Countries.

2018). The chemical reactions involved in the calcination of limestone or $CaCO_3$, which decomposes into oxides of calcium oxide and CO_2 at high temperatures, as well as the combustion of fossil fuels in the kiln to generate temperatures above 1000 °C, are primarily responsible for the emission of hazardous CO_2 into the environment. Besides these, CO_2 also evolved due to overall energy use in the extraction, transportation, and cementing of sites, electricity generation, etc. (Andrew 2018). Approximately 50–55 percent of CO_2 is released as a result of the limestone calcination process, 40–50% as a result of fossil fuel combustion, and 0–10% as a result of electrical energy consumption. In general, the production of 1 ton of cement emits 0.85 tons of CO_2 along with 3.00 kg of NO_2, 1.5 kg of SO_2, and 0.23 kg of particulate matter (SSEF 2013).

Moreover, cement production involves high-energy-consuming processes. As per Worrell et al. (2001), around 2% of global primary energy and nearly 5% of global industrial energy is consumed by the cement industry alone. The kiln process consumes the most energy, and the grinding process consumes the most electricity (Worrell et al. 2001). The anthropogenic CO_2 emitted by China's cement industry is almost 80 percent greater than that of the rest of the world. The steep slope lines in Fig. 7 represent the abrupt emissions of China and India, whereas the emissions of the remaining eight countries are very cautious. The reasons are obvious due to the exponential increase in production and consumption of cement in these two countries. Global CO_2 emissions are rising abruptly, and it is urgent to curb the emission of dangerous CO_2 into the atmosphere to maintain the integrity of the ecosystem.

Increasing CO_2 emissions endanger billions of people. The terrible impact of 10 °C on global warming is already being observed, leading to many disasters worldwide. It will be difficult to imagine a low-carbon world. Significant impacts of the rise in temperature are uninhabitable heat zones, sea-level rise, collapse of agriculture, mass extinctions, and extreme weather (Jha & Dev 2024). It is urgent to shift our vision to other sustainable alternatives to achieve greater carbon emission reduction and to help solve our global environmental crisis.

Several authors have assessed the environmental impact of the cement industry. Different studies have identified different methods to control carbon emissions, including a) the use of low-carbon-emission fuel, b) improvement of energy efficiency, c) carbon capture and storage, and d) identification of alternate cementation blends (Salas et al. 2016). This study explores the development of sustainable construction products using alternative cementation blends derived from agricultural and industrial rejects (Waghmare et al. 2025) and assesses their potential against conventional construction products. The most effective method for reducing energy consumption in buildings is to employ thermal insulation (Saleh et al. 2021). Artificial aggregates produced with sodium hydroxide with a molarity of 6.3 and sodium silicate with a molarity of 2.2 performed extremely well in aggregate tests examining specific gravity, water absorption, impact resistance, and abrasion (Kurzekar et al. 2024). The mechanical properties of rubberized concrete have been found to be equivalent to those of conventional concrete (Agrawal et al. 2025). The advantage of partially replacing expanded polystyrene separators and barriers (EPS) with fine aggregates in concrete is that it can contribute to pollution management (Khurge et al. 2025). By minimizing the dependency on natural aggregates and reducing adverse environmental impacts, incorporating refractory brick sand into concrete blends could serve as a potential option to promote sustainable building methods and protect human health and the environment (Kumar et al. 2025).

UTILIZATION OF AGRICULTURAL AND INDUSTRIAL WASTES AS AN ALTERNATIVE TO CEMENTITIOUS MATERIALS

In emerging countries such as India, rising urbanization, population expansion, and rapidly changing technologies boost the agricultural and industrial sectors, resulting in India being the second most rapidly expanding economy after China in 2019. However, uplifting the nation's economy leaves millions of tons of solid waste derived from agriculture and industrial waste, causing serious problems related to environmental pollution. Approximately 960 MT.y^{-1} of solid waste is generated in India, contributing around 350 MT/year of organic waste from the agriculture sector and 290 MT.y^{-1} of inorganic waste from the industrial and mining sectors (Pappu et al. 2007).

Agricultural Waste

In India, approximately 200 million hectares of land are used for agriculture (Venkata et al. 2018). Major crops such as rice, sugarcane, wheat, tea, jute, groundnut, cotton, and coconut generate agricultural waste such as paddy and rice husk, sugarcane bagasse, wheat straw, jute fiber, cotton stalk, coconut shell, and vegetable waste. The approximate annual generation of these wates are rice husk 22MT (Sen et al. 2024), sugarcane bagasse 27.2MT (Nikhade et al. 2025), wheat straw 145.44 MT (Sen et al. 2024), Jute stalk 3MT (Martin et al. 2024), Groundnut shell 0.11 MT (Sarkar et al. 2023), Cotton stalk 29.4 MT (Manna et al. 2024), Coconut husk 2.2 MT (Sarkar et al. 2023).This waste is used in the form of fodder and firewood called biofuel, which is utilized to generate electricity and other industrial thermal activities, leaving a significant amount of fine ash as a residue (Bisht & Ahmed 2017, Madurwar. et al. 2013, Wagh & Waghe 2022). Agricultural byproducts are produced in considerable quantities in India (Wagh & Waghe 2022, 2024). Approximately 4.5 billion tons of solid waste per year is generated in Asia alone, and 600 MT per year is generated by agriculture alone.

Industrial and Mining Waste

India generates approximately 290 MT.y^{-1} of industrial non-hazardous inorganic solid waste (Pappu et al. 2007). Thermal power plants generating coal combustion residues (CCR) are the leading generators of industrial solid waste, followed by coal mine waste derived from coal mines, blast furnace slag derived from iron and steel industries, and lime and fertilizers derived from paper and pulp industries(CPHEEO 2000). The solid waste generated by non-ferrous industries, such as red mud and spent spot lining from aluminium industries, slag, dross, sludge, slime, mill scales, flue dust, and so on from copper industries, leach residue, zinck tailing, -cake, jarosite residue, and so on from zinc industries, and ISF slag, BF slag, and so on from lead industries(Agrawal et al. 2004). The compressive strength of concrete improved with the incorporation of silica nanoparticles but decreased with the addition of polystyrene granules (Saleh et al. 2023). The Imperial Smelting Furnace (ISF) process, which simultaneously extracts zinc and lead from their combined ores, produces ISF slag, a non-metallic byproduct. It may contain small quantities of heavy metals, such as zinc, lead, cadmium, and arsenic, however, its primary components are silicates and oxides produced from gangue minerals and fluxes (Łaźniewska-Piekarczyk et al. 2024).

Availability of Different Agricultural and Industrial Waste

Details of the sources and availability of different agricultural and industrial solid waste generated in India are summarized in Table 1 below.

