Journal of Material Cycles and Waste Management (2022) 24:1663–1678
https://doi.org/10.1007/s10163-022-01436-3

REVIEW

Flyash-based bricks: an environmental savior—a critical review

Mohammad Nadeem Akhtar[1] · **Khaldoon A. Bani-Hani**[1] · **J. N. Akhtar**[2] · **Rizwan Ahmad Khan**[3] · **Jamal K. Nejem**[1] · **Khansa Zaidi**[4]

Received: 19 August 2021 / Accepted: 5 May 2022 / Published online: 28 May 2022
© Springer Japan KK, part of Springer Nature 2022

Abstract
The extraction of unsustainable natural resources like sand and topsoil for construction is disturbing ecological balance, affecting local hydrology and wildlife. The inter-governmental panel of climate change (IPCC) has discussed its adverse impacts worldwide and has restricted its extraction. This article has mooted some of its potential threats and remedies to combat climate change and other social issues associated with the brick industry. Bricks made of clay are commonly used as a building material for masonry works in densely populated South Asian countries such as India, Pakistan, and Bangladesh. To make clay bricks, the topsoil of the floodplain area where most agriculture productivity is carried out is utilized in millions of tons every year. The main drawbacks of topsoil removal are the depletion of the seed bank, removing soil biota, and diminishing soil properties and functions. Furthermore, the process often involves burning firewood as emitting fuel CO_2, SO_2, NO_2 and suspended particulate matter (SPM). Thus, the clay brick-making industry contributes to greenhouse gases directly affecting soil fertility. The primary focus of this review article is to promote research on flyash-based bricks for the brick industry and provide safe and cost-effective sustainable materials to substitute clay bricks. This review article presents the worldwide production of clay bricks and their harmful impact on the environment. The current and future scenarios on flyash, systematic literature review (SLR) on flyash-based bricks, the practical utility of clay and flyash-based bricks, and issues and opportunities were also discussed. The findings obtained from the past published studies on flyash-based bricks give an insight to the researchers. The review article also presents the prospects for researchers and designers.

Keywords Climate change · Clay bricks · Agriculture soil · Flyash-based bricks · Systematic literature review

Introduction

Since ancient times, man has been using bricks for building purposes, from Egyptian palaces to Gothic-style buildings in the Baltic countries till the Middle Ages. Bricks date back to the Neolithic period (8300–7600BC), Fiala et al. [1] the oldest known building component. Earlier bricks were made from clay/mud combined with water and some straw as a binder to increase durability and baked for sundry until fired bricks-baked kilns came into fashion. The ruins of two great ancient civilizations along the Nile River and Indus valley are the living evidence that shows bricks were used as building material at that time. As necessity is the mother of inventions, this necessity has given the most significant breakthrough with the discovery of fired brick (3,500 BC); hence, the need for bricks became popular in cold climates. The transition from hand-made bricks to mechanized mass production during the Industrial Revolution increased demand and led to the explosion of brick as a modern building material. Amid the early twentieth century, brick had established itself as the most preferred building material for commercial purposes.

The rapid growth of urbanization and industrialization in developing nations has been evolving with a great demand for construction activities, which has resulted in the invasive growth of brick manufacturing. To fulfill the need for increasing demand and supply of bricks has given rise to

✉ Mohammad Nadeem Akhtar
nakhtar@fbsu.edu.sa

1 Department of Civil Engineering, Fahad Bin Sultan University, Tabuk, Saudi Arabia

2 University Polytechnic, Aligarh Muslim University, Aligarh, India

3 Department of Civil Engineering, Aligarh Muslim University, Aligarh, India

4 Department of Geology, Aligarh Muslim University, Aligarh, India

illegal contracts in areas vulnerable to air quality and agricultural land degradation. All these activities are impacting human health and creating ecological imbalances. The primary raw material required in the brick industry, the topsoil layer with a small amount of Magnesium (Mg), Barium (Ba), and other additives, are blended with clay to give different shades. Excessive excavation of this layer reduces the soil quality and makes it vulnerable to other threats like the decline in the water table, prone to floods, and waterlogging.

In soil, the fluoride concentration is up to 500 ppm, fluoride in the soil can retain in kilns at 1000 °C released to open air through the chimney in a gaseous state Jha et al. [2]. In addition, other pollutants, CO_2 $SO_{2,}$ can pose a potential threat to human health, such as Asthma, Tuberculosis, skin allergies, burning eyes, which are more common. Therefore, to minimize future potential threats, remedial measures should be looked upon to alter ecological conditions effectively and economically.

According to the National Institute of Health (NIH) [3], recycling resolves the non-renewable resource problem. It takes < 95% of energy consumption to recycle waste material than to generate new products. Recycling also generates employment and boosts the economy; in one statistical data, about 1.1 million jobs were created and 236 billion USD in gross annual sales by the recycling industry in the USA [3]. Hence, it becomes important to understand the positive influence of the construction industry's waste and recycled material. This field is increasingly becoming indispensable as it is being explored by researchers where the focus is mainly on the efficient use of recycled, appropriate waste, and reused waste. More generally, flyash, silica fumes, rooftop shingles, layers of palm fruits, peeling of citrus, kiln dust cement, foundry sand, glass, slag, plastic, crumb rubber, asphalt, and construction and demolition waste are used.

Increasing concerns related to global changes in climate, a demand rises that companies must cope and evolve by shifting towards more sustainable construction materials such as green building materials (GBM). It will play a crucial role in reducing air pollution and combating climatic changes brick by brick. The civil engineering industry is one of the most significant industrial waste digesters in its range of applications, such as building materials, road materials, bridge materials, dam materials, waste-landfills, railway track processes, filling, and cutting. Amongst all mentioned applications, construction and building materials are a demanding sector of the industry. Recycling reuse and recovery of industrial waste materials have become a more appealing alternative to the disposal and replacement of natural materials, as it has a lower carbon footprint [4–7].

Clay brick is a solid masonry unit made up of clay mixed with water. In comparison, flyash bricks are those whose basic component is flyash, a waste produced by the combustion of fossil fuels like coal in thermal power plants. Flyash-based bricks have emerged as suitable alternatives for replacing clay bricks as a construction material. According to the report [8], building materials accessories used for decoration like tiles blocks are produced using only 9.94% flyash. Statistical data demonstrate that 6.65 billion bricks are manufactured annually, consuming 2800 clay bricks per unit in India. Tang et al. [9] reviewed those new materials for walls, such as brick, aerated concrete block, hollow block, etc., are generated with the aid of flyash. The utilization of these products adds up to 26% of flyash total yearly consumption in China. According to one estimate of the Government of India, in the year 1998–99, 0.70 million tons of flyash were consumed by cement sectors to make flyash-based bricks, blocks, tiles, etc., which increased to 21.39 million tons in 2019–20 reported in a report [10]. Lingbawan [11] reports that some countries have promoted flyash in different industries with increased environmental concerns but have implied government regulations through legislation. For example, India has made it obligatory for the clay brick industry to integrate a minimum of 25% flyash in brick sectors. However, the clay brick kilns should be in the vicinity of the thermal power plant. This paper discusses the available literature review, drawing attention to the technologically advanced research related to recycled waste uses specially flyash to produce flyash-based bricks. The main criterion for selecting a material is its popularity and its wide-scale practical applications in construction activities. In this review article, the worldwide clay bricks production and its environmental impact, the demand for flyash, and current and future scenarios on flyash are presented. The systematic literature review (SLR) on flyash-based bricks and their practical applications were reviewed. Concerns related to issues and opportunities and future research gaps were also investigated and reported. Facts and information observed by agencies/individuals that was produced through past reviews was further (assessed to create awareness of the latest developments in the field. This awareness and assessment have helped states about the importance of the utilization and safe disposal of flyash in the brick industry.

Global scenario of clay bricks

If we divide the world into two halves, the most populated, polluted, and fertile regions are part of the developing nations. Recent advances in technologies and mass migration towards cities to earn a better living require more habitats; therefore, to meet these needs, bricks kilns have shifted in the vicinity of the cities. The annual global production of baked clay bricks is estimated to be 1.5 trillion, reported by CSE-India [12]. It contributes to 20% of the world's black carbon. Out of the 1.5 trillion bricks productions, only 13.33% is the total share of the western world. In contrast, South Asia is the most significant contributor (86.67%), 90% of which producers are China, India, Pakistan, Vietnam, and Bangladesh. Major cities of this nation have contributed to 91% in particulate matter emission in open air due to lack of proper management and policies; it has taken the lives of some 7 million people annually Lopez et al. [13].

