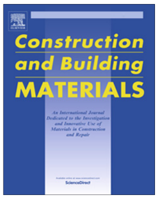
Construction and Building Materials 188 (2018) 1101–1118

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat



Review

A review of studies on bricks using alternative materials and approaches

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HIGHLIGHTS

- Two types of alternative bricks, namely material-oriented and process-oriented.
- Geopolymerisation is a preferable way to produce bricks.
- Clay-based geopolymer bricks can be one of the focuses of brick-related research.
- The key challenge is to improve the reactivity of clay at a low cost.

ARTICLE INFO

Article history:
Received 31 March 2018
Received in revised form 20 August 2018
Accepted 23 August 2018
Available online 4 September 2018

Keywords:
Alternative bricks
Alternative material
Alternative process
Sustainable development

ABSTRACT

Bricks have been playing a significant role in building and construction for thousands of years. Despite the reliable workability and accessibility, it is widely known that the production of fired clay brick has always been a rather energy- and resource-intensive process. Many researchers have been conducting a wide range of studies regarding sustainable and innovative bricks, to mitigate the large carbon footprint of brick industry. To better understand the development and current context of sustainable and innovative bricks during the past several decades, this paper provides an up-to-date review on the recent studies of bricks, categorising these publications according to the materials used and methods employed for the production of innovative bricks. This review found that firing is still the most common method to produce bricks, while this process involves enormous energy consumption and carbon footprint. Considering that cement and lime-based calcium-silicate-hydrate bricks are also not sustainable, Geopolymerisation is a preferable way to produce bricks, but corresponding cost and benefit analyses need to be conducted for relevant research. In addition, this paper suggests that clay-based geopolymer bricks could be one of the focuses of future brick-related research, and the key challenge is to improve the reactivity of clay at a low cost.

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https://doi.org/10.1016/j.conbuildmat.2018.08.152
0950-0618/

1. Introduction

Bricks have been playing a significant role in building and construction for thousands of years because of its outstanding properties such as great durability, high strength, low costs and so forth. The first brick produced by human beings traced back to 10,000 BCE, found in Egypt [1]. Clay block bricks were hand-moulded and sun-dried at that time. The ancient city of Ur (modern Iraq) around 4000 BCE was the earliest construction adopting clay bricks as the main materials. Dating back to 5000 BCE, there has been some records about using fire to produce clay bricks to yield better performance. Since then, the brick industry has been enormously developing and evolving especially benefited from modern machinery, such as powerful excavation equipment, motors, tunnel kilns and so forth. These significantly stimulated the capacity of brick production. In 2015, the global annual fired brick production was estimated at 1500 billion units [2].

Generally, there are 6 phases within the modern brick firing cycle: evaporation (20–150 °C), dehydration (149–650 °C), oxidation (300–982 °C), vitrification (900–1316 °C), flashing (1150–1316 °C), and cooling (1316–20 °C) [3,4]. The evaporation phase entails removal of the moisture content within raw materials and water added for brick shaping. Gradual temperature increasing rates in this phase is applied to avoid cracking caused by the difference of contraction rates between surface and core of the bricks. In the dehydration phase, the carbonaceous substances and some other hydrates within bricks will be decomposed and removed. Gradual temperature rising rates are still employed in this phase since rapid increasing rate can result in bloated bricks. The oxidation phase involves further combusting the carbonaceous remnants and oxidising the metal residues. This is essential for the manufacture of good quality bricks. To achieve this, excess oxygen will be provided to the combustion chamber in this phase. The next phase is the vitrification, which is the most important phase since it is directly related to the strength development of bricks. When the firing temperature is above 900 °C, the sintering process will start. This process transforms partial solid particles into liquid, which covers the rest of the solid particles. The liquid will solidify as the temperature falling, forming as glass binding the solid particles together. This is where the strength of fired bricks developed. The last two phases are flashing and cooling. The flashing phase is related to the colour of the final product, affected by the peak temperature and corresponding holding time. Bricks are finally produced after a gradual cooling period from the peak temperature to ambient temperature.

Despite the reliable workability and accessibility, it is undeniable that the production of fired clay brick has always been a rather energy- and resource-intensive process. It is reported that the mean energy consumed per tonne of bricks is estimated at 706 kWh and the emission of carbon dioxide per tonne was measured at 0.15 tonne [5]. Such high energy consumption and large carbon footprint obviously contradict with the requirement of sustainable development. Due to the both environmental and economic issues raised by the high demand for energy, many researchers have been conducting a wide range of studies regarding sustainable bricks, trying to mitigate the large carbon footprint of the brick industry.

This paper provides an up-to-date review on the recent studies of bricks to better understand the development and current context of sustainable bricks during the past several decades. The experimental designs and results of these publications are reported. A discussion about some missing elements in the existing literature is also conducted.

2. Previous reviews

A number of review papers [6–13] have been delivered, identifying many key issues regarding the characteristics, manufacture and potential of these bricks utilising alternative materials and/or approaches. Table 1 summarises the number and period of references, classification criteria, and key finding of these review papers.

According to Table 1, it can be found that the existing review papers has been slightly out-of-date. Most of the brick-related reviews covered the publication up to 2013. Although Boltakova et al. [13] reviewed the studies up to 2015, whereas it merely focused on the studies done by Russian researchers, neglecting the other relevant research projects. In addition, most of the previous review articles classified brick-related studies as per single criterion only, such as types of waste [7,12], functions of waste [6,11] and methods of manufacturing [8,10]. Some of these papers only covered a single kind of waste materials or manufacturing approach, such as agro-waste [9], industrial inorganic waste [12] and fired bricks [13]. The range of these review papers were not sufficiently extensive. Moreover, some of these publications simply listed the benefits of bricks using alternative materials and/or manufacturing methods but did not mentioned and analysed the drawbacks and future opportunities in the field of brick.

Therefore, to provide a wider coverage, this paper will contain bricks studies involving utilisation of alternative materials and manufacturing approaches, namely material-oriented and method-oriented sustainable bricks. The reviewing period will be set from 1970 to 2017. The factors related to the properties of bricks are to be reviewed, including material characteristics, shaping methods, firing/curing conditions, additives and so on. Lastly, a discussion in terms of the benefits and drawbacks as well as insights into future brick-related research will be provided.

3. Material-orientation

Material-oriented innovative bricks refer to those bricks incorporating different kinds of waste materials. Fig. 1 shows the recycling and recovery status of many types of waste materials in Australia. Although a certain amount of these waste materials has been recycled and recovered, there is still considerable waste simply landfilled and/or stockpiled. Incorporating these waste materials into bricks is one possibility to address the issue. This review divides material-oriented studies as per the type of waste they utilised. Two main groups are classified: municipal-waste-added and industrial-waste-added bricks.

Table 1
Summary of previous review papers about bricks.

Review papers	No. of references	Period	Classification Criteria	Key findings
Dondi et al. [6]	91	1977–1997	Functions of waste materials	• The most suitable waste materials are those abundant in carbonaceous and/or organic substances. There is significant energy savings caused by the combustion while firing. • However, the impacts of adding waste were not always positive. The prime examples include possible toxicity and high additional transportation costs.
Kadir and Mohajerani [7]	53	1980–2010	Types of waste materials	• Waste materials were categorised into fly ash, sludge and others. • It was argued that solid waste has been able to be used as alternative materials in fired clay brick production.
Raut et al. [8]	40	1982–2010	Methods of manufacturing	• The brick-related studies were classified as per treatments: pressing, drying at ambient temperature, drying in oven, curing & drying in oven and firing. • It was pointed out that the bricks using paper processing residue and waste paper pulp possessed the relatively high compressive strength compared with the bricks incorporating the other waste materials. • Studies on the strength of brick-mortar bond and the carbon footprint need also to be conducted to further examine the properties and viability of waste-create bricks.
Madurwar et al. [9]	59	1983–2012	Focusing on agro-waste	• Compressive strength and water absorption were two of the most common properties examined. • All the bricks in the reviewed papers satisfied the compressive strength requirement of standards while the water absorption did not.
Zhang [10]	98	1996–2013	Methods of manufacturing	• Firing, cementing and geopolymerisation were the three main methods to produce bricks. • Compressive strength and water absorption were two primary properties examined in each relevant study. • While many of these studies argued that the bricks manufactured with addition of waste materials could fulfil a variety of standards and some patents related to these bricks have been approved, there were few successful cases where the research outcomes were applied for commercial production of bricks. Concerns for potential contamination caused by waste materials and the slow industrial and public acceptance rate could be the reasons for this circumstance.
Monteiro and Vieira [11]	150	1972–2013	Functions of waste materials	• The brick-related research was divided into two groups as per the functions of the waste – fuel or organic and fluxing or inorganic. • This review criticised Zhang [10]'s argument that using firing method to produce waste added bricks has significant drawbacks such as high energy consumption and large carbon footprint. • It was possible to produce less-energy-consuming fired clay bricks incorporating the carbonaceous waste since these waste materials can make noticeable energetic contribution to firing process. • Geopolymerisation is an acceptable method to fabricate bricks but the suitable types of waste materials for this method are limited.
Velasco et al. [12]	63	2002–2013	Focusing on fired bricks; Types of waste materials	• The waste materials used in these studies were divided into four classifications, which were organic waste, inorganic residues, ashes and sludge. • The differentiations among these studies are in the shaping, drying and firing processes. • Water absorption and compressive strength were two of the most common tests performed for the bricks. • An increase in the amount of waste materials led to a decrease in compressive strength and an increase in water absorption. • This review suggested that other properties, such as water suction, thermal conductivity and acoustic response should also be tested as these properties have significant impacts on users' comfort.
Boltakova et al. [13]	100	2000–2015	Focusing on Russian studies; industrial inorganic waste	• All the research mentioned in the review was about fired bricks. • The most common tests were compressive strength and water absorption. • The review discussed several benefits provided by producing bricks with waste materials, such as the improvement in the properties of bricks, reduction in the manufacture costs, lower firing temperature, enclosure of toxic elements within waste and so forth