Physical and Chemical Characteristics Of Agricultural and Industrial Solid Waste

To utilize industrial and agricultural solid waste materials as raw materials at different levels for developing sustainable construction products, the chemical composition of waste has been identified by many authors. Tables 2–4 present a comparative analysis of the chemical properties of various agricultural and industrial solid wastes.

Tables 2, 3, and 4 show that the solid wastes derived from various agricultural and industrial processes are rich in oxides and have the potential to be used as pozzolanic materials for the production of construction products. Simultaneously, the fine particle size of this solid waste also acts as a micro-filler material, which helps to improve the strength of the product (Razak & Wong 2005, Chusilp et al. 2009).

Table 1: Solid Waste generation in India.

Sr. No	Solid waste	Source of Generation	Quantity (Million Tones per Annum)	Source / Author
a) Agriculture solid waste				
01	Bagasse Ash (BA)	Produced from the sugar industries	90	(Pappu et al. 2007)
02	Rice hull Ash (Rise Husk Ash)	By-product of rice production during milling	20	(Pappu et al. 2007)
03	Jute Caddies (Jute Fiber waste)	Obtained from Jute Industry	14.5	(Pappu et al. 2007)
04	Rice Wheat Straw	residues after wheat and barley grain	12	(Pappu et al. 2007)
05	Groundnut Shell	Leftover substance behind after groundnut seeds are extracted from their pods.	11	(Pappu et al. 2007)
b) Industrial waste				
01	Coal Combustion Residues (Fly ash)	Thermal power stations that use coal	176	(Surabhi 2017)
02	Cole Mine Waste	Coal Mines	60	(Pappu et al. 2007)
03	Lime stone wastes	Lime stone quarry’s	50	(CPHEEO 2000)
04	Steel and Blast furnace	Conversion iron to steel	35	(CPHEEO 2000)
05	Iron tailing	Iron Ore	18	(Das et al. 2000)
06	Construction Waste	Construction Sites	14.5	(Pappu et al. 2007)
07	Marble Dust	Marble Industries	6	(Pappu et al. 2007)
08	Waste Gypsum	Gypsum Industries	6	(Pappu et al. 2007)
09	Phosphogypsum	Phosphoric acid plants, Ammonium phosphate	4.5	(CPHEEO 2000)
10	Red mud/ Bauxite tailing	extracting alumina from bauxite	4.71	(Patel & Pal 2015)
11	Lime Sludge	Obtained from fertilizer Industry	4	(Pappu et al. 2007)
12	Zinc Tailing	Waste obtained from mines	3	(Pappu et al. 2007)
13	Kiln dust	Cement plants	1.6	(CPHEEO 2000)
14	Brine mud	Caustic soda industries	0.02	(CPHEEO 2000)
15	Copper slag	byproduct of copper smelting	0.0164	(CPHEEO 2000)
16	Mica scraper waste	Mica mining areas	0.005	(CPHEEO 2000)
17	Alum Sludge	By-product of water treatment plants	0.08	(Owaid et al. 2018)

Table 2: Physical properties of agriculture solid waste.

Agricultural waste	Mean particle size mu -m	Specific gravity	Blaine fineness [$m^2.kg^{-1}$]	Source/Author
Bagasse Ash	66.9–107.9	1.9–2.4	--	(Aprianti et al. 2015)
Rise Husk Ash	5-70	2 – 2.2	350.0–376.8	(Aprianti et al. 2015, Bisht & Ahmed 2017)
Wheat Straw Ash	--	2.31	--	(Biricik et al. 1999)
Palm Oil Fuel Ash	10.5	1.9–2.4	493.0	(Aprianti et al. 2015)
Groundnut Shell	--	2.10	--	(Nwofor and Sule 2012)

UTILIZATION OF ALTERNATIVE CEMENTITIOUS BLEND FOR THE PRODUCTION OF SUSTAINABLE CONSTRUCTION MATERIALS

In the current situation of a degrading global environment and declining non-renewable resources, waste is one product that cannot be eliminated (Venkata et al. 2018). The residue generated during agricultural activities and industrial cogeneration processes appears to be a sustainable resource (Urade et al. 2024), addressing not only the pollution problem but also an economical option for developing green concrete. Green concrete is a sustainable alternative to conventional concrete, designed to reduce the negative environmental impact and carbon footprint of construction materials. It

Table 3: Chemical properties of agriculture solid waste.

Constitutions in %	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	SO_3	Na_2O	LOI	Source
Bagasse Ash	51.66-86.79	1.03-20.69	0.9-10.08	1-18.9	0.07-8.65	1.2-9.28	0.02-4.45	0.01-1.23	5.7-24.15	(Nwofor and Sule 201, James & Pandian 2017, Bisht & Ahmed 2017, Aprianti et al. 2015) (Madurwar et al. 2014, Bahurudeen et al. 2015, Rukzon & Chindaprasirt 2012, Rattanashotinunt et al. 2013, Onyelowe 2012, Rajasekar et al. 2018, Bahurudeen & Santhanam 2015, Zareei et al. 2018, Rukzon & Chindaprasirt 2014, S. Demis et al. 2014, Katare and Madurwar 2017, Prusty et al. 2016, Wagh & Waghe 2024)
Rise Husk Ash	80.7-95.9	0.22-1.6	0.2-1.5	0.39-5.5	0.01-1.32	0.54-3.9	0.35-1.2	0.2-1.2	0.54-10.39	(Bisht & Ahmed 2017, Aprianti et al. 2015, Zareei et al. 2017, Rukzon & Chindaprasirt 2014)
Wheat Straw Ash	19-20.6	4.31-6.14	2.4-3.72	62.9-63.65	1.29-18	0.82	2.55-3.24	0.14	1.42-3.1	(Biricik et al. 1999, Jankovsky 2017)
Palm Oil Fuel Ash	55.5-66.9	1.6-9.2	1.4-5.7	4.9-12.4	3-4.5	5-7.5	0.2-0.5	0.1-0.8	6.6-10.1	(Aprianti et al. 2015, Demis et al. 2014, Sata et al. 2004)
Groundnut Shell	16.21-33.36	5.82-6.73	0.5-2.16	8.69-10.91	4.72-6.74	15.73-20.02	1.86-6.4	1.15-9.02	22	(Oriola 2010, Duc et al. 2019, Mahmoud 2012)

Table 4: Chemical properties of industrial solid waste.