In less developed countries, only China and Vietnam in Asian countries have adapted recent and coherent brick-making technologies by Mitra [14]. The study done by Zhang [15] reported that South Asia has almost a quarter of the total world bricks production. ICIMOD [16] reports that there are estimated to be 260 billion bricks approximately. However, India's existing yearly demand for bricks is evaluated to rise from 200–250 billion bricks to 778 billion bricks with a rural-to-urban ratio of 30:70 shortly. Eil et al. [17], approximately 7000 brick kilns produce about 27 billion bricks per annum in Bangladesh, contributing 1% to the national GDP. There are about 1700 brick kilns in Nepal, with 5 billion bricks produced annually. As recorded by a report Statista [18], Great Britain (UK) produced 2.03 billion bricks in 2018, reported the highest since 2013, crossing more than two billion marks. Figure 1 shows the world brick production percentage published by the world bank report [19].

Climate change defies world security with its ubiquitous impacts felt worldwide. Scientists opine that increasing unforeseeable weather cycles, acute rainfall, and mightier droughts result from climate change. So, why does South Asian Region (SAR) become so vulnerable in brick kiln production? The answer is simple: the SAR has extensive reserves of Permian-carboniferous coal; the fuel required in a brick kiln is cheap and readily available. However, burning fossil fuels leads to increased black carbon emission, CO_2, PM 10, PM 2.5, and SO_x, all hazardous for air quality and global warming. Therefore, IPCC and world leaders should focus on alternatives and promote switching to eco-friendly sources.

Regional scenario

The South Asia Region (SAR) has been undergoing unparalleled rapid urbanization with a growth of 1.96 billion, making up 24.89% of the world's total population. The average capital growth of SAR is at the rate of 6%. Economic growth and urbanization have led to a surge in residential and commercial space demand, increasing the demand for construction materials. In Asian Countries, brick features as a primary building material. The SAR produces 1.2 trillion bricks per annum, making them the largest producers of the bricks. China is the only nation that produces 1 trillion bricks annually, followed by India (11%), Pakistan (8%), and Bangladesh 4% in clay bricks production. Indo-Gangetic plain encompasses 7×10^5 km^2, an area of which 60,000–70,000. Fixed Chimney Bull's Trench Kilns (FCBTK) bricks are located in this region alone Agarwal [20]. A large population is confined in major cities in India, and 70% is yet to be rebuilt. Despite being a prominent brick-producing region, SAR employs traditional brick-making technologies. These traditional technologies have been used for over a century now, rendering them obsolete, unproductive, and environmentally unsustainable.

Contrary to this, recent and dominant technologies are Clamp Kilns (CKs), Mobile Chimney Kilns (MCs), Fixed Chimney Kilns (FCKs), and Zigzag Kilns (ZZKs) Eil et al. [17]. The most potent air pollution is the FCBKT kilns, which consume more power than Zigzag kilns. According to one report, the strategy proposed to minimize the emission

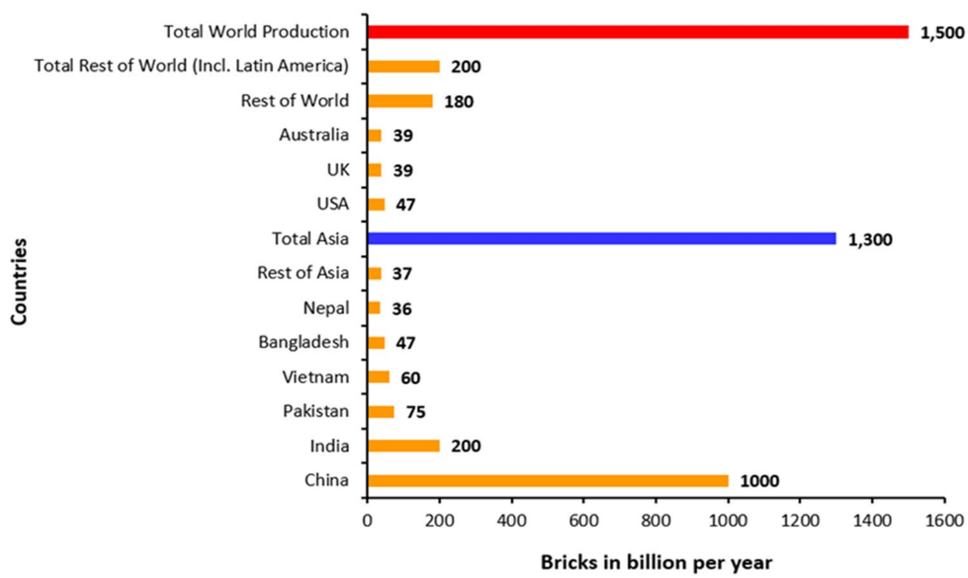

Fig. 1 World brick production published by the World Bank report

from the kilns is to alter the brick production method by switching to Zigzag kilns instead of BKT and FCBKT Lopez et al. [13]. The flow chart in Fig. 2 presents a systematic procedure for clay brick manufacturing in the SAR region.

Environmental issues

The main reason to advocate for a green and eco-friendly alternative to clay bricks is ecological imbalances causing harm to our planet. The participation of the brick industry in land degradation and deterioration of air quality is much higher than other thermal power plants because it uses the poor quality of cheap fuel. The primary essential factor that makes an industry successful is the easy availability of raw material; in bricks, the essential commodity is natural clay excavated readily for ages. However, illegal excavation has aggravated land and fertility dangers due to the recent smart cities model. Here, we have discussed two parameters that are the building blocks of the brick industry.

Bricks industry impacts on agro-economy

The SAR, the Indo-Gangetic plain, comprises a 700,000 km^2 area fertile for agriculture and a large urban area Misra et al. [21]. The plains are the world's most densely populated regions, with 400 million people living due to the increase in population. These plains are at a higher risk of shortages of resources such as water; about 60,000–70,000 brick kilns are situated in these plains, which is a potential threat to fertility. Most of the SAR brick kilns sites are in low-lying areas. Topsoil is a veneer of the outermost layer that extends up to a depth of 5–10 in. in the ground. The topsoil horizon is vital for plant growth; soil texture, organic content, and pH levels are the three main properties that determine production productivity and the soil itself. To maintain its produce, topsoil exhaustion will be a massive loss in the agro-economy as topsoil is the most high-yielding layer of any agricultural land. The nutrients present in the topsoil like nitrogen, phosphorous, calcium, some trace elements Fe, Zn, B, Cu, Mn and Mo are the building blocks for maintaining soil quality and nutrient value Das and Sarkar [22]. Nitrogen enhances soil productivity and helps in the atmospheric fixation of nitrogen to crops. The rhizobium presents in the leguminous plants fix about half of the atmospheric nitrogen of the soil, and the rest is taken from the soil. It shows that no artificial manure or fertilizers were required if more leguminous plants were grown. One of the studies in the Philippines suggests that a loss of 12.5 kg/ha in corn productivity is due to loss in one ton of soil Francisco and Angeles [23].

Further, Carson [24] demonstrates that topsoil damage up to a millimeter leads to loss of Nitrogen 10 kg/ha, 7 kg phosphorus/ha, and 15 kg potassium/ha. To repay the damage to soil fertility, farmers adhere to excessive use of artificial fertilizers, which causes unintentional damage to the natural process operating in the soil system. India is one of the few countries that restrict topsoil use for brick-making; however, a lack of stringent enforcement leads to adverse impacts of pH levels in soil from the toxic emissions reported by Maria et al. [25].

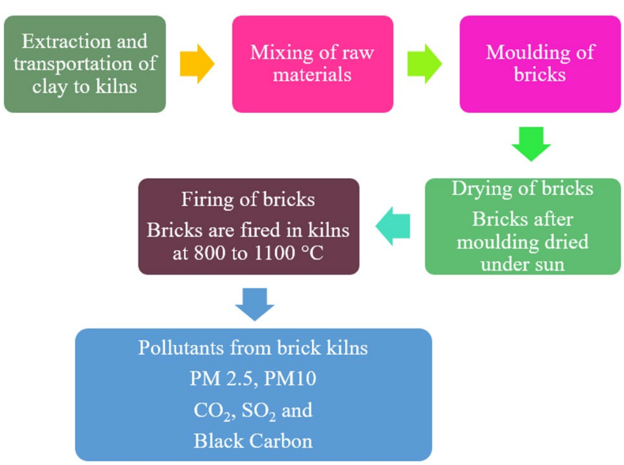

Fig. 2 Flow chart depicting the brick-making process used in SAR

Energy consumption

The construction sector is also an emitter of toxic gases and pollutants like PM 2.5 in the SAR. Maximum contributors in the construction sector are steel, cement, brick, and lime [26]. Toxic emissions are causing adverse impacts on the environment and human health. India mainly produces maximum black carbon in South Asia. Its brick sector share is 9% of two-thirds of the total black carbon emissions in the manufacturing sector Eil et al. [17]. India is the 2nd major consumer of coal with yearly utilization of 62 million tons in the brick sector alone, while Bangladesh and Nepal's annual consumption is 5.1 million tons and 1 million tons. Besides coal, natural gas and diesel are also used in some mechanized operating processes. Poor quality of coal lignite is used in the brick sector in most kilns, which are artisanal types in SAR. The study ascertains that the aggregate fuel competence of the brick sectors in Bangladesh, Nepal, and India will be 170–200 g of coal per brick is consumed. These findings assume that around > 700 g coal is spent to produce 3 kg brick by weight Heierli et al. [27]. However, it should be acknowledged that the fuel efficiencies of similar kilns exhibited differently. Since kilns are not designed as per standards and are regulated improperly by local contractors hence, proving more hazardous to the environment. Additionally, the fuel quality, clay physical parameters such as moisture content, specific gravity, binding capacity, and global warming are alarming issues. Due to an informal operation of brick kilns, the energy consumption monitoring and data collection system is generally unscientific.