3.1. Municipal waste

Municipal waste (MW) is defined as inevitable by-products generated by human activities [15]. It primarily contains organics, glass, plastics, paper and metals. Amongst these types of MW, glass and plastics have higher potential to be used as the substitution material in the brick manufacturing. This is because not only they are abundant and accessible but also the current recycling situation of the two types of waste is disappointed. Although most countries have adopted relevant policies with regards to recycling plastic and glass waste, there is still a considerable amount of the plastic and glass waste being directly landfilled and/or simply stockpiled. In Australia, only 46.9% plastic packaging waste was recycled in 2014–2015 and for glass the figure was even lower at 41.4% [16]. While in Europe, it is in a better circumstance of glass recycling, there was still 30.8% of post-consumer plastic waste disposed to landfills [17]. In the U.S, the recycling rates for glass containers and polyethylene terephthalate (PET) bottles were only 32.5% and 31%, respectively [18]. These data are only of developed countries, not to mention those developing countries under much poorer circumstances. This suggested that over half of glass and plastic packaging waste were disposed without recycling. The unrecycled waste can last in the ground for up to hundreds of years as most of them were non-reactive and non-degradable. Hence, this will not only cause numerous environmental issues, but also significantly waste energy and resources. To tackle this problem, one possibility is to incorporate the glass and plastic waste as additives into clay bricks.

3.1.1. Glass

As early as 1970s, researchers have started to incorporate waste glass, mainly the glass packaging waste, into bricks as fluxing material and found that the soda-lime-glass could reduce the required firing temperature for the sintering process of clay bricks [19,20]. However, during that time, only a few brick manufacturers

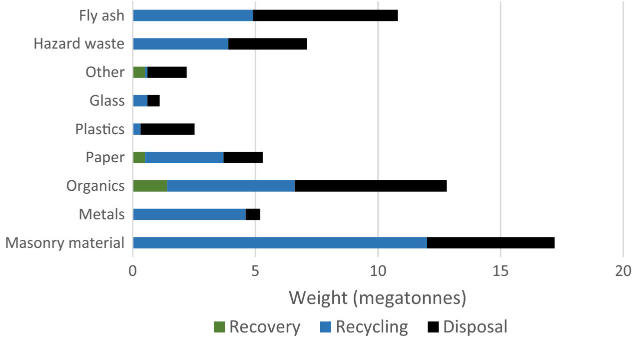

Fig. 1. Waste recycling and recovery situation, Australia 2014–15 (data sourced from Pickin and Randell [14]).

incorporated recycled glass into clay bricks as well as at a rather low substitution ratio. Kirby [21] explained this was because: 1) early studies mainly focused on very fine glass (200-mesh and finer); 2) using high volume fine glass can lower the workability of bricks; 3) the source of available economical fine glass is limited for brick manufacturing; 4) processing raw glass waste into very fine glass is not cost-effective.

The recent studies of glass-added bricks have not only limited to the use of packaging waste [21–36] but extended to other urban glass waste, such as thin film transistor liquid crystal display (TFT-LCD) [37], TV funnel & PC panel [38], fluorescent lamp [29,39,40], solar panel [41], cathode ray tube (CRT) funnel & panel [42,43], and laboratory borosilicate glass [32]. Table 2 summarises the details of these glass-related studies. A wide range of substitution ratios were employed in these research projects, as low as 1% and as high as 80%, but it is worth noting that most studies introduced glass waste at a ratio lower than 50 wt%. There are only two reviewed papers using over 50 wt% glass waste into bricks [29,36]. The particle sizes of waste glass used in these studies also varied, ranging from <0.075 mm to <4.75 mm. The X-Ray Fluorescence (XRF) results indicated that the chemical compositions of these glass waste were similar, mainly comprised of silicon dioxide (SiO_2), which qualifies glass waste as alternative construction materials. However, there were also some heavy metal elements in the glass waste such as TFT-LCD, fluorescence lamps and CRT funnel and panel. Thus, all the studies using these types of glass waste examined the leaching behaviours of brick samples. Most glass-related research used clay or shale as the binder material for bricks, while the particle size of the binder varied, ranging from <0.25 mm to <2.36 mm. There are two glass-related studies [33,36] employing fly ash, other than clay or shale as the binder material.

There are four types of specimens produced in these glass-brick studies; they are the ordinary-size, scale-down, bar, and cylinder samples. These samples were shaped through three ways: moulding [27,33], pressing [28,29,32,34,35,37,39–41,43] and extruding [22,24–26,38]. Most glass-added research projects introduced pressing method to produce samples, and the pressures applied ranged from 1 to 40 MPa. Once the samples were shaped, the drying process was performed. Nearly all the reviewed studies oven-dried their samples between 100 and 110 °C, while the air-drying process was not mentioned by these papers. The total drying duration varied between 3 hrs and 3 days. After drying, most glass-related studies chose to use firing method to process the samples. The firing temperature range from 650 [32] to 1200 °C, but most studies employed the temperature between 850 and 1100 °C. The heating ramp varied between 0.6 and 48 °C/min, and the flashing time or soaking time ranges from 1 to 6 h. It should be noted that only two of these glass-based papers used the method other than firing, using stabilising method instead [33,36].

It was found that three of the most common examined glass-added brick characteristics are water absorption (WA), compressive strength (CS), and shrinkage (SK). Basically, every study conducted tests to examine the three properties of their samples, and the findings were also similar. Most glass-related research found that the samples, containing relatively more glass and subject to relatively high firing temperature, possessed higher compressive strength and lower water absorption. Several reviewed papers examined the effect of the fineness of glass waste and found that the sample with relatively fine glass waste had higher strength and lower water absorption [24,31,42]. In addition, it should be noted that the effects of glass waste on brick shrinkage reported by these papers were not all consistent. Although most studies reported that addition of glass waste and higher firing temperatures could lead to higher shrinkage, there are four papers [26,27,30,42] mentioning that addition of glass waste tended to decrease the shrinkage.

In addition to the three most common properties, the other characteristics tested in the reviewed papers include flexure strength [21,27,29,35,38,39,42], thermal conductivity [33], energy consumption [21], crystalline phases [27,31,33,34,37,41], leaching behaviour [28,37,43], and durability [24,41]. It was reported by most studies that addition of glass waste could improve or provide comparable results in terms of these properties. A final point regarding these glass-related studies is whether they are laboratory based or industrial based. It was found that only three of the reviewed papers [22,23,42] were full or partial industrial-based.

3.1.2. Plastic waste

The existing research related to manufacturing clay bricks with plastic waste is much less than the use of glass waste. Table 3 summarises the recent studies about utilisation of plastic waste in brick manufacturing. The plastic waste used in these papers includes plastic containers (mainly PET bottles) [44–46], straws [47,48], PVC [49], low density polyethylene [50], and high impact polystyrene & acrylonitrile-butadiene-styrene [51]. Most plastic-related studies prepared the waste material by cutting it into little fibres (2–3 mm in size) or narrow strips (2–3 mm in length). There was one research project choosing to melt waste plastic bottle [44]. Plastic waste can be used to increase porosity of samples while firing or reinforce bricks under ambient temperatures. The substitution ratios normally range from 0.1 to 15 wt%, whereas there are two studies adding more than 50 wt%, up to 80 wt%, plastic waste into samples as they used the plastic waste as the binder material [44,50]. Only three reviewed studies mentioned the particle size of the clay used in their experiment, <2.36 mm [44] and<4.75 mm [45,46].