Constitutions in %	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	SO_3	Na_2O	LOI	Source
Coal Combustion Residues/Fly ash	50.5-59.26	23.83-30.2	4-13.77	1.1-4.7	0.38-1.77	0.6-1.35	0.22-1.29	0.1-2.22	0.6-5.9	(Nath & Sarker 2011, Kumar 2003, Dana et al. 2005, Zhao et al. 2014, Sharma & Khan 2017)
Lime Stone waste	0.26-8.97	0.25-1.02	0.3-0.37	34.95-56.19	2.38-14.44	0.13-0.4	0.33-0.67	0.02-0.1	39.54-42.65	(Omar et al. 2012, Sua-iam & Makul 2013, Algin & Turgut 2008)
Blast Furnace Slag	35.35-41.2	14.3-19.15	0.6	32.7-36.56	2.99-7.33	0.9-1.29	--	0.81	0.21	(Dana et al. 2005, Bayer Ozturk & Eren Gultekin 2015)
Iron Tailing	52.06-68.96	7.68-17.14	2.32-25.13	0.03-12.74	0.08-3.68	0.04-1.85	0.16	0.04-1.41	2.49-6.67	(Kuranchie et al. 2015, Zhao et al. 2014, Wang et al. 2016h)
Marble Dust	1.12-14.08	0.73-2.69	0.05-3.66	29.5-83.22	0.52-20.6	0.01-1.9	0.56	0.91-1.12	40.6-43.46	(Omar et al. 2012, Aliabdo et al. 2014)
Red Mud	4-16	15-26	25.6-62.78	0.23-14.6	--	--	--	3-9	10-15	(Agrawal et al. 2004, Patel & Pal 2015.)
Copper Slag	24.7-40.97	2.4-15.6	34.62-57.82	0.7-17.42	1-3.51	0.71	1.59	0.3-0.34	< 1	(Sharma & Khan 2017, Marghussian & Maghsoodipoor 1999)
Lime Sludge	2-25	0.8-8	0.5-6	35-70	0.1-10	--	0.2-9	0.8-2	20-50	(Sahu & Gayathri 2014, Prasanth et al. 2019)
Phosphogypsum	2.41-14.74	0.5-0.88	0.5-0.32	26.76-41	0.1-0.11	<0.22	36.97-44.67	0.13	18.9-21.06	(Lin. Yang et al. 2013, Değirmenci 2008)

uses sustainable techniques and supplies that minimize waste, conserve resources, improve durability, and reduce CO_2 emissions. The development process of green concrete includes the selection of Supplementary Cementitious Materials, Recycled Aggregates, Alternative Binders, optimization of mix design, production, quality control, applications, and performance monitoring (Sivakrishna et al. 2020).

Waste valorisation by enabling advanced technologies is one of the best alternatives for utilizing renewable resources without impacting the environment (Venkata et al. 2018). Waste valorisation is the process of converting resources from waste into more valuable products, such as chemicals, energy, or materials, rather than simply discarding them. It is a fundamental concept in sustainable waste management and the circular economy (Varjani et al. 2021). Fortunately, this resource has beneficial properties that boost the pozzolanic reaction. Several researchers worldwide are engaged in obtaining fruitful and optimum consumption of wasteful materials from industries and agriculture to develop sustainable products. Waste but rich in silica, alumina, calcium oxide, and ferrous such as fly ash, bagasse ash, steel and lime stone sludge, blast furnace slag, groundnut shell, etc., have been proven as cementation blends for making various construction materials such as ordinary and high strength concrete (Bahurudeen et al. 2015, Duc et al. 2019, Chowdhury et al. 2015, Vejmelková et al. 2010, Madurwar et al. 2015), paper mill residue(Raut et al. 2013) thermal insulating materials (Madurwar. et al. 2013), ceiling panels, particle boards or cement boards (Madurwar. et al. 2013, Garg & Jain 2010), flooring and wall tiles (Oriola 2010, Bayer Ozturk & Eren Gultekin 2015) etc, depending on their physical and chemical properties, these various solid wastes from various sources and generated at various temperatures either act as cementation blends (Rukzon & Chindaprasirt 2014) or as micro fillers (Pappu et al. 2007, Razak & Wong 2005) (Chusilp et al. 2009). Fly Ash, Ground Granulated Blast Furnace Slag, Silica Fume, RHA, Metakaolin are used as SCM, while Marble Dust, Stone Quarry Dust, Waste Glass Powder are used as micro filler in cementitious blend (Bheel et al. 2024)

In addition to virgin waste, chemically (Sada et al. 2013), mechanically, or thermally (Rajasekar et al. 2018) treated waste can also be proven to be effective as a cementation blend to develop sustainable construction products. This established cementitious blend offers unique advantages in coping with the current environmental challenges. The implementation of sustainable construction practices can promote the circular economy model by transforming waste into valuable material and supporting revenue generation (Das et al. 2025).

CONSTRUCTION PRODUCTS

Ordinary and High-Strength Concrete

Concrete is the product that uses the maximum percentage of cement with respect to other construction products, and it has become an essential construction material. With the increasing demand for concrete, the production and consumption of cement are also increasing exponentially. Furthermore, compared to ordinary concrete, the demand for high-strength or ultra-high-strength concrete is increasing to meet various construction challenges or requirements, such as long-span structures, tall structures, and the use of pre- and post-tension technology, resulting in increased cement consumption

Ordinary Concrete

Bahurudeen et al. (2015) produced blended concrete using different percentages of SBA. The compressive strength, durability, heat of hydration, and drying shrinkage of the blended concrete were examined. The compressive strengths of blended concrete with 5, 10, 15, 20, and 25% SBA replacement were investigated at 3, 28, and 56 days of curing. The resulting compressive strength was superior to that of the control concrete up to a 20% replacement. A marginal decline was observed for 25% replacement after 28 days of curing. The durability of the blended concrete was investigated using the rapid chloride penetration, oxygen permeability, chloride conductivity, DIN water permeability, water sorptivity, and Torrent air permeability tests. A significant reduction in permeability was observed. The heat of hydration was assessed using an adiabatic calorimeter for 10 and 20% SBA replaced blended concrete and compared with where a marginal reduction of 20% was observed in heat of hydration for control concrete. A marginal reduction in the heat of hydration was observed with 20% replacement (Bahurudeen et al. 2015). Cement (OPC) was replaced with groundnut shell ash (GSA) to produce concrete. The principal materials were cement partially replaced with groundnut shell ash (GSA), varying from 0 to 40%. The compressive strength of GSA blended concrete was analyzed, resulted 29% strength for 40 % replacement and 70 % for 10 % replacement as compared with the control mix at 28 days of curing. Therefore, it is suggested that OPC be replaced with GSA up to 10% for sustainable construction and adequate strength work (Duc et al. 2019). Chowdhury et al. (2015) investigated wood ash (WA)-blended concrete and used soft computing models to predict the strength parameters. The physical analysis of WA revealed finer particle sizes. WA was characterized using XRD, which revealed that WA contained amorphous silica. In this study, the authors evaluated the strength parameters of blended concrete prepared with WA blended cement in the form of strength properties. Test specimens were prepared using five different percentages of WA (5%, 10%, 15%, 18%, and 20%) with two different water-to-binder ratios, 0.4 and 0.45, were used for investigation and compared with control concrete specimens. The results indicate that the strength slightly decreases with an increase in the percentage of WA compared to the control concrete. However, the strength obtained was greater than the target strength (Chowdhury et al. 2015).