Air pollutants such as carbon monoxide and PM 2.5, mainly black carbon, are released into open air during brick production. These are toxic to human health and potentially alter global climate and seasonal phenomena such as weakening the monsoon (seasonal rainfall) and accelerating glacier melting. These seasonal and global changes threaten global food security, especially to unprivileged and war-torn people.

The ministries should take implementation and strict action to make the public and private sector aware of the associated health and environmental issues with the emission of PM and Black carbon. Data from Table 1 [28] shows that the maximum amount of CO_2 is generated by solid burnt clay brick FCBKT, Solid burnt clay from Zigzag Tunnel, whereas in the case of PM emissions again FCBKT stands first. The bricks made up of Pulverized fuel ash generated the lowest CO_2 and PM emissions.

Impact of land degradation

Land degradation is a collective term mainly used to decline the productivity of the land or soil, including forest areas, albeit there are deviating opinions related to the spatial and temporal scales to which land degradation is defined by Warren [29]. However, land degradation is a potential threat to our ecosystem, a lack of reliable global maps of its extent and severity [30–33].

Unintended impressions of climate change on land degradation are tough to enumerate due to several combining reasons. Changes in unsustainable land-use methods are very intricate, along with physio- biological and socioeconomic parameters [34, 35].

It is thought that an average of 95% of the world's topsoil has been displaced to their present location, and merely 5% of them are "residual soils" or are in situ USDA [36].

One of the factors of land-use alteration is the degradation of agricultural land. It results from unwanted anthropogenic activities (mining topsoil for bricks, illegal sand mining, and other metallic mineral mining); this will harm natural land converted for farming to suffice to yield. The excessive exploitation of topsoil will degrade soil quality and make it susceptible to erosion, resulting in loss of productivity, the efficiency of land, affecting local food security, and forcing non-agricultural lands such as forest areas to convert into agricultural land [32, 37, 38].

Land degradation plays an essential role in monitoring climate change. The pedogenesis microbial activity in soil controls the functioning of nitrous oxide (N_2O) associated with management and weather conditions. In contrast, the presence of methane (CH_4) determines the amount of carbon in soil and the limit of soil subjected to waterlogging Palm et al. [39]. According to an estimate presented by CSE-India [12], on average, 28 variegated soil samples contain approximately 1500 Gt of organic carbon. This finding infers that soil comprises 1.8 times extra carbon compared to the atmosphere and 3.3 times more than global terrestrial vegetation Ciais et al. [40]. Therefore, land degradation, including conversion of forest for farming excavating topsoil for bricks industry, will decline soil carbon content. Its aftermaths can potentially affect the concentration of CO_2 in the atmosphere considerably Olsson et al. [41].

Table 1 Comparison of resource efficiency

Parameters	Mined raw materials	Primary energy manufacturing	CO_2 emission manufacturing	PM emission manufacturing
Units	Kg/m^3	MJ/m^3	t CO_2/m^3	g/m^3
Solid burnt clay-FCBTK (Baseline)	1760	2080	0.19	1888
Solid burnt clay-flyash FCBTK	1009	1558	0.14	1547
Solid burnt clay—Zigzag kiln	1760	1680	0.15	368
Perforated burnt clay—Zigzag kiln	1584	1512	0.14	331
Hollow clay blocks—Tunnel kiln	815	1275	0.12	178
Autoclaved aerated concrete blocks	224	1276	0.14	151
Cellular light-weight concrete	338	1003	0.15	210
Pulverized fuel ash-lime bricks	450	1025	0.08	83
Pulverized fuel ash–cement bricks	711	811	0.12	161
Solid concrete blocks	2153	774	0.12	167
Hollow concrete blocks	1615	581	0.09	125
Compressed stabilized earth blocks	1976	653	0.10	139

Demand of flyash

The thermal power plants generate energy by igniting fossil fuels, of which flyash is the by-product. Akhtar et al. [42] reported that the amount of flyash produced from these plants, only 96 million tons, has been recycled out of (166 million tons) as a substitution in the cement industry in the last 5 years. Though China is one of the primary producers of flyash globally, Francisco and Angeles [23] have simultaneously promoted environmental protection acts by encouraging multipurpose use of flyash procured from the power plant as waste. Table 2 shows the consumption of flyash generation by Worldwide Coal Combustion Products Network for the year 2016 Harris et al. [43]. The most prominent countries in the production of flyash were China, India, Europe, and the USA. The estimated combustion production is about 1.2 billion for the year 2016. China and India are the only two countries that consume large quantities of coal and produce maximum flyash. A large percentage that is not being utilized by developed countries is Russia is 72.8% and 44% for the USA.

In contrast, the difference in flyash percentage that China and India are not utilizing is (29.9% and 39.03%). Despite being the most populous nation, India and China utilizes maximum quantities of their flyash. Therefore, they are playing their part in suppressing carbon emissions, while other developed nations like the USA and Russia have yet to join this race.

Table 2 Annual production and utilization of flyash in India and other nations

Country/Region	Flyash generation (Mt)	Flyash utilization (Mt)	% Utilization
Australia	12.3	5.4	43.5
Asia			
China	565	396	70.1
Korea	10.3	8.8	85.4
India	197	132	67.1
Japan	12.3	12.3	99.3
Other Asia	18.2	12.3	67.6
Europe	140		
EU15	40.3	38	94.3
The Middle East and Africa	32.2	3.4	10.6
Israel	1.1	1	90.9
USA	107.4	60.1	56.0
Canada	4.8	2.6	54.2
Russian Federation	21.3	5.8	27.2
Total	1221.9	677.7	63.9

The research and development departments of the governments and private sectors, NGOs, and freelance researchers Carson [24] have covered the significant prospects for utilizing flyash in different sectors in India. Case et al. and Sunil et al. [44, 45] considered the applications of flyash as a partial substitute of cement in the concrete mixes. Baeza et al. [46] demonstrate that flyash when mixed with different materials as a substitution in a fraction of cement in pastes and mortars (with 30% as OPC substitute), increases by 9% compared with the ordinary concrete sample. Smol et al. [47] report flyash as an alternative for cement and sand for highways, roadways, pavement, and embankments. Haleem et al. [48] present a literature overview of the usage of flyash in roads, bridges, and embankments. Das et al. [49] discuss sustainable utilization of various industrial wastes, collating new developments in reducing cement consumption to produce flyash-based geopolymer concrete (FBGC), which reduces greenhouse gas emissions and diminishes industrial waste's disposal cost. The admixture of flyash with cement improves concrete performance in fresh and hardened states. Its usage is also cost-effective. The flyash-based concrete has been used and tested in severe exposure applications in several highway projects worldwide. Some examples include the docks and piers of Tampa Bay's Sunshine Skyway Bridge. Another study conducted by Thomas et al. [50] shows that concrete having quarry dust as flyash aggregate exhibits less reduction in strength when subjected to a higher temperature. Kumar et al. [51] considers the use of flyash as a partial substitute in concrete/mortar to manufacture simple cellular blocks of concrete. Reviewed studies suggest a wide variety of potentials of flyash as recycled waste material in the construction sector. With the attributes of flyash and rising demand, it will hold a market share to reach 6.86 billion USD by 2026 [52]. Table 3 shows the precise current and future scenarios on the flyash market.

Flyash-based bricks and blocks industry is one of the most demanding sectors for flyash utilization. Flyash-based bricks and blocks are unconventional bricks and blocks manufactured by industrial waste in which flyash is the main ingredient, mixing with other materials such as cement, sand, and stone dust. The only difference in bricks and blocks are their mould sizes; the standard bricks and blocks sizes are 225 mm × 112.5 mm × 75 mm and are 300 mm × 200 mm × 100 mm, respectively.