Four types of specimens were employed by the reviewed studies: cubes [47,48], bars [49], cylinders [45,46] and cuboids [44,51]. Three shaping methods involved to shape these samples: moulding [44,47,48], pressing [45,46,51], and extruding [50]. It should be noted that heated moulding or extruding were applied when the substitution ratio of plastic waste was high [44,50]. Due to the low ignition temperature of plastics, most plastic-related studies adopted stabilising method to produce samples, using cement [45–48], lime [47,48,51], or bitumen [44] as the stabiliser. The curing period ranges from 7 days to 28 days. The only one paper employing firing method was regarding PVC waste, which is rather different from PET waste [49]. Addition of PVC increased the porosity of fired bricks.

Water absorption and Compressive strength are two of the most common tests conducted in these plastic-related studies. The results fairly depended on the production method. It was found that addition of plastic waste tended to increase the WA in the reviewed studies manufacturing samples using firing method or stabilisers such as cement and lime. However, the studies introducing the plastic waste as the binder material showed contrasting results in terms of WA. Regarding CS, most studies found addition of plastic waste decreased the CS but possibly increased the tensile strength (TS) of samples. In addition, several studies showed that the type and size of plastic waste affected the WA and TS of samples [45,46]. The larger and longer plastic waste could result in higher WA and TS. It should be noted that the shrinkage of samples was not mentioned in most plastic-related studies. Other examined properties include flexure strength [49], tensile strength [46], thermal conductivity [48], and acoustic performance [50]. The results showed that addition of plastic waste could improve the thermal and acoustic performance of bricks. Lastly, it is worth noting that there was no plastic-related reviewed paper based in industrial-scale.

3.1.3. Other municipal waste

Few other municipal waste materials were introduced into brick manufacturing. Apart from glass and plastics, waste tea [52] and cigarette butts [53–55] are another two types of municipal waste that have been studied in previous research projects. Table 4 shows the information of these studies.

Demir [52] investigated the possibility of incorporating waste tea leaves into fired bricks. Since firing method was employed, the addition of tea leaves played the role as the fuel to provide extra energy. The raw material was the clay passing through 1 mm. The results showed that substituting clay with processed waste tea leaves improved the compressive strength of samples and increased the water absorption and shrinkage. The high tea content (up to 5 wt%) led to the high compressive strength. It was suggested that the water absorption of this type of bricks could be an issue because the result exceeded the maximum allowable.

Kadir and Mohajerani [53–55] conducted a series of experiments to examine the bricks added with cigarette butts. The experimental data revealed that addition of cigarette butts decreased the compressive strength, but enhanced flexure strength slightly when the ratio was 2.5 wt%. Both the samples' properties of water absorption and shrinkage were impacted adversely. The result of leaching test showed that the concentration of the metal leached out from cigarette-butt-added specimens was neglectable in accordance with the standards. In addition, this study explored the effect of mixing duration and heating rate on the properties of butts-created bricks. It was found that the long mixing time and slow heating rate led to better performance of the bricks.

3.2. Industrial waste

Industrial waste is the by-products generated by a wide range of industrial activities. Since the mid-twentieth, the world has been experiencing enormous industrial development, from the early OECD countries to the current industrialising countries. This process has been generating a large quantity of industrial waste, which could significantly affect the environment if no measure was taken [56]. To

Table 2
Recent studies on bricks with glass waste.

No.	Glass waste type (size/wt %)	Specimen dimension (mm)	Shaping/drying/firing/curing condition	Characteristics examined	Reference
1	Recycled glass (<150 μm/0, 10, 15, 20%)	25 * 25 * 172	Extruded at 16% moisture content; air-drying for 25 hrs; oven drying at 105 °C for 24 hrs; firing at a rate of 38 °C/hr to 982, 1010, 1038, 1066 °C; 1.5 hrs soak time	Shrinkage; water absorption; compressive strength	[22]
2	Recycled coloured glass containers (<100 μm/0, 5 10%)	200 * 100 * 50	Firing up to 1040 and 1100 °C	Shrinkage; water absorption; compressive strength	[23]
3	Recycled glass (<1.7 mm/0, 25, 50%)	101.6 * 203.2 * 38.1	Drying at 93.3 °C for 2 h; further drying at 176.7 °C for 1 h; firing with a ramp at 538 °C per hour to 1010 °C; holding for 20 min; naturally cooling	Absorption; flexure strength; energy consumption	[21]
4	Recycled glass (150–300 μm; 75–150 μm; 75–150 μm; 45–75 μm/0, 5, 10, 15%)	24 * 48 * (140-155)	Mixing; extruded at 3.374 kPa; air drying at room temperature for 24 hrs; oven-drying at 110 °C for 12 hrs; programmed to a maximum temperature of 1035 °C in the electronic kiln;1 hr soak time	Compressive strength test; absorption; porosity; shrinkage	[24]
5	Thin film transistor-liquid crystal display (TFT-LCD) waste glass (<1.18 mm/0, 10, 20, 30, 40%)	50 * 25 * 50	Mixing; pressed at 6 MPa; air drying at room temperature for 24 hrs; oven-drying at 80 °C for 24 hrs; heating to 800, 900, 1000 °C at a rate of 10 °C/min;6 hr soak time; cooling to 300 °C for 6 hrs; cooling to room temperature	Density; shrinkage; water absorption; compressive strength; Crystalline phases; leaching behaviours	[37]
6	Soda–lime–silica (sls) waste glass (fine (D90 = 0.13 mm); coarse (D90 = 0.45 mm)/30%)	N/A	Mixing; extruded; 60 °C/min from room temperature to 600 °C; holding at 600 °C for 2 hrs; 40 °C/min from 600 °C to 900, 950, 1000 °C; 4 hrs soak time	DTG-TGA; microstructure; chemical composition	[25]
7	Recycled glass (<0.5 mm/0, 2.5, 5, 10%)	75 * 40 * 100	Extruded; air drying at room temperature (21 °C, 60% humidity) for 24 hrs; oven drying at 110 °C; heating in electronic kiln to 850, 950, 1050 °C at 3 °C/min; 2 hrs soaking time; cooling to the ambient temperature in the furnace	Compressive strength; porosity; density; water absorption; shrinkage; loss on ignition (LOI); microstructure	[26]
8	TV funnel and PC panel (<0.25 mm/0, 2, 5%)	10 * 20 * 100	Extruded; drying at ambient temperature for 48 h; further drying at 100 °C for overnight in an electronic oven; firing with a ramp at 100 °C per hour to 900, 950, 1000 °C; 4 hrs soaking; natural cooling	Shrinkage; modulus of rupture; water absorption; porosity; density; leaching behaviours	[38]
9	Recycled glass (<1 mm/0, 15, 30, 45%)	65 * 70 * 40, 65 * 140 * 40	Moulded; air drying until constant weight achieved; firing at 1000–1200 °C with a ramping rate of 3 °C/min; 60 mins holding time; natural cooling to room temperature	Density; water absorption; porosity; compressive strength; modulus of rupture; microstructure; crystalline phases	[27]
10	Fluorescent Lamp Glass Waste (<150 μm/0, 2.5, 5, 10%)	114.5 * 2.54 * 10 mm	Pressed at 18 MPa; drying at 110 °C for 24 hrs; firing at 850 and 1050 °C with a ramp of 2 °C/min; 2 hrs soaking time	Shrinkage; water absorption; flexure strength	[39]
11	Solar panel glass waste (<1.18 mm/0, 10, 20, 30, 40%)	50 * 25 * 50 mm	Pressed at 6 MPa; air-drying at room temperature for 24 hrs; oven-drying at 80 °C for 24 hrs; firing at 700, 800, 900, 1000 °C for 6 hrs at the ramp of 10 °C/min	crystalline phases; chemical composition; leaching behaviours; salt crystallisation; weathering; compressive strength; water absorption; density; porosity	[41]
12	Recycled glass bottles (<250 μm/0, 5, 10%)	Cylinder: 30 (d) * 30 (h)	Pressed at 1 MPa; air-drying for 24 hrs; firing at 1150 °C (2 hr increasing temperature, 2 hr soaking, and 2 hr decreasing temperature)	Compressive strength; water absorption; shrinkage; leaching behaviours	[28]
13	Recycled glass containers and fluorescence lamps (<500 μm/0, 70, 80%)	50 * 5 * 4, 100 * 8 * 8	Pressed under 40 MPa; firing in an electronic laboratory furnace at a ramp of 10 °C/min to 950, 1000, 1050, 1100 °C; soaking for 1 hr	Shrinkage; water absorption; porosity; density; flexural tests; microstructure	[29]
14	Cathode ray tube funnel and panel glass (0.1–0.6 mm/0, 5, 10, 15, 20%)	N/A	930 °C, 36 h in industrial cycle	Shrinkage; water absorption; flexure strength	[42]
15	Recycled glass (<4.75 mm/0, 70%)	Cylinder: 50 (d) * 100(h)	Moulded and compacted; curing at 50 °C for 3–7 days	Compressive strength, microstructure	[36]
16	Cathode ray tube glass (<500 μm/0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10%)	N/A	Pressed; oven-drying at 100 °C for 15 days; firing at 1000 °C for 2 days	Compressive strength; water absorption; shrinkage; leaching behaviours	[43]
17	Fluorescent Lamp Glass Waste (<150 μm/0, 10, 20, 30%)	114.5 * 2.54 * 10	Pressed at 18 MPa; drying at 110 °C for 24 hrs; firing at 850–1100 °C in a laboratory furnace with a ramp of 2 °C/min; 2 hrs soaking; natural cooling inside the furnace	Chemical composition; microstructure; optical dilatometry	[40]
18	Recycled glass (<100 μm/0, 5, 10%)	140 * 65 * 40	Moulded; drying at room temperature 25–30 °C for 24 hrs; oven drying at 110 °C for 24 hrs; firing to 900, 950, 1000 °C by 8 hrs; 1 hr soaking time	Shrinkage; water absorption; density; porosity; compressive strength	[30]
19	Crushed glass bottles (<0.212, <0.3, and < 0.5 mm/0, 20, 25, 30%)	190 * 100 * 50	Air-drying at room temperature for 72 hrs; firing at 1000 °C for 12 hrs	Compressive strength; water absorption; shrinkage; microstructure; crystalline phases	[31]
20	Ground soda-lime glass, coloured glass and borosilicate glass (<0.86 mm/0, 20, 35, 50%)	50 * 50 * 50	Pressed under 50-ton pressure; air-drying overnight; oven-drying at 240 °C for 24 hrs; firing at 650, 850, 1050 °C for 3 hrs with the ramp of 5 °C/min; soaking for 15 min	Porosity; density; shrinkage; compressive strength; crystalline phases	[32]
21	Recycled glass (<90 μm/0, 20, 25, 30, 35%)	210 * 100 * 100	Moulded and vibrated; drying for several days; curing for 28 days	compressive strength, density, water absorption, porosity, thermal conductivity	[33]