High Strength Concrete

Sumrerng Rukzon et al (2014) investigated high-strength concrete using a binary or ternary blend of Portland cement with pozzolans. In this study, Portland cement was partially replaced with fly ash (FA) and ground bagasse ash (BA) or ground rice husk-bark ash (RB) at 20% and 40% by weight. The chemical compositions of FA, BA, and RB were analyzed using XRF. Portland cement was replaced with either a single material or an equally weighted mixture of RB and FA, and BA and FA were employed. Ten different concrete mix proportions were prepared using a superplasticizer (SP) to ensure high workability. The compressive strength, modulus of elasticity of concrete, porosity, corrosion resistance, and chloride penetration were determined. Compressive strength tests were performed on cylindrical specimens at 7, 28, and 90 d. The results showed that the early strength development of blended concrete was slightly less than that of the control concrete, but the strengths of 40-FA, 40-RB, and 40-BA concrete evolved continually. at later stages. It is observed that, the strengths of 20-FA, 20-RB, and 20-BA concretes were superior to the control concrete. The Rapid Chloride Penetration Test (RCPT) was performed on samples, and the results showed that partial replacement of cement with an equally weighted blended portion of FA and RB or FA and BA significantly improved concrete resistance to chloride penetration, and this improvement increased as the blend replacement level increased. The resistances of corrosion of equal-weighted ternary blended concrete resulted ternary blended concrete were better than the control concrete or concrete with one pozzolan. (Rukzon and Chindaprasirt 2014). High-strength concrete was developed using a combination of Metakaolin, RHA & Sugarcane bagasse ash (SBA), and the performance of concrete in an acidic environment was better than that of the control mix concrete (Nikhade & Nag 2022, Nikhade & Pammar 2022). Lightweight geomaterials have been developed using SBA, glass fiber, and blast furnace slag (Nikhade & Lal 2021, 2022, Nikhade et al. 2023, 2024). In the development of self-compacting concrete, SBA and Metakaolin perform effectively together as a 15% cement replacement (Wagh et al. 2024).

Nath et al. (2011) developed a high-strength blended concrete using high-volume Class F fly ash. Six mixes with 30% and 40% replacement of cement with fly ash (FA) were used to prepare the test specimens. A naphthalene-based superplasticizer was used to enhance workability. The compressive strength, drying shrinkage, sorptivity, and chloride permeability were measured in the blended and control concrete specimens. Cylindrical specimens of size 100x200mm for each replacement were tested at 3, 7, 28, 56, 91, and 210 days. It was observed that the early age strength decreased with an increase in the percentage of fly ash compared to the control concrete. However, blended concrete gains greater strength at later stages. The 30% FA blended concrete showed better compressive strength than the 40% FA blended concrete. The drying shrinkage of blended concrete was observed to result in less than that of the control concrete. The concrete blended with 40% FA exhibited a slightly lower drying shrinkage effect than that blended with 30% FA. In addition, blended concrete showed less sorption than the control mix, and it decreased further at six months. Blended concrete demonstrated superior resistance to chloride ion penetration at both 28 and 180 d. (Nath & Sarker 2011).

Gritsada Sua-iam et al. (2013) have produced self-compacting concrete (SSC) by employing increasing use of BA and limestone powder waste (LS) as a partial or complete replacement of fine aggregate. The mineralogical compositions of cement (OPC), BA, and LS were identified using XRD and SEM. Nineteen batch formulations containing OPC, coarse aggregates, and river sand as fine aggregates were replaced with BA and LS in volumes of 0, 10, 20, 40, 60, 80, and 100%. With the help of a water-reducing agent, the mixes were intended for a sump flow diameter of 70 + 2.5 cm. The physicomechanical properties of the developed self-compacting concrete were observed to result in 20% BA and 20% LS, which showed improved properties compared to the control SSC and achieved all the requirements as per recommendations (Sua-iam and Makul 2013).

Bricks

Madurwar et al. (2014) developed BA bricks using three principal raw materials: BA, quarry dust (QD), and lime (L). SBA was characterized using XRF, XRD, and particle size distribution, TGA and SEM techniques revealed rough surfaces with fine pores. The proportions of SBA and QD were varied from 80% to 50% and 0% to 30%, respectively, with a constant lime content of 20%. Twenty brick samples of each combination, with dimensions of 23 × 11 × 8 cm3, were prepared and dried for 3 d, followed by wet curing and sun-drying for 7 d each. Physicomechanical, functional, durability, and environmental tests were performed on the brick samples. The optimum combination of 50% SCBA, 30% QD, and L 20% resulted in 19.70% water content with a compressive strength of 6.59 MPa. Moreover, the developed brick is 40% lighter, exhibits lower thermal conductivity (k), and consumes 60% less energy than locally available conventional bricks. The authors concluded that lightweight, energy-efficient bricks are viable for solving environmental and solid waste management problems effectively and satisfying local construction demand (Raut et al. 2013).

Raut et al. (2013) investigated lightweight bricks using (10–20% ordinary Portland cement (OPC) + (10–20%) rice-husk ash (RHA) + (70–80%) recycled paper mill residue (RPMR). PRMR and RHA were characterized using XRD, XRF, SEM, and TG-DTA. Thermogravimetric Analysis-Differential Thermal Analysis is commonly referred to as TG-DTA. This method for combined thermal analysis investigates how a material changes both physically and chemically when heated, cooled, or maintained at a constant temperature. TG-DTA has been applied in the characterization of cement, ceramics, and polymers(Hosseinian et al. 2022).

The silica content in RHA and RPMR contributed to the pozzolanic reaction and acted as a cementitious material. The results showed that bricks made from cement, RHA, and RPMR were 50% lighter than conventional bricks and had compressive strengths ranging from 15–11 MPa, which is five times higher than conventional clay bricks (Chowdhury et al. 2015).

Hegazy et al. (2012) investigated bricks (without clay) using water treatment plant sludge (WTP sludge) incorporated with rice husk ash (RHA) and silica fumes (SF) at proportions of 25% and 50% individually. Bricks of each combination were burnt at 900 °C, 1000°C, 1100°C and 1200°C. XRD was used to characterize the WTP sludge, RHA, and SF. The major chemical composition observed in all raw materials was silica, which provides good strength to bricks and is a good substitute for brick clay. The mix-proportion of 50% WTP sludge, 25% RHA, and 25 % SF stood for the optimum combination of bricks produced from lime sludge incorporated with RHA and SF (Hegazy et al. 2012).