Systematic literature review (SLR) on flyash-based bricks

Over the past decade (2010 to 2020), sustained research activity in recycling flyash for construction materials has been undertaken extensively. The present section investigates a Systematic literature review (SLR) on flyash-based bricks. Data extracted from literature are manually curated

Table 3 Current and future scenarios on selected recycling waste flyash

Type of waste	Current scenario	Future scenario	References
Flyash	Flyash has been classified as a toxic matter that causes soil, air, and water contamination. Therefore, we have begun to treat flyash as our essential raw material despite several related issues (land disposal requirements, groundwater contamination, handling problems, etc.)	The need to consider and analyze flyash's main program components and subcomponents and the key factors and sub-elements have helped define managing effects beneficial for stakeholders	[48]
	In 2020, the flyash global market was estimated at 3.5 billion USD	USD 4.9 billion to reach the world flyash market by 2027	[77]
	The market of flyash in the world was USD 4.13 billion in the year 2018	By the year 2026, it is estimated to surpass USD 6.86 billion	[78]
	Coal demand in 2010–11 is expected to rise by 730 million tons in India	In 2031–32, it is anticipated to be approximately 2000 million tons. 75% of the coal will go to the thermal power station	[79]
	China remains the most significant coal market globally, producing nearly half of the global emissions. However, the US's utilization rate (46.74%) and India (55.79%) reached 67.96%, higher than that	Nearly half of the world's coal in 2035 will be absorbed by China. The fastest increase in India's carbon consumption has overtaken the United States to become the world's second-largest carbon user	[79]

as a possible solution for critically reviewing the topic in question. Systematic Literature Review (SLR), or Systematic Review, as a technique, can be employed to recognize, appraise, and outline the up-to-date review of formulated well-defined questions. Databases under SLR are used restrictively to collect relevant data, where analysis involves lower bias than traditional reviews. The SLR approach has been used in various fields such as medical, engineering, and environmental studies. In the present study, peer-reviewed journal papers that used the SLR method have been selected as a guideline. Based on selected SLR-based studies, summaries are developed to understand the present trend of flyash-based bricks. Databases such as Google Scholar, PubMed, Science Direct, and Scopus have been used. Out of 45 screened research papers, 11 were selected based on the following five heads: title, abstract, materials, results and discussion, conclusions, and full-text reading. Thus, 11 papers were included in the SLR section of this review article. The papers have been arranged in chronological order. A review studies list leading waste material (LWM), other mixing materials (OMM), and invented materials (IM). The comprehensive SLR with different characteristics of invented materials (IM) are presented in Table 4.

The practical utility of clay and flyash bricks

Flyash is a waste product of thermal power plants. It is an inexpensive substitute for the OPC industry, usage of flyash as concrete is century-old, where it had been first used as concrete for the construction of the Hoover Dam in the US. Typically, concrete designers used 30% of flyash infractions to substitute the whole cementitious composition OPC. Still, recent research and developments have opened a new domain for flyash as a primary commodity in the civil sector. The experimental studies report that adding flyash in proportion with cement increases the concrete load-bearing capacity and will be fruitful for the future. The combinations of different waste products have been undergone experimental analysis to manufacturing better quality bricks [53–62]. The flyash characteristics that make it worthy of being used in the concrete design are odorless, non-toxic, inflammable, inexplosive. It does not pose any threat to humans. The substitution of OPC with flyash in the concrete mixture will prove the panacea by creating a more cementitious paste. It can be understood from Eqs. 1 and 2. Other properties that make it advantageous over clay bricks are summarized in Table 5. The cement reaction is shown in Eq. 1, and calcium silicate hydrate a different paste formation is presented in Eq. 2.

$$\mathrm{OPC} + \mathrm{H_2O} = \mathrm{C{-}S{-}H} + \mathrm{Ca(OH)_2} \quad (1)$$

$$\mathrm{Flyash} + \mathrm{Ca(OH)_2} = \mathrm{C{-}S{-}H}. \quad (2)$$

The clay brick industry is an ancient building material, widely used since the third millennium BC, with documented evidence from Warren's early Mesopotamian civilization Warren [63]. Brick as a building material is prepared by mixing clay with some additives, placed for moulding, followed by slow drying under sun later baked in an oven. Baking provides strength and increases its durability. The porosity of brick demonstrates an inverse relation to its strength lesser the pore spaces higher the binding strength of bricks Culbert and Christel [64]. The factors that make flyash-based bricks economical are their tendency to enhance workability, reduce permeability and hydration, and make it

Table 4 Systematic literature review (SLR) on flyash-based bricks

Research	LWM	OMM	IM	Key findings
[80]	Flyash	Cement, river sand, stone dust, geo fiber	Flyash-based bricks	Flyash was treated by adding 1.5% lime in the plain flyash to enhance the cementitious properties of flyash When 25% stone dust and 10% river sand cement is mixed Highest compressive strength is achieved by Fiber-reinforced flyash limestone dust brick Amount of processed flyash changes with the ratio of stone dust and sand replacement, increment in compressive strength of 8.98 MPa max, which is very close to Standard first-class clay brick (10.30 MPa) when the amalgamation of 25% sand and stone dust mixed with flyash (50%) However, the study reveals that excellent strength and durability characteristics were missing in flyash-based bricks
[81]	Flyash	Cement, lime, Shell ash, sand, Polypropylene fibers, Industrial gypsum, Carboxylic styrene-butadiene polymer rubber (SBR), water-reducing admixture	Unfired flyash bricks	Compressive and flexural strength were found highest at 15% Shell ash content. In addition, a study shows that the strength of unburned bricks is remarkably influenced by shell ash Carboxylic styrene-butadiene polymer and Polypropylene fiber emulsion as a fused material eloquently affect the flexural strength of unfired flyash bricks Ratio of Optimum mixture is discovered to attain top performance: 41% flyash, 25% cement, 15% lime, 15% shell ash, 4% gypsum, 3% of SBR, 0.10% fiber, 0.50% admixture that lessens water content. Sand is to cement amount is 0.5 and water to cement is 0.3 The deficit of unburnt brick mass in the optimum mixture ratio is 1%, and the Compressive strength is 26 MPa when placed 15times in the freezing–thawing cycle. Therefore, it satisfies standard requirements set by JC239-2001 "China Flyash Brick."
[82]	Flyash	Slag, lime, cement	Flyash-based autoclaved bricks	The Flyash-based autoclaved bricks compressive strength is 14.3 MPa Due to flyash–slag Brick's porous structure, their density was 1.65 g/cm^3, which is even lesser than ordinary sintered clay brick Autoclaved bricks absorb higher water content (16.5%) than ordinary sintered clay bricks (15%) Autoclaved brick experimental data shows that when placed for freeze–thaw cycles 15 times, the mass deficit was 1.8% and compressive strength 9.5 MPa, satisfying the Chinese standard GB/T 11945-1999 requirement for 10 MPa set by autoclaved brick

Table 4 (continued)

Research	LWM	OMM	IM	Key findings
[83]	Flyash	cement, river sand, stone dust	Flyash-based bricks tiles	Regular and processed flyash tiles were subjected under compression; the maximum compressive strength in the range of 3.86–4.44 MPa was noted by combining 15% fine and 5% coarse sand The increased strength of processed flyash tiles was experiential with stone dust and found an increase in strength to 5.8 MPa with 15% fine Sand and stone dust 5% If 60% of processed flyash is combined with 15% fine sand and 15% stone dust, the compressive strength will reach 6.8 MPa max, about 15% lower than standard clay brick tiles strength (7.8 Mpa) Study results found a good correlation between the strength characteristics and available clay brick tiles; however, durability characteristics were missing
[84]	Flyash	natural Malaysia sand, alkaline liquid, sodium hydroxide solution, and sodium silicate	Flyash-Based Geopolymer Bricks	The highest strength of flyash-based geopolymer bricks was found at 20.3 MPa when subjected to cure for 60 days at room temperature after removing oven treatment The lowest percentage for water absorption of flyash-based geopolymer bricks is 3.5%, shown by bricks cured for 60 days Results obtained show that geopolymer bricks exhibited better characteristics and properties due to high compressive strength (5–25 MPa), low water absorption (3.5–7%), and the range of density between 1800 and 1950 kg/m^3 is suitable for use in construction compared to conventional clay and cement bricks However, the study reveals excellent strength results in flyash-based geopolymer bricks with durability characteristics missing
[85]	Flyash	slaked lime	Flyash lime-based bricks	The average compressive strength value of flyash lime-based bricks was 7.5 MPa by tests conducted on 10 bricks It was discovered that the average flyash flexural strength with lime-based bricks is 0.55 MPa The Heat conduction of brick (0.225 W/m/K) is analogous to aerated cellular concrete and is better than clay bricks The mass loss was 9.53% in flyash lime-based bricks after repeating the 25 times freeze–thaw process
[86]	Flyash	cement, coarse sand, red stone dust, waste polythene fiber	Sustainable flyash-based roof tiles	Treated flyash stone dust roof tiles reported maximum compressive strength at 20% cement combination (9.01 MPa), almost the same as an average sample of 10 locally available clay roof tiles (9.05 MPa) Permeability ($k = 10^{-7}$) of flyash-based roof tiles composites is near the value of clay in the market used for making bricks and roof tiles The curves of stress–strain obtained from experiments compared with standard clay brick tile displayed similar patterns The study reveals excellent results in strength and seepage characteristics of flyash-based roof tiles; however, durability characteristics were missing