(*continued on next page*)

Table 2 (*continued*)

No.	Glass waste type (size/wt %)	Specimen dimension (mm)	Shaping/drying/firing/curing condition	Characteristics examined	Reference
22	Recycled glass (425–475 µm/ 0, 20, 40%)	65 * 125 * 40	Pressed at 7.6 MPa; drying for 3 days; firing: N/A	chemical composition; microstructure	[34]
23	Ground coloured glass bottles (–/0, 5, 10, 15%)	100 * 20 * 12	Pressed at 6 MPa; air-drying at room temperature for 24 hrs; oven-drying at 60 °C for 24 hrs; firing to 1020 °C at the ramp of 48 °C/min; 5 hrs soaking time	Density; loss on ignition; shrinkage; open porosity; water absorption; flexure strength	[35]

Table 3
Recent studies on bricks with plastic waste.

No.	Plastic waste type (size/wt %)	Specimen dimension (mm)	Shaping/drying/firing/curing condition	Characteristics examined	Reference
1	Straw (–/2%), plastic fibres (–/0.1%), or polystyrene fabric (–/0.5%)	150 * 150 * 150 mm	Moulded and vibration; fibres were place at the position of 1/3 and 2/3 sample height; no firing; curing for a week	Compressive strength; water absorption	[47,48]
2	PVC waste (–/3%)	1.2 * 2 * 15 cm	Firing in a furnace between 900 and 1200 °C for 2 hrs at the ramp of 10C/min	Shrinkage; water absorption; flexure strength	[49]
3	PET Bottles (–/0, 65, 70, 75, 80%)	20 * 10 * 10 cm	Mixing molten plastic bottles with laterite soil; pouring the mixture in moulds then vibrating; demoulding 30 min later; air-drying for 24 hrs	Compressive strength; water absorption	[44]
4	PET Bottle fibres and Kit fibres (in width of 2–3 mm and length of 1–2 cm/0.1, 0.2%)	diameter of 101.5 mm and a height of 117 mm	Pressed under pressures from 1.25 to 7.5 MPa; moist curing under Jute bags for 28 days	Water absorption; sorptivity	[45,46]
5	LDPE (–/49%)	N/A	Preheating sawdust to 70 °C and LDPE to 100 °C; casting the bricks through thermoplastic extrusion techniques	Acoustic performance	[50]
6	High impact polystyrene (HIPS) (–/15%), or acrylonitrile–butadienestyrene (ABS) (–/15%)	40 * 40 * 160 mm	Compressed under the pressure of 20 MPa; saturated water steam temperature equal to 203 °C and pressure equal to 1.6 MPa for 8 hrs	Compressive strength; water absorption; density; softening coefficient	[51]

Table 4
Recent studies on bricks with other municipal waste.

No.	Municipal waste type (wt %)	Specimen dimensions (mm)	Shaping/drying/firing conditions	Characteristics examined	Reference
1	Processed waste tea leaves (0, 2.5, 5%)	40 * 70 * 100	Unfired: Dispersing waste tea in water for 24 hrs then mixing with clay; shaped with an extrusion machine; air-drying for 72 hrs; oven-drying until constant weight; Fired: same as unfired bricks; firing to 900 °C at a ramp of 2 °C/min until 600 °C then 5 °C/min; 2 hr soaking time	Crack; shrinkage; porosity; bulk density; apparent density; water absorption; compressive strength	[52]
2	Cigarette butts (0, 2.5, 5, 7.5, 10%)	100 * 100 * 100, 300 * 100 * 50, 225 * 110 * 75	butts were disinfected at 105 °C for 24 hrs; mixed with clay using mixer for 5, 10, and 15 min, respectively; moulded and demoulded; air-drying at 105 °C for 24 hrs; firing to 1050 °C	Compressive strength; flexure strength; density; water absorption; microstructure	[53]
3	Cigarette butts (0, 2.5, 5, 10%)	225 * 110 * 75	butts were disinfected at 105 °C for 24 hrs; mixed with clay using mixer for 5 min; moulded and demoulded; air-drying at 105 °C for 24 hrs; firing to 1050 °C	Leaching behaviour; toxicity characteristic	[54]
4	Cigarette butts (0, 2.5, 5, 7.5, 10%)	100 * 100 * 100, 300 * 100 * 50, 225 * 110 * 75	butts were disinfected at 105 °C for 24 hrs; mixed with clay using mixer for 5, 10 and 15 min, respectively; moulded and demoulded; air-drying to 105 °C for 24 hrs; firing to 1050 °C at the ramps of 0.7, 2, 5 °C/min, respectively	Compressive strength; flexure strength; water absorption; shrinkage; density; thermal conductivity; leaching behaviour; emissions; energy consumption	[55]

address this issue, many research projects had been conducted. This review divided these reviewed industrial waste related studies into several sub-groups according to the types, namely sludge, slag, ash and other industrial waste.

3.2.1. Sludge

The studies reviewed by this paper covered a few different types of sludge waste, including tannery sludge [57,58], wastewater and sewage treatment sludge [59–67], textile sludge [68,69], masonry industry sludge [70], paper mill sludge [71], glass cutting and polishing sludge [72], oil refining and extracting sludge [73]. Table 5 provides the details of these studies.

Since sludge is a kind of semi-dry slurry, some treatments may need to be done on it. Three types of treatments were involved in these sludge-related studies. In most of the studies, sludge was dried and ground and with the particle size ranging from 0.063 to 2 mm. One paper chose to incinerate the sludge at 500 °C [59], and another one kept the sludge untreated with rich moisture content [73]. As the sources of the studied sludge were quite different, the properties were distinct as well. Many research projects did not examine sludge through XRF, but the pozzolanic materials within sludge were sufficient to qualify it as alternate construction materials. One of the common points was that all the sludge materials contained heavy metal, including Co, Cr, Pb, Ni. The researchers intended to immobilise these heavy metals by incorporating them into bricks. Most reviewed studies used clay as the main binder material, while Okuno and Takahashi [60] substituted all the raw brick material with the sludge and there is a study employing incinerator bottom ash as the binder material [65]. In addition, it should be noted that most researchers did not mention the particle size of the raw clay used. The mentioned sizes of raw clay ranged from <0.15 mm to <1 mm. Regarding the substitution ratios, 0–50 wt% were introduced by most sludge-related studies. Lin et al. [65] investigated the effects of addition of high-volume sludge, ranging from 70 to 98 wt%.

Four types of samples were employed by the sludge-related papers; they are ordinary-size [62,63,69,72], scale-down [71,73], cube [70], and cuboid [59,68,70]. Three shaping methods were introduced to produce these samples: moulding

Table 5
Recent studies on bricks with sludge.