Mortar

Rukzon et al. (2013) developed a mortar using three pozzolanic materials: FA, RB, and ground BA, followed by OPC blended with single or double pozzolons in different percentages. Eleven different combinations of the principal materials, FA (10, 20, or 40%) + RB (10, 20, or 40%) + BA (10, 20, or 40%), were prepared. The physical and chemical properties of the pozzolans were determined. Compressive strength and porosity tests were performed for 7, 28, and 90 days, and RCPT and Accelerated corrosion tests were performed for 28 days. The test results showed that employing ternary blends of CT, FA, and RB or BA outperformed the binary blended mortar in terms of porosity. The RCPT of the mortar increased significantly with the partial replacement of CT+FA, CT+RB, and CT+BA. The application of ternary blends of CT, FA, and RB/BA generated mortars with good strength and resistance to chloride penetration (Rukzon & Chindaprasirt 2013).

Chindaprasirt et al. (2013) investigated the RCPT of blended cement (OPC) containing palm oil fuel ash (POA), ground RHA, and fine fly ash (FA). With the aid of a superplasticizer (SP), 10, 20, and 40% of OPC was replaced with single or double pozzolans, followed by a constant w/c ratio of 0.5. The compressive strength, RCPT, rapid migration test (RMT), and chloride penetration depth were measured after the mortars were immersed in a 3% NaCl solution for 30 days. Mortars containing equivalent amounts of POA+ FA or RHA+ FA exhibited good strength and resistance to chlorine penetration. It also requires less superplasticizer than standard OPC mortar.

Autoclaved Aerated Concrete

Chang-long Wang et al. (2015) developed autoclaved aerated concrete (ACC) using waste coal gangue (CGC) and iron ore tailings (ITOs). Waste Coal Gangue (CGC) is a solid waste generated during the mining and washing of coal, whereas the byproducts that remain after iron is extracted from ore during beneficiation are known as iron ore tailings (Jahandari et al. 2023). Seventeen different combinations of principal materials (CGC, ITOs, lime, cement, and gypsum) were prepared, followed by the addition of 0.06% aluminum powder and 60% water. The composition and morphology of the AAC were analyzed using differential scanning calorimetry, thermogravimetric analysis, XRD, and SEM. AAC, or autoclaved aerated concrete, is a lightweight precast construction material composed of cement, lime, silica, water, and aluminum powder. The morphology of AAC is characterized by a homogeneous distribution of air voids, a matrix of hydrated calcium silicate phases, fine crystalline and amorphous phases, and a low-density and porous structure (Kumar et al. 2022).

Test results showed that the bulk density and compressive strength of autoclaved aerated concrete samples were approximately 609 kg.m^{-3} and 3.68 MPa, respectively, which satisfied all the requirements as per recommendations. Many researchers have developed various environmentally friendly, sustainable, and energy-efficient construction products utilizing the optimum use of agricultural and industrial solid wastes, as summarized in Table 5.

As shown in Table 5, various authors have successfully replaced cement with agro-industrial rejects for the development of different sustainable construction products. After extensive research by different researchers, solid waste is now treated as a valuable feedstock and is believed to be a

Table 5: Average percentages of Agricultural and Industrial solid wastes used for the development of different construction products.

A	Studies on Production of High Strength Concrete or Ordinary Concrete Prepared by Replacing Cement with Agro-Industrial Rejects				
Sr. no	Solid waste used	Raw material and its proportions in the mix	Optimum Percentage of partial replacement of solid waste	Average	Reference
01	Fly ash	OPC + Fly ash (30- 40 %)+ Sand + granite with naphthalene-based superplastizer	Fly ash - 40%	Average Fly ash – 33%	(Nath & Sarker 2011)
02	Fly ash + SBA + RHA	Portland Cement + Fly ash / Bagasse Ash / Rice husk-bark ash (20 and 40%) + Fine and Coarse Aggregate + superplasticizer	Fly ash - 20%		(Rukzon & Chindaprasirt 2014)
03	Iron Ore tailings + Fly ash	Cement + Iron Ore Tailings (20-100%) + Fly ash (35 %) + Silica Fume (15%) + superplasticizer	Fly ash- 35%		(Zhao et al. 2014)
04	Fly ash + Copper Slag	OPC + Copper Slag (0-100%) + Fly ash (40%)	Fly ash – 40%		(Sharma & Khan 2017)
05	RHA	Cement +Micro silica (10%) + RHA (0-25%)+ sand+ Gravel + Plasticizer	RHA -25%	Average RHA- 20%	(Zareei et al. 2017)
06	Fly ash + SBA +RHA	Portland Cement + Fly ash / Bagasse Ash / Rice husk-bark ash (20 and 40%)+ Fine and Coarse Aggregate + superplasticizer	Rice husk-bark ash - 20%		(Rukzon & Chindaprasirt 2014)
07	RHA	OPC+ RHA(5 - 25%) + water reducing admixture	RHA - 15%		(Sathurshan et al. 2021)
08	RHA	OPC+ RHA(10- 20%) + superplasticizer	RHA - 15%		(Chopra et al. 2015)
09	SBA	OPC + SBA (10-30%) + Fine and Coarse Aggregate + superplasticizer	SBA- 30%	Average SBA - 21 %	(Rukzon & Chindaprasirt 2012)
10	SBA	OPC + Treated Bagasse ash + Silica fumes +quartz power +quartz sand+ steel fiber and superplasticizer	SBA- 15 %		(Rajasekar et al. 2018)
11	SBA + Lime stone waste	OPC + SBA + Lime stone waste + water reducing admixture	SBA- 20%		(Sua-iam & Makul 2013)
12	Fly ash + SBA +RHA	Portland Cement + Fly ash / Bagasse Ash / Rice husk-bark ash (20 and 40%)+ Fine and Coarse Aggregate + superplasticizer	Bagasse Ash - 20%		(Rukzon & Chindaprasirt 2014)
13	SBA	OPC + SBA + Fine and Coarse aggregate	SBA -25%		(Bahurudeen et al. 2015)
14	SBA	Cement + Sugarcane Bagasse (0-25 %) + Micro-silica(10%)	SBA -15%		(Rukzon & Chindaprasirt 2014)
15	Palm oil Fuel ash	Cement + Palm oil Fuel ash + sand + coarse aggregate+ Silica fumes + superplasticizer	Palm oil Fuel ash 20 %	Palm oil Fuel ash 20 %	(Sata et al. 2004)
16	Copper Slag + Fly ash	OPC + Copper Slag (0-100%) + Fly ash (40%)	Copper Slag - 20 co %	Copper Slag - 20 %	(Sharma and Khan 2017)
17	Limestone wastes	Cement + Lime stone wastes + Sand+ Aggregate + Super Plasticizer	Limestone wastes -20%	Average Lime stone wastes – 30%	(Kibriya & Tahir 2017)
18	SBA + Lime stone waste	OPC + SBA + limestone waste + water reducing admixture	Limestone waste-20%		(Sua-iam & Makul 2013)
19	Lime Stone waste + Marble powder	Cement + Lime stone waste (25, 50 and 75 %) + Marble powder (5, 10, 15%) + Superplasticizer	Lime Stone waste - 50%		(Omar et al. 2012)
20	Marble powder	Cement + Marble dust (0-15 %) +sand + coarse aggregate + Admixture	Marble powder -15%	Average Marble Powder -15%	(Aliabdo et al. 2014)
21	Marble powder + Lime Stone waste	Cement + Lime stone waste (25, 50 and 75 %) + Marble powder (5, 10, 15%) + Superplasticizer	Marble powder-15%		(Omar et al. 2012)
22	Construction Waste	Portland cements + Fly ash + Recycled Concrete Aggregate + Metacoline + superplasticizer	Construction Waste -20%	Construction Waste -20%	(Kubissa et al. 2017)
23	Groundnut Shell Ash	Cement + Fine and Coarse Aggregate + Groundnut shell (0-75%) +	Groundnut Shell Ash -75%	Average Groundnut Shell Ash -75%	(Sada et al. 2013)
24	Groundnut Shell Ash	Cement + Fine and Coarse Aggregate + Groundnut shell (0-40%) +	Groundnut Shell Ash -75%		(Duc et al. 2019)