Table 4 (continued)

Research	LWM	OMM	IM	Key findings
[87]	Flyash	Cement, aggregate, additives	Coal flyash-based bricks	By carefully examining experimental tests, research data discovered that new advanced development has an extensive practical application prospect in utilizing coal flyash-based bricks in the industry In a research, it is found that by upgrading a production line of a brick plant with new technology, around 37,000 tons of bricks/blocks of flyash-based can be prepared annually, in return cutting off the cost of production up to 15–20% The total number of brick plants in China is around 2200; these plants can take the initiative to utilize 48–65 million tons of flyash every year
[88]	Flyash	Lime, wood, aggregates	Coal flyash-based earth bricks	The compressive strength of coal flyash-based earth bricks is significantly higher than reference cement stabilized unfired earth bricks Unburnt earth bricks strengthened with an aggregate mixture of lime-coal and ash-wood display no signs of dry shrinkage behavior even though no changes in dimensions were done before and post-curing the specimens Unburnt earth-made bricks were strengthened with (10%) lime, (10%) coal flyash, and (1.5%) aggregates of wood provide compressive strength (8.3 MPa) max, which is significantly more than that of robust bricks cement (7 MPa)
[89]	Flyash	Clay, bottom ash	Flyash-based clay bricks	Bricks' keen and apparent specific gravity exhibits good compressive strength under 950 °C to those fired at 1050 °C By increasing flyash amount, an increase in superficial voids spacing and water soaking capacity is seen. Still, a significant decrease in bricks' bulk density and thermal conductivity is observed An increase in Flyash and Bottom Ash amount leads to a noteworthy decline in the compressive strength of bricks. However, bricks posing 5% FA, 5% BA, and 10% BA display similar compressive strength to the control bricks It has been reported that 340 billion tons of good-quality topsoil are excavated every year globally for the brick industry. According to an estimate, if preliminary actions were taken on time, then $340 \times 30\% = 102$ billion tons of topsoil can be successfully restored. Therefore, recycled waste like flyash should be encouraged. Furthermore, the research promotes an insight to use more flyash and bottom ash as primary raw materials

Table 4 (continued)

Research	LWM	OMM	IM	Key findings
[90]	Flyash	Ceramic Powder Waste, silica fume	Flyash-based geopolymer bricks	Waste by-products of ceramic made up of metakaolin can be utilized for this purpose and cost-effective materials. Furthermore, adding metakaolin to the samples at different proportions will increase the geopolymer bricks' compressive strength to 250.26 kg/cm^2 after 28-day curing Flyash tends to enhance mortar compressive strength and provides stability. The results of samples compressive strength display add 90% flyash and Ceramic dust (meta-kaolin) by 10% of the total weight of admixture; raises compressive strength to three folds compared to samples containing flyash metakaolin in similar quantity When various proportions of silica fume with flyash and metakaolin, geopolymer mixtures led to unsatisfactory outcomes, like the amalgamation swells up The increment is seen in compressive and flexural strength when water and binder ratio reach (0.3); the pragmatic results of the w/b ratio (0.3) increase compressive strength to 50% or more, reaching 19 MPa. Thus, the ultimate Geopolymer bricks flexural load was 270 kg

heat resistant. Moreover, resist chemical reactions like sulfates and chloride's improving strength, gives even finishing, reduces shrinkages on walls. The strength and durability characteristics of clay and flyash-based bricks are compared in Table 5 [65].

Specimen bricks were designed using clay as a raw material by baking them at variable temperatures. The physical and mechanical properties are avidly monitored for the bricks. Later, these data are compared to bricks prepared with flyash. It was done to assess the variations in the quality of bricks shown by flyash-based and clay bricks. The use of flyash as an additive in bricks can be an innovative techno-economic raw material for brick-and-mortar designers. It will serve as a competent resource by recycling it. Typically clay bricks vary in colors due to artificial chemical-based colors, whereas flyash bricks have an even and pleasing natural color of their own, like cement. Regular clay bricks are fragile, whereas flyash are composed densely. Plaster is required to protect standard clay brick walls, whereas, in flyash bricks, no plaster is needed. These flyash bricks are also lighter in weight than clay bricks.

The flyash-based bricks and blocks are manufactured by specification and quality standards as per IS 12894 [66] and IS 16720 [67]. The process of flyash-based brick consists of four Phases. Phase 1 includes the pre-production phase, phase 2 production phase, phase 3 curing phase, and phase 4 quality control and dispatch. The main constituent in flyash-based bricks is flyash, and other mixing materials are binding material cement, filler materials, sand, and stone dust. The prepared material is processed for mixing, handling, pressing, stacking, and curing, as shown in Fig. 3b.

In many cases, flyash bricks have more compressive strength than clay bricks and are less porous. Figure 3a shows the building constructed using flyash-based bricks and blocks. Figure 3b presents the systematic diagram showing the production of flyash-based blocks in the industry. Figure 3c shows clay and flyash-based brick unit images, and Fig. 3d exhibits a traditional clay brick kiln.

Issues and opportunities

Environmental and sustainability issues associated with clay bricks have become apparent with increasing climate change. It is essential to curtail energy consumption and carbon dioxide emissions from brick kilns, directly affecting climate change. Flooding, drought, and heat waves have hit the UK, lately witnessing the most drastic impact of climate change. The anthropogenic accumulation of GHGs in the atmosphere, mainly CO_2 emission due to non-renewable fuels igniting, has escalated the global temperature. Other climatic phenomenon has come into effect, like frequent cyclones, drought, delay in monsoon, etc. The recent disappearance of north-pole Greenland glaciers and the disintegration of

Table 5 Comparison of flyash-based bricks over clay bricks

Properties	Clay Bricks	Flyash-based Bricks	Remarks
Compressive strength	30–35 kg/cm^2	95–100 kg/cm^2	High load-bearing capacity
Density	> 16,500 kg/m^3	> 1700 kg/m^3	-
Absorption	25%	14%	Absorbs less moisture
Water intake	More water	less water	Improves water and cement ratio
Plastering	Unevenly spread over walls	It gives a smooth and even plaster	Saves up to 20% of plaster