No.	Sludge waste types (wt %)	Specimen dimensions (mm)	Shaping/drying/firing conditions	Characteristics examined	Reference
1	Tannery sludge (0, 10, 15%)	N/A	Firing at 950 °C	Shrinkage; water absorption; flexure strength; frost resistance; porosity; leaching behaviour; emissions	[57]
2	Wastewater treatment sludge: dried sludge and sludge ash (0, 10, 20, 30, 40, 50%)	40 * 20 * 20	Shaped with an extrusion machine; air-drying at 100 °C for 24 hrs; firing at 1000+ °C in a kiln for 24 hrs	Shrinkage; water absorption; compressive strength	[59]
3	Sewage sludge (100%)	N/A	Pressed under 98 MPa with vacuuming under 26 kPa; firing to 1000 °C and over at a ramp of 600 °C/hr; 4 hr cooling time	Shrinkage; water absorption; compressive strength; flexure strength; leaching behaviour; energy consumption	[60]
4	Sewage sludge ash (0, 10, 20, 40%)	N/A	N/A	Water absorption; density; compressive strength	[61]
5	Sewage sludge (0, 10, 20, 30, 40, 50, 100%)	230 * 110 * 60	Sludge was dried at 103 °C for 1 day then incinerated at 800 °C to remove organic substance; moulded with 13–15% moisture content; air-drying for 24 hrs; oven-drying at 105 °C for 24 hrs; firing to 950, 1000, 1050 °C for 6 hrs	Shrinkage; loss on ignition; water absorption; bulk density; compressive strength	[62]
6	Tannery sludge (0, 10, 20, 30, 9%)	60 * 20 * 8	Dried mixed and ground for 24 hrs; mixed using PVA; pressed and moulded at 20 MPa; oven-drying at 110 °C for 24 hrs; firing to 1000, 1100 and 1180 °C for 2 hrs	Water absorption; porosity; shrinkage; rupture strength; environmental compatibility	[58]
7	Wastewater treatment sludge (0, 10, 20, 30, 40%)	230 * 110 * 60	Moulded; 24 hr maturation; oven-drying at 103 °C for 24 hrs; firing to 880, 920, 960, 1000 °C for 6 hrs	Shrinkage; loss on ignition; water absorption; bulk density; compressive strength; leaching behaviour	[63]
8	Sewage sludge (0, 10, 20, 30, 40%)	N/A	hand-moulded by compaction using a rammer; oven-drying at 150 °C for 85 hrs; firing to 985 °C for over 12 hrs; 14 hr soaking time; 16 hr cooling time	Shrinkage; water absorption; compressive strength	[64]
9	Textile effluent treatment sludge (0, 10, 20, 30%)	190 * 90 * 90	N/A	Compressive strength; water absorption; efflorescence	[68]
10	Water treatment sludge: dried and ground (70, 75, 80, 85, 90, 95, 98%)	N/A	Mixing ash with the sludge in different particle sizes; pressed at 11 MPa; oven-drying at 105 °C for 48 hrs; firing to 900, 1000, 1050, 1100, 1150, 1200 °C at the ramp of 3–5 °C/min; soaking for 60–360 min	Shrinkage; density; water absorption; compressive strength; permeability	[65]
11	Wastewater treatment sludge (3.3–23.8%)	50–120 in. length	Extruded under the pressure ranging from 0 to 2.05 MPa; cut into 5–12 cm length testing pieces; firing to 980 °C at the ramp of 160 °C/h; 3 hr soaking time; 12 hrs cooling time	Compressive strength; density; porosity; leaching behaviour; thermal performance	[66]
12	Water treatment sludge (0, 10, 15, 20%)	60 * 20 * 5	Pressed under 19 MPa; drying; firing to 850, 900, 1000, 1100, 1150 °C, respectively	Shrinkage; water absorption; porosity; flexure strength	[67]
13	Hot-dip galvanisation sludge (0, 3, 6%)	120 * 50 * 14; 55.3 * 36 * 36; 30 * 30 * 30	Extruded; drying at 105 °C; firing at 870, 920, 970, 1020 °C, respectively, at the ramps of 1.4 °C/min before 610 °C and 2.5 °C/min after; 2 hr soaking time	Compressive strength; water absorption; porosity; Leaching behaviour	[70]
14	Texture laundry sludge (0, 5, 10, 15, 20%)	73 * 35 * 55; 200 * 100 * 150	Extruded; drying at 100 °C for 24 hrs; firing to 900 °C for 3 days	Flexure strength; water absorption; leaching behaviour	[69]
15	Sludge from oil refining industry and pomace oil extraction industry (0, 2.5, 5, 7.5, 10, 15, 20, 25, 30%)	30 * 10 * 60	Pressed under 54.5 MPa; firing to 950 °C at the ramp of 3 °C/min for 4 hrs	Appearance; density; shrinkage; loss on ignition; porosity; water absorption; compressive strength; thermal conductivity; leaching behaviour	[73]
16	Paper mill sludge (0, 5, 10, 15, 20%)	61 * 29 * 19	Mixing sludge with clay at the 20–25% moisture content; hand-moulded; air-drying at room temperature for 24 hrs; oven-drying at 105 °C for 24 hrs; firing to 850 and 900 °C for 7–8 hrs; 1 hr soaking time	Shrinkage; water absorption; density; porosity; compressive strength; modulus of elasticity	[71]
17	Glass polishing and cutting sludge (0, 5, 10, 15, 20, 25%)	228 * 114 * 76	dry-mixed; adding water and mixing; sun-drying for 3 days; firing at 850 °C for 36 hrs in a kiln	Shrinkage; density; compressive strength; porosity; flexure strength; water absorption; efflorescence; freeze and thaw; sulphate resistance; ultrasonic pulse velocity	[72]

[62,63,71], pressing [58,60,64,65,67,73] at the pressures ranging from 1 to 98 MPa, and extruding [59,66,69,70] with or without vacuuming. Nearly all the reviewed studies oven-dried their samples at the temperatures ranging from 100 to 110 °C. It is worth noting that all these sludge-related studies were based on the firing method, employing the temperatures between 850 and 1200 °C, at the ramps from 1.4 to 10 °C/min, and with the soaking time from 1 to 6 h.

For these reviewed sludge-related papers, the three most common tested properties are Water absorption, Compressive strength and Shrinkage as well. For WA, it was found that addition of all the sludge increased the WA of samples, except the waste glass sludge [72]. This should be because the waste glass sludge is very rich in SiO_2. The same trend was also observed in terms of the strength of samples. Waste glass sludge was the only waste material tending to increase the strength of samples. As for SK, over half of the reviewed papers showed that addition of sludge increased the shrinkage, whereas there are still several papers obtaining the contrasting results [60,62,64,72]. Since the sludge usually contains many heavy metals, the leaching behaviour of samples were examined in most reviewed papers. All the results showed that the heavy metals were well immobilised in the samples. This should be attributed to the use of firing method.

Other properties tested in the reviewed papers involved flexure strength, thermal conductivity, durability, emissions, and energy consumption. Most reviewed studies found that addition of sludge could improve these properties. Furthermore, there are several interesting findings that need to be noted. The first is that addition of sludge possibly lead to cracking and bloating problems about bricks [64]. The second is that coarse sludge has the potential to produce permeable bricks [65]. The last is that the bricks manufactured in the industrial-scale can possess better properties [69]. Again, regarding the problem of laboratory- or industrial-scale, relatively more reviewed sludge-related studies are in full/partial industrial-scale [57,60,69,72].

3.2.2. Slag

Slag is a type of glass-like by-products that generated from the industrial activities such as metal extraction, incineration and so forth. The types of slag reviewed by this paper include granulated blast furnace slag (GBFS) [74–78], molten slag [79], integrated gasification combined cycle (IGCC) slag [80], municipal solid waste incinerator slag [81], waelz slag [82], ferrochromium slag [83]. Over half of these studies were about GBFS. Table 6 summarises the information about the experimental design and results of these papers.

The particle sizes of slag ranged from <0.074 to <5 mm. The XRF results showed that CaO, SiO_2 and Al_2O_3 were the main compositions of all the slag materials. The existence of CaO enabled the slag-based bricks to be manufactured at room temperatures other than 1000 °C-high temperature, indicating the potential of slag to be utilised as construction and building materials. Most slag-related studies employed clay as the binder materials, while there was one paper using only slag as the binder material and adding a small proportion of sintering accelerator [79]. Most projects employed the raw clay passing through 5 mm, while several papers indicated the finer raw clay was used varying from <0.075 mm to <0.7 mm. Regarding the substitution ratios, most of the studies introduced the slag at the ratios below 50 wt%, except the above one.