Table Cont....

B	Studies on the production of BRICK prepared by replacing cement with agro-Industrial rejects				
Sr. no	Solid waste used	Raw material and its proportions in the mix	Optimum Percentage of partial replacement of solid waste	Average	Reference
01	Fly ash	Cement + fly ash, quarry dust and billet scale	fly ash = 50%	Average Fly ash- 60% ash- 60%	(Shakir et al. 2013)
02	Bottom Ash	Cement + Bottom Ash (70%-90% + lateritic clayey soil + sand	Bottom Ash – 70%		(Vinai et al. 2013)
03	SBA	SBA(90-50%) + quarry dust(0-40%) + Lime (10-30%)	SBA -50%	Average SBA – 50%	(Madurwar et al. 2015)
04	SBA	SBA (80 -50%)+ Quarry dust(0-30%) + Lime (20%)	SBA -50%		(Madurwar et al. 2013)
05	SBA	SBA (80 -50 %) + Quarry dust (0-30%) + Lime (20%) + OPC	SBA - 50%		(Madurwar. et al. 2013)
06	RHA	(10- 20%) OPC + (10- 20%) Rice - husk ash + (70- 80%) Recycle paper mill residue	RHA – 20%	RHA – 20%	(Raut et al. 2013)
07	Wood sawdust + limestone powder	OPC + Wood sawdust and limestone powder (10–30%)	Wood sawdust -30%	Wood sawdust -30%	(Turgut & Murat Algin 2007)
08	Limestone Powder Waste +Waste Glass Powder	OPC+ Limestone Powder Waste +Waste Glass Powder	Waste Glass Powder = 30%	Waste Glass Powder = 30%	(Turgut 2008)
09	Recycle paper mill waste	OPC + Recycle paper mills waste (80- 95%)	Recycle paper mills waste = 80%	Recycle paper mills waste = 80%	(Raut et al. 2012)

C	Studies on the production of MORTAR prepared by replacing cement with agro-Industrial rejects				
Sr. no	Solid waste used	Raw material and its proportions in the mix	Optimum Percentage of partial replacement of solid waste	Average	Reference
01	Fly ash + rice husk-bark ash	fly ash (10-20%)+ rice husk-bark ash (10-20%)	fly ash –20%	Average Fly ash – 21%	(Rukzon & Chindaprasirt 2013)
02	Fly ash + bagasse ash	fly ash (10-20%)+ rice husk-bagasse ash (10-20%)	fly ash –20%		(Rukzon & Chindaprasirt 2013)
03	Fly ash	OPC+ Fly ash (25%)	fly ash –25%		(Cho et al. 2019)
04	Fly ash	OPC+ Fly ash (10-20%)	fly ash –20%		(Hsu et al. 2018)
05	Palm oil fuel ash + ground RHA + fine fly ash	OPC + palm oil fuel ash (20 and 40%) + ground RHA (20 and 40%) + fine fly ash (20 and 40%)	fine fly ash -20%		(Chindaprasirt & Rukzon 2008)
06	Bagasse ash	Cement + SBA (5-30%)	Bagasse ash - 20%	Average Bagasse Ash = 23%	(Amin & Ali 2011)
07	Bagasse ash	Cement+ bagasse ash (10- 40%)	Bagasse ash - 30%		(Chusilp et al. 2009)
08	Fly ash + bagasse ash	Cement + fly ash (10-20%)+ rice husk-bagasse ash (10-20%)	bagasse ash - 20%		(Rukzon & Chindaprasirt 2013)
09	Fly ash + rice husk-bark ash	Cement +fly ash (10-20%)+ rice husk-bark ash (10-20%)	rice husk-bark ash –20%	Average RHA – 20%	(Rukzon & Chindaprasirt 2013)
10	Palm oil fuel ash + ground RHA + fine fly ash	OPC + palm oil fuel ash (20 and 40%) + ground RHA (20 and 40%) + fine fly ash (20 and 40%)	RHA -20%		(Chindaprasirt & Rukzon 2008)
11	Palm oil fuel ash + ground RHA + fine fly ash	OPC + palm oil fuel ash (20 and 40%) + ground RHA (20 and 40%) + fine fly ash (20 and 40%)	Palm oil fuel ash -20%	Palm oil fuel ash -20%	(Chindaprasirt et al. 2008)
12	Palm oil fuel ash	OPC + palm oil fuel ash (20 and 40%)	Palm oil fuel ash -20%		(Rukzon & Chindaprasirt 2009)

Table Cont....

D	Studies on the production of AUTOCLAVED AERATED CONCRETE prepared by replacing cement with agro-Industrial rejects				
Sr. no	Solid waste used	Raw material and its proportions in the mix	Optimum % of partial replacement of solid waste	Average	Reference
01	Iron Ore tailings + Coal gangue	Portland cement (10%)+ Iron ore tailing (20 -59 %) + Coal gangue (1-40 %) + Lime (25%) + Desulphurization gypsum (5%) + Aluminum powder (0.06%)	Iron Ore tailings - 40 %	Iron Ore Tailing - 40 %	(Wang et al. 2016)
02	Phosphogypsum + Blast furnace slag	Cement (15%) + Phosphogypsum (55%) + Blast furnace slag (0-35%) + Lime (3- 15%) + Na_2SO_4 (1.6%) + Aluminum powder (0.074%)	Phosphogypsum -55%	Phosphogypsum -55%	(Lin. Yang et al. 2013)
03	Iron Ore tailings + Coal gangue	Portland cement (10%)+ Iron ore tailing (20 -59 %) + Coal gangue (1-40 %) + Lime (25%) + Desulphurisation gypsum (5%) + Aluminum powder (0.06%)	Coal gangue - 20 %	Coal gangue - 20 %	(Wang et al. 2016)
04	Phosphogypsum + Blast furnace slag	Cement (15%) + Phosphogypsum (55%) + Blast furnace slag (0-35%) + Lime (3- 15%) + Na_2SO_4 (1.6%) + Aluminum powder (0.074%)	Blast furnace slag -30%	Blast furnace slag -30%	(Yang et al. 2013)

Fig. 8: CO_2 emissions by the cement industries of the top 10 countries.