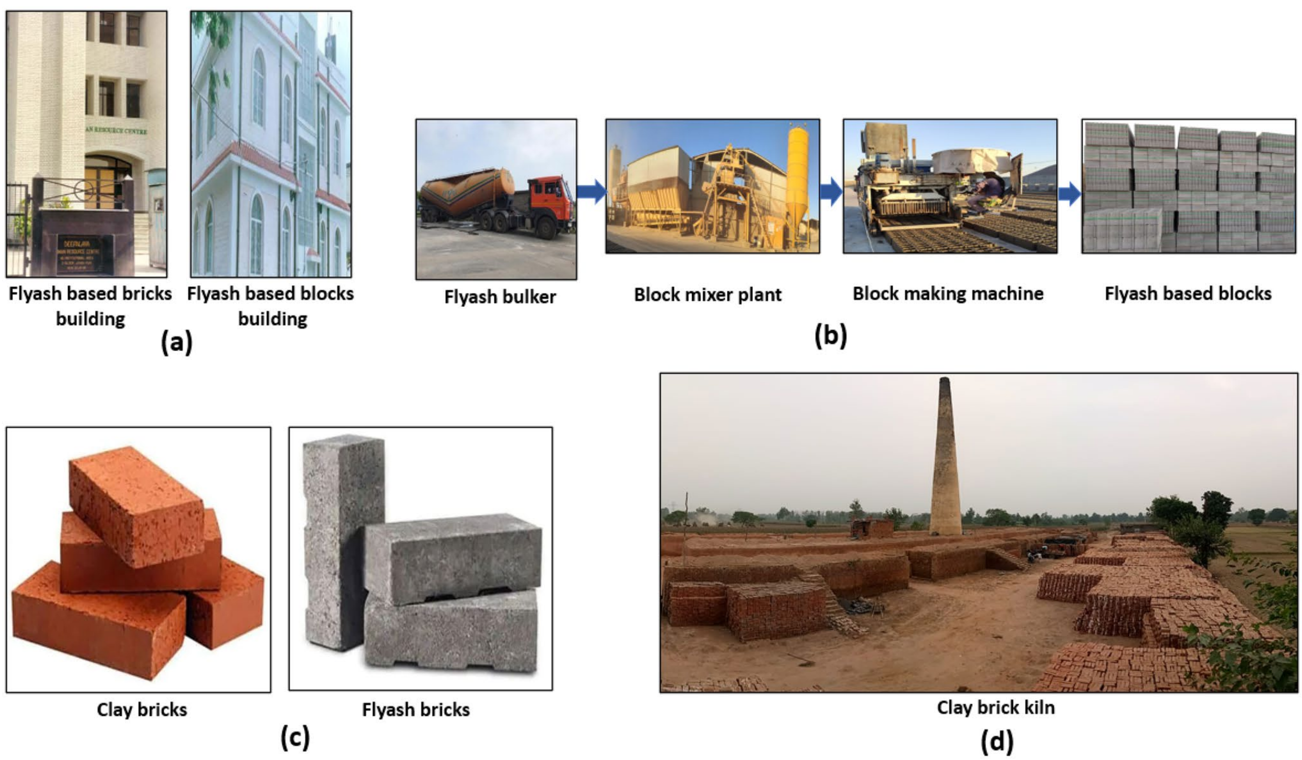

Fig. 3 Clay and flyash-based bricks examples

the "doomsday glacier" in Antarctica suggests global climate changes contributed to local seasonal changes. These changes will cause mayhem to our planet with frequent flash floods and droughts, cloud burst events, food security at the edge, making occupants more significant risks unless corrective actions are implemented Oti and Kinuthia [68]. The burning of low-grade coal in brick kilns is one primary factor contributing to air pollution in SAR. India is second to China in brick production. The WHO report on diseases reveals that air pollution was the cause of 62,700 premature infant deaths in India alone in 2010. About 1000 brick kilns or more in Delhi's vicinity are supposed to be significant contributors (10%) of total air pollution by the report [69] in the Delhi-National Capital Region (NCR) region. Guttikunda and Calori [70] over 1,00,000 tons of yearly black carbon emissions are estimated in Indian bricks kilns. The three major air pollutants of brick kilns are dust, sulfur dioxide (SO_2), Black carbon, PM 2.5, and nitrogen oxides (NO_x) as per China's National Mandatory Standard [71]. The rise in respiratory diseases and disruptive ecological balance are some of the outcomes of brick kilns Zhang et al. [72].

In China, the elementary building material is clay bricks with over 60,000 clay bricks plants operating, with 800 trillion bricks per annum. Velasco et al. [73] assessed the significance of sustainable construction material. Velasco et al. [73] tried to draw the construction industry's attention towards its uses like recycling waste in plastic or buildings or waste of thermal power plants like flyash. An advanced and innovative design for making brick using asphalt mix as an additive Bonet et al. [74]. Aguilar et al. [75] designed their construction material from wastes to make ecologically green bricks. Alwetaishi et al. [76] briefed the reuse of Aluminum wastes as a raw material to manufacture green clay bricks. We propose that China and India, along with other South Asian clay brick industries, should alter their methods to switch to alternative material applications as a substitute for clay raw material.

In this article, use of flyash has been counseled as a substitution of fresh unused primary material for clay to make baked bricks. It is one of the beneficial initiatives to save land degradation and lessen pollution. As far as environmental study is concerned, unrestricted use of flyash-based bricks will not lead to any severe environmental problems Leiva et al.[57]. Figure 4 represents the Issues and opportunities analysis.

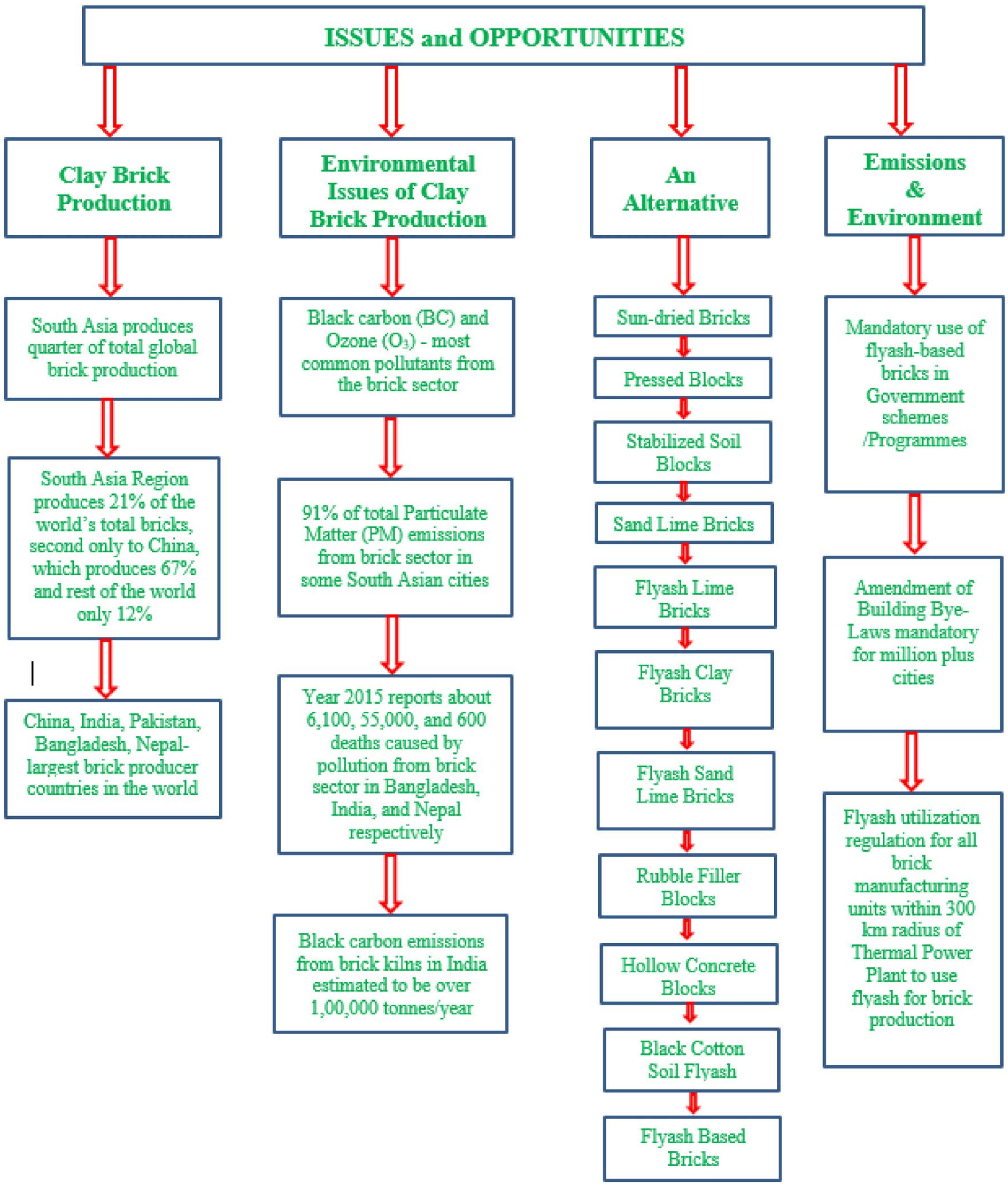

Fig. 4 Issues and opportunities analysis

Prospect

This review article presents the scope and direction for industry and research organizations. In this review article, issues related to clay bricks are discussed. The findings obtained from the past published studies on flyash-based bricks give a broad understanding to future research. Available research data on flyash-based bricks are presented, and research gaps for future work on flyash-based bricks were proposed.

The review article suggests that flyash-based bricks and blocks can be made by incorporating supplementary wastes such as (recycled crushed sand, crumb rubber, stone dust, and silica fume). The strength and durability of sustainable flyash-based bricks and blocks can be assessed. A comparative cost analysis program on flyash-based bricks and blocks will be developed. It would contribute to the industry by enhancing profitability and promoting sustainable construction materials with the help of new technologies. The study can be a good proposition for future research in the industry.