Four types of specimens were prepared by these slag-related studies; they are ordinary-size [76–79], scale-down [82,83], cube [74,75], and cuboid [81] samples. These samples were shaped through three ways: moulding [74], pressing [76–81,84] and extruding [82]. For the pressing method, the forming pressures range from 6 to 22.5 MPa. The drying process followed the shaping process. Unlike above glass and sludge papers, the drying temperatures for slag-added samples were mainly between 40 and 80 °C, other than the temperature between 100 and 110 °C. Firing method was still the most common way employed by these studies. Although there were 3 out of 10 slag-related papers using the lime-stabilising method, they were all done by the same research team [76–78]. The firing temperatures range from 800 to 1175 °C. For the studies using lime as the stabiliser, the samples were cured at 20 °C for 7–90 days

The three most common brick properties tested in these slag-related papers were still Water absorption, Compressive strength and Shrinkage. Most of the studies obtained the result that addition of slag could reduce the WA of samples, regardless of the type of slag. There was one interesting result showing that the firing temperature of 1125 °C could result in lower WA. El-Mahllawy [75] found and explained this that 1125 °C is the temperature, at which silica polymorphous transformation occurs, so samples fired at this temperature have a lower WA. The silica polymorphous transformation also affected the CS of samples, leading to a higher CS of samples. As to other slag-related papers, the effects of slag on CS were not all the same. For example, Shih et al. [74] found that the CS increased when 5% slag was added but decreased when the addition ratio was over 5%, while Lin [81] found the similar result but at the ratio of 10%. Also, some studies [82,83] found addition of slag only decreased the strength. This may be because different types of slag have different effects on samples. Nevertheless, all these reviewed slag-related studies reported that the samples could meet the requirement of standards in terms of CS. In relation to SK, few studies commented on the effects of slag on this property, but there was an interesting result showing that the finer slag tended to increase the SK of samples [80].

Other properties tested in these reviewed papers include flexure strength [79,82,83], leaching behaviour [79,81,82], durability [76,80], emission and energy consumption [78,82], and thermal conductivity [83]. It was found that addition of slag tended to improve these properties or make it comparable to common bricks, except the thermal conductivity [83]. Lastly, it is worth noting that 4 out of the 10 reviewed papers were in full/partial industrial-scale.

3.2.3. Coal ash

Coal Ash is powder-like by-products produced by the process of firing, mainly found in power plants. Table 7 provides the details of the recent coal ash-related studies. The particle sizes of these ashes range from 0.1 to 1 mm. SiO_2 and Al_2O_3 were the main compositions of these ash. There were less CaO in the coal ash compared with slag. The abundance in pozzolanic substances such as SiO_2 and Al_2O_3 allowed the ash-added samples to be produced through alkali-activation or geopolymerisation. Clay was not the only binder material used in these ash-related studies and the particle size ranged from <0.1 mm to <10 mm. Other materials such as metal finishing waste [84], rice husk ash [85] were also introduced the samples. A wide range of substitution ratios were adopted in these ash-related papers, from as low as 1.5 wt% [86] to as high as 100 wt% [84,87,88].

Five types of specimens were involved in these reviewed papers, including ordinary-size [85,89–92], scale-down [93], cube [94], cuboid [86,94,95], and cylinder [84,87–90,96]. Three forming methods were used by these studies: moulding [87,91,92,95], pressing [84,85,88–90,96], and extruding [86,93]. The forming pressures for pressing method range from 6.25 to 38 MPa. It should be noted that 7 out of 13 reviewed ash-related papers adopted the methods other than firing to produce their samples. Oven-drying was not required for the samples in these studies. Thus, for the samples using the methods other than firing, they were cured at ambient temperature or heat-cured at the temperatures ranging from 55 to

Table 6
Recent studies on bricks with slag.

No.	Slag waste types (size/wt %)	Specimen dimensions (mm)	Shaping/drying/firing/curing conditions	Characteristics examined	Reference
1	Molten slag (–/45.5, 91%	200 * 100 * 60	Pressed under 6 MPa; drying at 110 °C for 48 hrs; firing to 900 °C (15 hrs) and 1000 °C (17 hrs); 2 hr soaking time	Density; shrinkage; permeability; flexure strength; compressive strength; leaching behaviour	[79]
2	Integrated gasification combined cycle slag (<4 or 0.62 mm/0, 30, 50%)	N/A	Pressed; drying at 65 °C; firing at 930 °C	Water absorption; water suction; compressive strength; shrinkage; loss on ignition; frost resistance; microstructure	[80]
3	Stainless steel slag (<0.074 mm/0, 5, 10, 20, 30%)	50 * 50 * 50	mixed with 60% moisture content; moulded; air-drying for 24 hrs; oven-drying at 80 °C for 24 hrs; firing to 500 °C for 2 hrs then to 800, 950, 1000, 1050 or 1100 °C for 6 hrs; 6 hr soaking time; cooling down to 300 °C in 6 hrs then to room temperature	Shrinkage; loss on ignition; water absorption; compressive strength	[74]
4	Municipal solid waste incinerator slag (<1.1 mm/0, 10, 20, 30, 40%)	50 * 25 * 50	Mixing; pressed under 6 MPa; air-drying at room temperature for 24 hrs; oven-drying at 80C for 24 hrs; firing to 800, 900, 1000 °C at the ramp of 10 °C/min	Shrinkage; density; loss on ignition; water absorption; compressive strength; leaching behaviour; microstructure	[81]
5	Granulated blast furnace slag (<90 μm/10, 20, 30, 40, 50%)	50 * 50 * 50	Pressed under 22.5 MPa; oven-drying at 80 °C for 24 hrs; firing to 1100, 1125, 1150, 1175 °C at the ramp of 5 °C/min; 4 hr soaking time	Shrinkage; density; water absorption; acid weight loss; compressive strength	[75]
6	Granulated furnace blast slag (–/5–11%)	215 * 102 * 65	Cast through a hydraulic press under 15 MPa; curing in a plastic container at 20 °C for 7, 28, 56, 90 days	Water absorption; compressive strength; voids; resistance to freeze and thaw; microstructure; energy consumption and emissions	[76–78]
7	Waelz slag (–/5, 10, 15, 20, 25, 30, 35%)	100 * 80 * 20	Mixing; extruded; drying at 96–104 °C; firing to 850 °C at the ramp of 0.85 °C/min; cooling down at the ramp of 1.14 °C/min	Density; water absorption; porosity; flexure strength; leaching behaviour; emission	[82]
8	Ferrochromium slag (–/0, 5, 10, 15, 20, 30%)	100 * 50 * 20	Dry-mixing for 30 min; wet-mixing at 15% moisture content; pressed under 20 MPa; air-drying for 24 hrs; oven-drying at 40 °C for 12 hrs and at 100 °C for 24 hrs; firing to 900 °C at the ramp of 5 °C/min; 2 hr soaking time	Density; loss on ignition; porosity; water absorption; compressive strength; flexure strength; thermal conductivity; microstructure	[83]

Table 7
Recent studies on bricks with coal ash.