Table 6: Average % of agro-industrial rejects used as a blended material.

Sr. No	Products	Average % of Waste used as a blended Material
01	High Strength and Ordinary Concrete	26.4%
02	Brick	45%
03	Mortar	21%
04	Autoclaved Aerated	36%
	Average	**32%**

supplementary cementation material to a great extent in the correct proportion. Due to its enormous stock and fruitful composition, it is being considered a potential resource for future sustainable models. The use of engineering tools for resource recovery is gaining attention in the quest for a sustainable world. Currently, India has the potential to digest a large quantity of generated waste to develop value-added sustainable construction products. These waste-derived products eloquently address the majority of sustainable goals (Venkata et al. 2018). The average optimum replacement of different agro-industrial rejects for the development of blended concrete, bricks, mortar, and Aerated Concrete is summarized and shown in Fig. 8.

The mathematical analysis of the data acquired from the referred papers indicates that a reasonable 32% of cement could be successfully replaced with different agro-industrial rejects for the production of various construction products, as shown in Table 6. Fig. 9 shows the schematic diagram representing the average % of Waste used as a blended material for the development of construction products.

Assessment of the Reduction in Environmental Impact Due to the Utilisation of Ssolid Waste

In India, 146 MT of cement was produced in 2006, which increased to 375 MT in 2023, emitting approximately 177 MT of CO_2. If we cannot control this exponential demand for cement, the forecasted demand for cement may reach up to 712 MT by 2050, which may evolve to approximately 375 MT of $CO_{2,}$ which is almost 2.1 times that of 2023.

The successful research on the utilization of agro-industrial rejects as a blended material to replace cement as a binding and filler material for the production of construction products not only helps to break the chain of this exponential emission of greenhouse gases, but also helps to reduce the energy required for the production and transportation of cement and indirectly solves agricultural and industrial waste stacking problems.

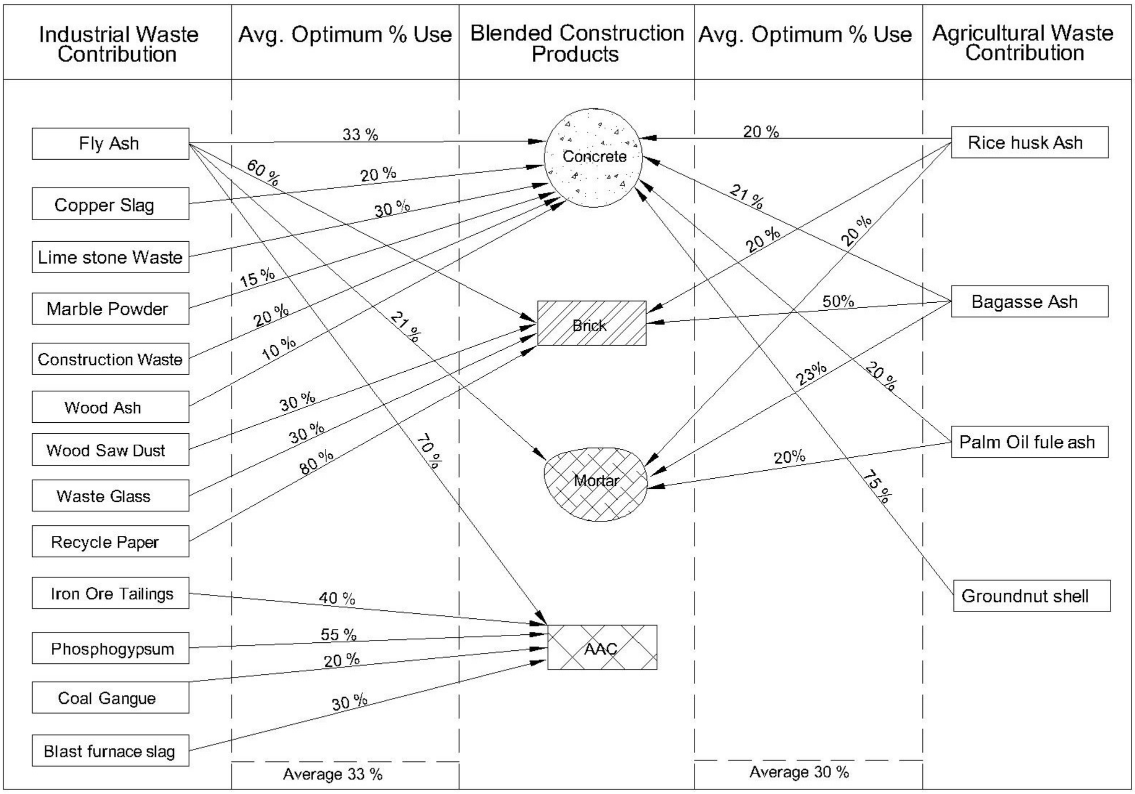

Fig. 9: Schematic Diagram shows the average of optimum percentage of industrial or agricultural waste use for the development of blended construction products.

Table 7: Reduction in emissions of GHG.