Based on the reviewed studies and discussion, the following technical prospect is made:

- Comprehensive research is available on the strength characteristics of flyash-based bricks and blocks.
- It has been found that a detailed durability analysis on flyash-based bricks and blocks is not reported extensively.
- Long-term durability analyses can be done on the flyash-based bricks and blocks.
- The addition of crumb rubber can improve the thermal resistance of flyash-based bricks and blocks with crumb rubber combinations.
- The addition of silica fume can improve durability, and partial replacement of cement will help reduce CO_2 emissions.
- The addition of recycled crushed sand also improves strength and durability characteristics, and its utilization will help maintain the ecological balance.

Conclusion

The objective of this review article was to discuss the alternatives of clay bricks for construction activities globally and in the South Asian Region notably. Based on observations and learnings, it is found that the traditional way of clay brick-making kilns is prevalent in the South Asian Region. However, the practice of using this type of kiln is a threat to our ecosystem. This review article aims to draw the attention of many researchers and scientists towards the rising climate changes globally. Ensuring that all clay brick kilns gradually switch from traditional to a more sustainable approach shall involve many consolidated efforts at the regional, national, and international levels. Processes and initiatives are mandatory to provide the fundamental edge to utilize waste materials such as flyash in brick manufacturing. Research associated with new technology for construction bricks containing significant flyash content can be a successful alternative to traditional clay bricks.

Proper flyash usage in brick manufacturing can successfully resolve environmental problems associated with clay bricks. An urgent consideration with studied actions is required for fundamental modernization in the bricks industry, especially in South Asian Region. As a development priority, governments must initiate projects to modernize brick manufacturing start-ups in their policies. Environment-friendly building materials such as flyash-based bricks will consume minimum energy, cause negligible pollution, and possess multi-faceted recycling attributes leading to better opportunities. The flyash-based bricks will help consolidate coherent resources, better environmental monitoring protection, and cleaner production. Flyash-based bricks are the renewed form of ancient times bricks making procedures.

References

1. Fiala J, Mikolas M, Krejsova K (2019) Full brick, history and future. In: IOP conference series: earth and environmental science, p 012139
2. Jha S, Nayak A, Sharma Y, Mishra V, Sharma D (2008) Fluoride accumulation in soil and vegetation in the vicinity of brick fields. Bull Environ Contam Toxicol 80:369–373
3. NIH (2018) Benefits of recycling. NIH Environmental Management System
4. Akhtar MN, Ibrahim Z, Bunnori NM, Jameel M, Tarannum N, Akhtar J (2021) Performance of sustainable sand concrete at ambient and elevated temperature. Elsevier, Amsterdam
5. Akhtar M, Khan M, Akhtar J (2014) Use of the falling-head method to assess permeability of fly ash based roof tiles with waste polythene fibre. Int J Sci Eng Res 5:476–483
6. Alam J, Akhtar M (2011) Fly ash utilization in different sectors in Indian scenario. Int J Emerg Trends Eng Dev 1:1–14
7. Akhtar MN, Akhtar J, Tarannum N (2019) Physiochemical characterization and dematerialization of coal class F flyash residues from thermal power plant. Civ Eng J 5:1041–1051
8. D. C. S. F. Ash (2020) Low carbon and resource efficient technology: scaling up of fly ash brick technology in India
9. Tang Z, Ma S, Ding J, Wang Y, Zheng S, Zhai G (2013) Current status and prospect of fly ash utilization in China. In: Proceedings of world of coal ash conference (WOCA), p 1–7
10. Report (2019–2020) Flyash generation at coal/lignite based thermal power stations. Ministry of Power, New Delhi, India
11. Lingbawan SG (2009) Thermal properties of fly ash bricks. The UNSW Canberra at ADFA. J Undergrad Eng Res 2:12–13
12. CSE-India (2015) Overview on brick kiln: pollution, technology and where we need to go? March 11 2015

13. Lopez A, Lyoda N, Segal R, Tsai T (2012) Building materials–pathways to efficiency in the South Asia brick-making industry. The Carbon War Room, School of Advanced International Studies, Johns Hopkins University
14. Mitra D (2016) Brick by brick/environment. Human Labour & Animal Welfare. United Kingdom
15. Zhang L (2013) Production of bricks from waste materials—a review. Constr Build Mater 47:643–655
16. ICIMOD (2017) Resource efficient burnt-clay bricks in India. International Centre for Integrated Mountain Development
17. Eil A, Li J, Baral P, Saikawa E (2020) Dirty stacks, high stakes: an overview of brick sector in South Asia
18. Statista (2021) Annual levels of brick production in Great Britain (GB) 2013–2018.
19. Baum E (2017) The brick industry worldwide. ESMAP & World Bank report. Ministry of Construction Vietnam, Vietnam
20. Agarwal A (2012) Overview of brick kiln sector in the country. AAEIT
21. Misra P, Imasu R, Hayashida S, Arbain AA, Avtar R, Takeuchi W (2020) Mapping brick kilns to support environmental impact studies around Delhi using Sentinel-2. ISPRS Int J Geo Inf 9:544
22. Das S, Sarkar R (2019) Impact of brickfields on soil quality of agricultural land along the Bhagirathi-Hugli river basin, West Bengal, India. Spat Inf Res 28:1–14
23. Francisco HA, de Los Angeles MS (1998) Soil resource depreciation and deforestation
24. Carson B (1992) The land, the farmer, and the future. International Centre for Integrated Mountain Development (ICIMOD)
25. Maria S, Croitoru L, Khaliquzzaman M, Ferdausi SA, Li J (2011) Introducing energy-efficient clean technologies in the brick sector of Bangladesh. Government of Bangladesh. Washington DC: Energy Sector Management Assistance Program (ESMAP), The World Bank
26. DMG-Events (2015) Construction market in India
27. Heierli U, Maithel S, Osborn P (2008) Brick by brick: the Herculean task of cleaning up the Asian brick industry. Swiss Agency for Development Cooperation, Natural Resources and Environment
28. Maithel S, Ravi A, Kumar S (2018) Roadmap for promoting resource efficient bricks in India: a 2032 strategy
29. Warren A (2002) Desertification is contextual. Land Degrad Dev 13:449–459
30. Gibbs H, Salmon JM (2015) Mapping the world's degraded lands. Appl Geogr 57:12–21
31. Turner KG, Anderson S, Gonzales-Chang M, Costanza R, Courville S, Dalgaard T et al (2016) A review of methods, data, and models to assess changes in the value of ecosystem services from land degradation and restoration. Ecol Model 319:190–207
32. Van der Laan C, Wicke B, Verweij PA, Faaij AP (2017) Mitigation of unwanted direct and indirect land-use change–an integrated approach illustrated for palm oil, pulpwood, rubber and rice production in North and East Kalimantan, Indonesia. Gcb Bioenergy 9:429–444
33. Prince S, Von Maltitz G, Zhang F, Byrne K, Driscoll C, Eshel G et al (2018) Status and trends of land degradation and restoration and associated changes in biodiversity and ecosystem functions. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem (ed)
34. Lambin EF, Turner BL, Geist HJ, Agbola SB, Angelsen A, Bruce JW et al (2001) The causes of land-use and land-cover change: moving beyond the myths. Glob Environ Chang 11:261–269
35. Lambin EF, Meyfroidt P (2011) Global land use change, economic globalization, and the looming land scarcity. Proc Natl Acad Sci 108:3465–3472
36. USDA. Soil formation. United States Department of Agriculture
37. Lambin E, Geist H, Lepers E (2003) Dynamics of land-use and landcover change in tropical regions. Ann Rev Environ Resour 28:205–241
38. Drescher J, Rembold K, Allen K, Faust H, Jaya N, Knohl A et al (2015) Ecological and socioeconomic functions of tropical lowland rainforest transformation systems: an integrative approach. Philos Trans R Soc 371:20150275
39. Palm C, Blanco-Canqui H, DeClerck F, Gatere L, Grace P (2014) Conservation agriculture and ecosystem services: an overview. Agric Ecosyst Environ 187:87–105
40. Ciais P, Sabine C, Bala G, Bopp L, Brovkin V, Canadell J et al (2014) Carbon and other biogeochemical cycles. In: Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (ed) Climate change 2013: the physical science basis. Cambridge University Press, Cambridge, p 465–570
41. Olsson L, Barbosa H, Bhadwal S, Cowie A, Delusca K, Flores-Renteria D et al (2019) Land degradation: IPCC special report on climate change, desertification, land 5 degradation, sustainable land management, food security, and 6 greenhouse gas fluxes in terrestrial ecosystems. In: ed: Intergovernmental Panel on Climate Change (IPCC). IPCC Special Report on Climate Change, Desertification, Land 5 Degradation, Sustainable Land Management, Food Security, and 6 Greenhouse gas fluxes in Terrestrial Ecosystems, p 1
42. Akhtar MN, Tarannum N (2018) Flyash as a resource material in construction industry: a clean approach to environment management. In: Sustainable construction and building materials, IntechOpen, New York
43. Harris D, Heidrich C, Feuerborn J (2019) Global aspects on coal combustion products. In: Proceedings of the world of coal ash (WOCA), St. Louis, MO, USA, pp 13–16
44. Case RJ, Duan K, Suntharavadivel TG (2012) On effects of fly ash as a partial replacement of cement on concrete strength. Appl Mech Mater 204–208:3970–3973
45. Sunil B, Manjunatha L, Ravi L, Yaragal SC (2015) Potential use of mine tailings and fly ash in concrete. Adv Concr Const 3:055
46. Baeza F, Payá J, Galao O, Saval J, Garcés P (2014) Blending of industrial waste from different sources as partial substitution of Portland cement in pastes and mortars. Constr Build Mater 66:645–653
47. Smol M, Kulczycka J, Henclik A, Gorazda K, Wzorek Z (2015) The possible use of sewage sludge ash (SSA) in the construction industry as a way towards a circular economy. J Clean Prod 95:45–54
48. Haleem A, Luthra S, Mannan B, Khurana S, Kumar S, Ahmad S (2016) Critical factors for the successful usage of fly ash in roads & bridges and embankments: analyzing Indian perspective. Resour Policy 49:334–348
49. Das K, Mishra J, Mustakim SM (2018) An overview of current research trends in geopolymer concrete. Int Res J Eng Technol (IRJET) 5:2395–2456
50. Thomas J, Mohan A, Rajesh P (2020) Properties of concrete containing quarry dust–fly-ash cold-bonded aggregates subjected to elevated temperature. J Mater Civ Eng 32:04020178
51. Kumar V, Mathur M, Sharma P (2000) Fly ash: a billion dollar resource-wasted so far. cbrienvis.nic.in (nd)
52. Market F (2019) The global fly ash market size was valued at USD 8.54 billion in 2019 and is projected to reach USD 13.33 billion by 2027, exhibiting a CAGR of 5.83 % during the forecast period
53. Dominguez EA, Ullman R (1996) 'Ecological bricks' made with clays and steel dust pollutants. Appl Clay Sci 11:237–249
54. Wiebusch B, Seyfried CF (1997) Utilization of sewage sludge ashes in the brick and tile industry. Water Sci Technol 36:251–258
55. Low carbon and resource efficient technology: scaling up of fly ash brick technology in India (2020)