No.	Coal Ash waste types (size/wt %)	Specimen dimensions (mm)	Shaping/drying/firing/curing conditions	Characteristics examined	Reference
1	Orimulsion fly ash (–/0, 1.5, 3, 6%)	100 * 20 * 10	Hand mixing and storing for 7 days; extruded; drying at room temperature for 48 hrs; oven-drying at 100 °C for 24 hrs; firing with 3 thermal cycles	Shrinkage; modulus of rupture; density; water absorption; porosity;	[86]
2	Fly ash (–/0, 50, 60, 70, 80%)	60 * 60 * 25	Unfired: mixing; moulded; drying at room temperature for 2 days; oven-drying at 60 °C for 4 hrs and 100 °C for 6 hrs. Fired: same as unfired; firing to 1000, 1050, 1100 °C at the ramps of 100 °C/hr below 500 °C and 50 °C/hr beyond 500 °C	Compressive strength; porosity; water absorption; density	[95]
3	Coal fly ash (33 μm/90, 100%)	20 in. diameter, 5 g in weight	Pressed at 38 MPa; drying at 105C for 12 hrs; firing to 1000, 1050, 1100, 1150, 1200, 1225, 1250 °C at the ramp of 20 °C/min; 1 hr soaking time; cooling to room temperature at the ramp of 20 °C/min	Density; water absorption; shrinkage; crystalline phases; microstructure	[84]
4	Fly ash (<0.1 mm/5%)	30 * 30 * 30, 5 * 5 * 3, 1 * 1 * 1	Mixing; firing to 800, 900, 1000 °C	Poisson coefficient; Young's modulus; shear modulus; bulk modulus; compressive strength; absorption; durability	[94]
5	Coal fly ash (<100 μm/30, 100%)	Cylinder: 50 in. diameter, 100 in. height	Mixing at the liquid to fly ash ratio (L/FA) of 0.4, 0.5, 0.6, 0.7; pressed; kept at 27–30 °C for 24 hrs; heat-cured at 65, 75, 85 °C for 24, 48, 72 hrs	Compressive strength; leaching behaviour	[96]
6	Coal fly ash (<100 μm/30, 50, 70%)	Cylinder: 50 in. diameter, 100 in. height, 230 * 90 * 75	Mixing at the liquid to fly ash ratio (L/FA) of 0.4, 0.5, 0.6, 0.7; pressed; kept at 27–30 °C for 24 hrs; heat-cured at 55, 65, 75, 85, 120, 130, 140 °C for 24, 48, 72, 120, 168 hrs	Compressive strength; microstructure	[89]
7	Coal fly ash (<1 mm/88, 90, 92%)	Cylinder: 45 in. diameter and 100 in. height, 200 * 200 * (90–110)	Mixing; pressed at 6.25 MPa; autoclaved at 1.2 MPa for 6 hrs	Compressive strength; density	[90]
8	Class F fly ash (–/338.5 kg/m3)	220 * 105 * 60	Mixing fly ash with alkaline activator; adding rice husk ash and sand then mixing; pouring into mould; pressed at 35 MPa; demoulded; uncovered curing at 35 °C and 50% relative humidity	Compressive strength; flexure strength; density; water absorption; void	[85]
9	Class F fly ash; Bottom ash (<10 mm/at the bottom ash/fly ash ratios of 1:1, 1:0.75, 1:0.5, 1:1.25	200 * 90 * 60	Mixing bottom ash with cement in dry state for 2 min; adding fly ash and mixing for another 2 min; adding water and mixing; pouring into mould; curing at 22 °C and 95% relative humidity	Compressive strength; ultrasonic pulse velocity (UPV); modulus of rupture; water absorption; initial rate of suction; fire resistance; durability	[91]
10	Co-combustion fly ash (<0.1 mm/0, 20, 40, 60, 80, 100%)	Cylinder: 32.5 in. diameter and 50 in. height	Mixing; pressed at 10 MPa; demoulded; drying at 60 °C until constant weight; firing to at the ramps of 100 °C/h below 500 °C and 50 °C/h beyond 500 °C to 800, 900, 1000 °C; 8 hr soaking time	Density; water absorption; shrinkage; compressive strength; efflorescence; leaching behaviour	[88]
11	Fly ash (FA) and bottom ash (BA) (–/at FA/BA of 1:2, 1:3, 1:4)	215 * 102.5 * 65	Mixing; pouring into mould; heat-curing at 70 °C for 24 hrs; curing for 7 days	Compressive strength; water absorption	[97]

140 °C. It is worth noting that the ambient temperature differs amongst different geological locations. For example, the ambient temperature of Thailand is between 27 and 30 °C [89,96], while others are only 20 °C. In addition, some studies cured their sample at a specific relative humidity, such as 50% [85], 95% [91] and 100% [87], in case of rapid loss of moisture. For the other papers using firing method, the samples were similarly oven-dried at the temperature between 60 and 100 °C after shaping process. The firing temperature for these samples range from 800 and 1250 °C.

Water absorption and Compressive strength are two of the most common properties examined in these review papers. It was found that addition of coal fly ash increased the WA when the samples were produced by firing method. The contrasting trend was found in the coal fly ash studies stabilising samples with cement or alkaline activator. For rice husk ash, it was found that addition of unground rice husk ash could result in an increase in WA [85]. An interesting finding is that finer fly ash could decrease the WA [95]. As to CS, the reviewed papers using firing method showed that increased addition of ash reduced the CS, whereas the paper using cement [91] showed the contrasting result. The studies using alkaline activator found that the highest CS appeared in the group with the activator/ash of 0.6. There was not a monotonous relationship between the CS and ash content [89,96].

Additional properties of samples tested in these papers contain flexure strength [85,93], modulus of rupture [86,91,94], crystalline phases [84,89], durability [91,94], leaching behaviour [87,88,93,96], and fire resistance [91]. It should be noted that all the review ash-related studies were laboratory-based.

3.2.4. Biomass ash

Apart from coal ash waste, biomass ash waste materials, such as wood ash, rice husk ash, municipal waste incinerator ash, have also been researched in terms of the viability for brick manufacturing (see Table 8). All the biomass ash was treated via calcination to eliminate organic contents. The chemical composition varied from ash to ash. The common parts included SiO_2 and CaO, both of which could qualify these biomass ash as alternative construction materials regardless of manufacturing methods. All of the reviewed studies employed clay as the binder materials except [87], who used incinerator ash and coal fly ash only for brick making. The particle sizes of the clay material varied from 0.5 mm to 6 mm, and some research did not mention this parameter. Amongst the biomass ash-related studies, the substitution ratios of waste ranged from 0 to 100 wt%, while most of the research projects examined the effect of high volume ash (at least 30 wt%) on the properties of samples.

Three types of samples were introduced by these studies, namely ordinary size [98], scale down [93,99,100] and cylinder [87]. The samples were shaped via extruding, moulding or pressing. The pressing pressure ranged from 20 to 54.5 MPa. Firing was still the main method adopted by the researchers [93,99,100]. The firing temperature varied between 950 and 1075 °C. The other studies used the stabilising method, adding lime or cement into mixtures.

Nearly every biomass ash-related articles examined the compressive strength and water absorption of the samples. It was found that all the samples incorporating biomass had inferior properties of CS and WA compared with control groups without biomass ash. Regarding shrinkage, different waste ash had distinct effects on it. For example, gasification and incinerator ash tended to decrease the shrinkage of samples, while rice husk and wood ash increased the shrinkage [93,99,100].

Other characteristics mentioned by these papers includes leaching behaviours [87,93,100], efflorescence [98], flexure strength [93,98] and thermal behaviours [100]. It was reported that utilisation of biomass ash in bricks could fulfil the requirement of leach behaviours and improved the samples' thermal performance when introducing rice husk and wood ash. There was only one study producing samples in industrial cycles among the reviewed publications [98].

Table 8
Recent studies on bricks with biomass ash.

No.	Biomass Ash waste types (size/wt %)	Specimen dimensions (mm)	Shaping/drying/firing/curing conditions	Characteristics examined	Reference
1	Biomass gasification ash (<0.3 mm/15, 20%)	130 * 30 * 20	Extruded; oven-drying until constant weight; firing to 1000, 1025, 1050, 1075C using 2 firing cycles: 4 °C/min below 400 °C, 3 °C/min from 400 to 700 °C, 2 °C/min beyond 700 °C, 4 hr soaking time, cooling down at 4 °C/min; and 3 °C/min below 400 °C, 2 °C/min from 400 to 700 °C, 1/min beyond 700 °C, 4 hr soaking time, cooling down at 4 °C/min	Water absorption; bending strength; shrinkage; leaching behaviour	[93]
2	Biomass incinerator ash (<0.15 mm/0, 10, 20, 30, 40, 50%)	60 * 30 * 10	Mixing at 10% moisture content; pressed under 54.6 MPa; oven-drying at 110 °C for 48 hrs; firing to 950 °C at the ramp of 10 °C/min for 24 hrs	Loss on ignition; shrinkage; density; suction water; water absorption; compressive strength; microstructure	[99]
3	Municipal solid waste incinerator ash; coal fly ash (−/75% MSWI-FA, 25% FA)	Cylinder: 30 in. diameter, 60 in. height	Mixing; pouring into mould; heat-curing at 60 °C for 3 days under 100% relative humidity; curing at 25 °C for 1, 3, 7, 14, 28 days	Compressive strength; microstructure; amount of reacted sodium silicate and water; leaching behaviour	[87]
4	Sugarcane bagasse ash (D60 = 45 μm/50, 55, 60, 65, 70, 75, 80%)	230 * 110 * 80	Mixing; mould-pressed under 20 MPa; 3-day drying; 7-day moist-curing; 7-day sun-drying	Compressive strength; water absorption; efflorescence; density; shear strength; flexure strength	[98]
5	Rice husk ash (RHA) and wood ash (WA) (<0.1 mm/0, 10, 20, 30%)	60 * 30 * 10	Mixing; pressed under 54.5 MPa; firing to 900, 1000 °C at the ramp of 3 °C/min for 4 hrs	Shrinkage; water absorption; porosity; density; compressive strength; microstructure; thermal conductivity; leaching behaviour	[100]

3.2.5. Other industrial wastes

In addition to sludge, slag, ash, a wide range of other industrial waste materials were also examined by researchers. These industrial waste materials include boron waste [101], limestone dust and wood sawdust [102], circulating fluidised bed combustion ash [103], phosphogypsum [104], low-silicon tailings [105], spent foundry sands [106], biodiesel production residues [107], biomass incinerator ash [99], recycled paper mill waste [108,109], cotton waste [110], cement kiln dust [111], waste clay bricks [112], borogypsum [113], Rice husk ash [85,100,109], bio-solids [114], red mud [115], arsenic and fluoride bearing spent absorbent [116], and gangue and tailings from feldspar mining [117]. Different waste materials were processed into distinct shapes and sizes. The particle sizes ranged from <0.1 mm to <4.75 mm. The chemical compositions of these waste materials varied significantly. The common component of SiO_2 rendered them able to be used as alternative materials for brick manufacturing. In addition, immobilisation of the heavy metals was still the main purpose of researchers to incorporate these waste materials into bricks. Table 9 shows the experimental design and results of these other industrial waste-related studies.