	Year	Consumption of Cement in India in Million tons	Forecasted Consumption of Cement after utilization of 32% Indo-Agriculture waste as a blended material in Million Tons	Reduction in Cement Production Per Year in Million Tons	Reduction in emissions of greenhouse gases into the Environment				Energy saved in GJ
					Reduction in CO_2 emissions in the atmosphere per year in Million Tons	Reduction in NO_2 emission in the atmosphere per year in Million Tons	Reduction in SO_2 emission in the atmosphere per year in Million Tons	Reduction in emission of particulate matter in the atmosphere per year in Million Tons	
Forecasted	2025	393	267	126	107	0.38	0.19	0.03	502
	2026	405	276	130	110	0.39	0.19	0.03	519
	2027	418	284	134	114	0.40	0.20	0.03	535
	2028	431	293	138	117	0.41	0.21	0.03	552
	2029	444	302	142	121	0.43	0.21	0.03	568
	2030	456	310	146	124	0.44	0.22	0.03	584
	2031	469	319	150	128	0.45	0.23	0.03	601
	2032	482	328	154	131	0.46	0.23	0.04	617
	2033	495	336	158	135	0.47	0.24	0.04	633
	2034	507	345	162	138	0.49	0.24	0.04	650
	2035	520	354	166	141	0.50	0.25	0.04	666
	2036	533	362	171	145	0.51	0.26	0.04	682
	2037	546	371	175	148	0.52	0.26	0.04	699
	2038	559	380	179	152	0.54	0.27	0.04	715
	2039	571	388	183	155	0.55	0.27	0.04	731
	2040	584	397	187	159	0.56	0.28	0.04	748
	2041	597	406	191	162	0.57	0.29	0.04	764
	2042	610	415	195	166	0.59	0.29	0.04	780
	2043	622	423	199	169	0.60	0.30	0.05	797
	2044	635	432	203	173	0.61	0.30	0.05	813
	2045	648	441	207	176	0.62	0.31	0.05	829
	2046	661	449	211	180	0.63	0.32	0.05	846
	2047	673	458	215	183	0.65	0.32	0.05	862
	2048	686	467	220	187	0.66	0.33	0.05	878
	2049	699	475	224	190	0.67	0.34	0.05	895
	2050	712	484	228	194	0.68	0.34	0.05	911
				4715 Mt	**4008 Mt**	**14 Mt**	**7 Mt**	**1 Mt**	**18862 GJ**

The estimated reduction in emissions of anthropogenic CO_2 and other greenhouse gases and the reduction in energy use after the utilization of an average of 32% of agro-industrial rejects as a cementitious blend are illustrated in Table 7. Table 8 reveals the forecasted greenhouse gases emitted and energy consumed by the cement industry with and without the utilization of agro-industrial rejects as a blended feed from 2024 to 2050. Fig. 10 shows the expected cement consumption with and without the use of agro-industrial waste.

CONCLUSIONS

- The world is advancing toward a circular, sustainable economy by replacing linear, fossil fuel-based economies. Sustainable construction has become a growing trend in the concrete industry in recent years because of its environmental impact.
- The literature shows that utilizing waste-based, sustainable building materials promotes a waste-based

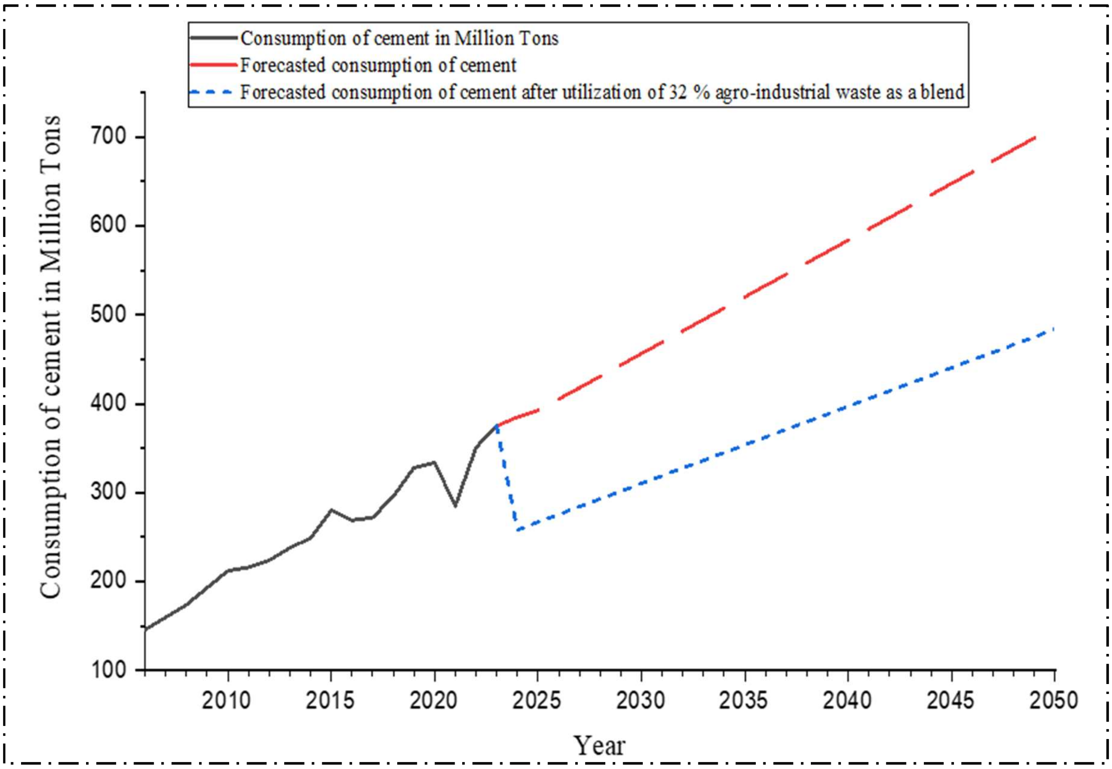

Fig. 10: Forecast consumption of cement with and without utilization of agro-industrial rejects.

Table 8: Forecasted greenhouse gases emitted and energy consumed by the cement Industry with and without utilization of agro-industrial rejects as a blended feed from year 2024 to 2050.

Greenhouse gases	**Without the** utilization of Agro-Industrial rejects as a blend	**With the** utilization of Agro-Industrial rejects as a blend	Reduction in the emission of greenhouse gases	% Saving
CO_2 in Mt	12525	8517	4008	32 %
NO_2 in Mt	44	30	14	
SO_2 in Mt	22	15	7	
Particulate matter in Mt	3.4	2.4	1	
Energy in GJ	58940	40078	18862	

economy and provides advantages such as waste management, employment, economic development, and environmental protection.

- These environmentally friendly products promote eco-friendly construction methods while addressing limited resources and climate change.
- Energy usage and greenhouse gas emissions can be reduced by partially replacing cement with agro-industrial waste. This may meet the demand for the next 15 years by reducing cement production by 5000 Mt, lowering CO_2 emissions by 3400 Mt, and saving 16,000 GJ of energy by 2050.

FUTURE SCOPE

1. The utilization of agro-industrial waste may significantly strengthen the frameworks of the circular economy. The development of closed-loop systems that minimize waste production requires integrated models that link waste producers, processors, and ultimately users.
2. The development of efficient real-time energy recovery, leachate, and emission monitoring systems would provide enhanced validation of environmental impact reductions. AI, IoT, and remote sensing may increase the possibilities for collecting and analyzing data.

3. Developing mixed formulations that effectively absorb CO_2 (carbonation curing, CO_2 mineralization) and employing carbon capture technology during cement manufacture are intriguing possibilities for further research. This makes it possible to create carbon-negative or net-zero construction materials.
4. Several recent developments have been made using modular components and additive manufacturing. The development of customized cementitious blends for 3D printing and prefabricated structures could lead to advancements in expedient and environmentally friendly buildings.

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