56. Yang J, Liu W, Zhang L, Xiao B (2009) Preparation of load-bearing building materials from autoclaved phosphogypsum. Constr Build Mater 23:687–693
57. Leiva C, de Alcázar LS, Arenas C, Rodriguez-Galan M, Alonso-Fariñas B, Cornejo A et al (2014) Fired bricks with replacing clay by combustion fly ash in high volume ratio. In: Proceedings of the GPE–4th international congress on green process engineering, Sevilla, Spain
58. Kazmi SM, Abbas S, Saleem MA, Munir MJ, Khitab A (2016) Manufacturing of sustainable clay bricks: utilization of waste sugarcane bagasse and rice husk ashes. Constr Build Mater 120:29–41
59. Deng Y, Gong B, Chao Y, Dong T, Yang W, Hong M et al (2018) Sustainable utilization of municipal solid waste incineration fly ash for ceramic bricks with eco-friendly biosafety. Mater Today Sustain 1:32–38
60. Esmeray E, Atıs M (2019) Utilization of sewage sludge, oven slag and fly ash in clay brick production. Constr Build Mater 194:110–121
61. Guo X, Zhang T (2020) Utilization of municipal solid waste incineration fly ash to produce autoclaved and modified wall blocks. J Clean Prod 252:119759
62. Elavarasan S, Priya A, Kumar VK (2021) Manufacturing fired clay brick using fly ash and M-sand. Mater Today Proc 37:872–876
63. Warren J (1999) Conservation of brick
64. Culbert B, Christel A (2004) Continuous solid-state polycondensation of polyesters. Modern polyesters: chemistry and technology of polyesters and copolyesters, p 143–194
65. (2021) Fly ash bricks and comparison with clay bricks. https://theconstructor.org/building/fly-ash-bricks/5330/
66. IS-12894 (2002) Pulverized flyash-lime bricks-specification. Bureau of Indian Standards, New Delhi
67. IS-16720 (2018) Pulverized fuel ash-cement bricks—specification. Bureau of Indian Standards, New Delhi
68. Oti J, Kinuthia J (2012) Stabilised unfired clay bricks for environmental and sustainable use. Appl Clay Sci 58:52–59
69. Report. Brick kilns major source of air pollution in South Asia
70. Guttikunda SK, Calori G (2013) A GIS based emissions inventory at 1 km × 1 km spatial resolution for air pollution analysis in Delhi, India. Atmos Environ 67:101–111
71. MEP A (2012) GB 3095–2012 Ambient air quality standards. China Environmental Science Press, Beijing
72. Zhang J, Srinivasan RS, Peng C (2020) Ecological assessment of clay brick manufacturing in china using emergy analysis. Buildings 10:190
73. Velasco M, Morales Ortíz MP, Giró M, Velasco M (2014) Erratum: Fired clay bricks manufactured by adding wastes as sustainable construction material—a review. Constr Build Mater 63:97–107
74. Bonet-Martínez E, Pérez-Villarejo L, Eliche-Quesada D, Castro E (2018) Manufacture of sustainable clay bricks using waste from secondary aluminum recycling as raw material. Materials 11:2439
75. Aguilar-Penagos A, Gómez-Soberón JM, Rojas-Valencia MN (2017) Physicochemical, mineralogical and microscopic evaluation of sustainable bricks manufactured with construction wastes. Appl Sci 7:1012
76. Alwetaishi M, Kamel M, Al-Bustami N (2019) Sustainable applications of asphalt mixes with reclaimed asphalt pavement (RAP) materials: innovative and new building brick. Int J Low Carbon Technol 14:364–374
77. Reportlinker. Global fly ash industry. https://www.reportlinker.com/p05956793/?utm_source=GNW
78. Watson J (2019) Increased usage of fly ash into concrete and its corrosion resistance properties as well as alkali-silica reactivity is expected to increase demand for the product. www.reportsanddata.com
79. Yao Z, Ji X, Sarker P, Tang J, Ge L, Xia M et al (2015) A comprehensive review on the applications of coal fly ash. Earth Sci Rev 141:105–121
80. Akhtar J, Alam J, Akhtar M (2010) An experimental study on fibre reinforced fly ash based lime bricks. Int J Phys Sci 5:1688–1695
81. Sun ZJ, Tian ML, Fang YF (2011) Experimental research on mixture ratio and mechanical properties of unburned brick with shell ash and fly ash. Adv Mater Res 250–253:3299–3304
82. Zhang Z, Qian J, You C, Hu C (2012) Use of circulating fluidized bed combustion fly ash and slag in autoclaved brick. Constr Build Mater 35:109–116
83. Alam J, Khan M, Akhtar M (2013) Fly ash based brick tiles: an experimental study. Int J Emerg Trends Eng Dev 6:35–44
84. Ibrahim WMW, Abdullah M, Sandu AV, Hussin K, Sandu IG, Ismail KN et al (2014) Processing and characterization of fly ash-based geopolymer bricks. Rev Chim 65:1340–1345
85. Çiçek T, Çinçin Y (2015) Use of fly ash in production of lightweight building bricks. Constr Build Mater 94:521–527
86. Akhtar MN, Akhtar J, Al Hattamleh OH, Halahla AM (2016) Sustainable fly ash based roof tiles with waste polythene fibre: an experimental study. Open J Civ Eng 6:314
87. Wang L, Sun H, Sun Z, Ma E (2016) New technology and application of brick making with coal fly ash. J Mater Cycles Waste Manag 18:763–770
88. Masuka S, Gwenzi W, Rukuni T (2018) Development, engineering properties and potential applications of unfired earth bricks reinforced by coal fly ash, lime and wood aggregates. J Build Eng 18:312–320
89. Sutcu M, Erdogmus E, Gencel O, Gholampour A, Atan E, Ozbakkaloglu T (2019) Recycling of bottom ash and fly ash wastes in eco-friendly clay brick production. J Clean Prod 233:753–764
90. Hodhod OA, Alharthy SE, Bakr SM (2020) Physical and mechanical properties for metakaolin geopolymer bricks. Constr Build Mater 265:120217

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.