Clay was not the only kind of binder material in these papers, and others include fly ash [85,103–105,116], cement [102,103,108], and sand [104,112]. The particle sizes of raw clay varied from <0.1 mm to <1.2 mm. Most studies introduced these other industrial waste materials at the ratios under 50%, while several ones added the waste at a higher ratios, such as circulating fluidised bed combustion ash [103], low-silicon tailings [105], and recycled paper mill waste [108].

Four types of specimens were involved in the studies about other industrial waste: ordinary-size [85,102,104–106,108,115,117], scale-down [99–101,106,107,116], cylinder [111,114], and cuboid [103] samples. These samples were shaped through moulding [108,112], pressing [85,99–105,107,111,114–117], and extruding [106,113]. The process after shaping depends on the manufacturing methods. Firing is subject to the studies using traditional firing method [99–101,106,107,113,114,116,118], and curing is subject to the studies adopting stabilising method. The used firing temperatures ranged from 700 to 1220 °C. The curing condition was usually at ambient temperatures, 35 or 65 °C. It should be noted that autoclaving is also a curing method [105], at 0.75–1.75 MPa.

Various tests were performed for the samples in these reviewed other industrial waste-related papers. Water absorption and Compressive strength were two of the most common characteristics. The results varied a lot, significantly depending on the type of waste. The waste materials tending to increase the WA include boron waste, wood sawdust, circulating fluidised bed combustion ash, paper mill waste, cement kiln dust, borogypsum, rice husk ash, biosolid, and biomass ash. It is worth noting that the effects of some waste on WA were related to the amount of the waste, non-monotonous, such as the spent earth from biodiesel filtration [107]. Similar results were found in terms of CS, whereas the trend was contrasting.

Other properties tested in these reviewed papers contain flexure strength [85,101,102,104,106], durability [104,105,111–113], thermal conductivity [100,107,114], crystalline phases [99,100,106,107,112,113,115,117], and leaching behaviour [100,115,116]. All the results showed that the influences of these waste materials were acceptable. Lastly, it should be noted that the there was only one study based in industrial scale [106].

4. Process orientation

The process-oriented innovation refers to introducing innovative methods into the process of brick manufacturing. As is known to all, nearly all the current bricks are produced using firing method. The bricks manufactured by other methods only account for a minimal proportion of the global brick production. This renders the brick industry rather non-sustainable, attributed to the high energy consumption and high emissions of firing process. Many researchers have tried to search for alternative ways for brick manufacturing to address this issue. This review divides these process-oriented innovative studies into three groups, namely calcium-silicate-hydrate (CSH) based, geopolymer based, and others.

4.1. Calcium-silicate-hydrate based

The bricks in these CSH studies are attributed to the formation of CSH gel during the brick manufacturing process. There are three types of CSH based studies according to the sort of stabiliser; they are cement [45,46,91,102,118,119], lime [76,104,120], and other cementitious material [105,112]. The three materials were all rich in CaO and SiO_2, which were the fundamental for formation of CSH. Amongst the studies still using clay, the particle sizes were all around <5 mm. Table 10 provides details of these papers.

Two types of specimens were used in these CSH based studies: ordinary-size [76,91,102,104,105,118,119] and cylinder [45,46,119,120] samples. Two types of shaping methods, moulding [45,46,76,102,104,105,118,120] and pressing [91,112,119], were introduced. The forming pressures range from 0.5 to 30 MPa. Several curing conditions were applied in these studies. Over half of the CSH based papers moist-cured their samples at the ambient temperature between 20 and 22 °C and at the RH between 90 and 95%. Other curing conditions include saturated-lime-water-curing [102,118] and autoclaved curing [104,105].

Compressive strength is the most common property tested in the CSH-related papers. It was found that relatively more cement or lime could result in higher CS [46,91,104,119]. For the samples using alkaline activator, the higher concentration of NaOH led to

Table 9
Recent studies on bricks with other industrial wastes.

No.	Waste types (size/wt%)	Specimen dimensions (mm)	Shaping/drying/firing/curing conditions	Characteristics examined	Reference
1	Boron clay waste (CW) or fine waste (FW) (–/5, 10, 15%)	50 * 12 * (7–8)	Grinding and heating at 100 °C; mixing at 5% moisture content; pressed under 30 MPa; drying at room temperature for 2 days; firing to 700, 800, 900 °C for 1 hr	Shrinkage; water absorption; compressive strength; flexure strength; appearance	[101]
2	Wood sawdust waste (WSW), Limestone powder waste (LPW) (<1.18 mm/LPW/WSW: 2936/0; 2706/54; 2405/108; 2117:162)	105 * 90 * 75, 105 * 225 * 75	Mixing at water/cement ratio of 0.5; moulded and pressed under 17, 8, 4, 2 MPa for 4 hrs, respectively; demoulded; curing at room temperature for 24 hrs; curing in lime-saturated water at 22 °C for 28 days; drying at 105 °C for 24 hrs for testing	Compressive strength; flexure strength; absorption; UPV	[102]
3	Stockpiled circulating fluidised bed combustion ash (SCFBCA) (<0.079 mm/58.3–100%)	90 * 65 * 90	Mixing; pressed under 55.2 MPa for 1 min; curing at 23 °C and 100% relative humidity for 1 day; curing at room temperature until the age of 3, 7, 14, 28 days	Compressive strength; water absorption; density	[103]
4	Phosphogypsum (PG) (–/30, 35, 40, 50%)	240 * 115 * 53	Mixing; pressed under 20 MPa; steam autoclaved at 0.8 MPa for 4 hrs	Compressive strength; flexure strength; durability	[104]
5	Low-silicon tailings (–/85%)	240 * 115 * 53	Mixing; pressed under 12–23 MPa; sealed curing for 6 hrs; autoclaved at 0.75–1.75 MPa for 8 hrs	Compressive strength; freeze–thaw durability; water absorption	[105]
6	Spent foundry sands (<2 mm/0, 10, 20, 25, 30, 35%)	100 * 70 * 20, 670 * 520 * 70	Mixing; extruded; drying at room temperature; oven-drying at 100 °C for 24 hrs; firing to 800, 850, 900 °C at the ramp of 1.6 °C/min; 4 hr soaking time	Water absorption; porosity; compressive strength; flexure strength; density; microstructure	[106]
7	Spent earth from biodiesel filtration (SEBF) (–/0, 5, 10, 15, 20%)	60 * 30 * 10	Mixing; pressed at 54.5 MPa; firing to 1050 °C at the ramp of 3 °C/min; 4 hr soaking time	Shrinkage; water absorption; density; water suction; compressive strength; thermal conductivity; microstructure	[107]
9	Recycle paper mill waste (RPMW) (–/80, 85, 90, 95%)	230 * 105 * 80	Mixing; moulded; demoulded; sun-drying until 15% moisture content reduced; further pressed until 10% moisture content reduced; sun-drying again	Compressive strength; water absorption; porosity; shrinkage	[108–110]
10	Copper mine tailings (MT) (0.12 mm/0, 2.5, 5, 10%); cement kiln dust (CKD) (0.036 mm/0, 2.5, 5, 10%)	Cylinder: 33.4 in. diameter and 72.5 in. height	Mixing; pressed under 0, 0.5, 25 MPa for the moisture content of 20, 16, 12%; demoulded; uncovered curing at 90 °C for 7 days	Compressive strength; water absorption; durability	[111]
11	Red clay brick waste (RCBW) (0.021 mm/25, 33%)	N/A	Paste sample: mixing for 4 min, moulded, sealed curing at 65 °C; mortar sample: mixing with sand, moulded and vibrated for 4 min, curing at 65 °C and relative humidity of 90–95% for 3, 7 days	Compressive strength; porosity; microstructure; weight loss	[112]
12	Borogypsum (BG) (<1 mm/0, 2.5, 5, 7.5, 10, 15%)	N/A	Preparing BG slurry; mixing with clay for 60 min; stored in plastic bag for 1 day; extruded; air-drying for 1 day; oven-drying at 100C until constant weight; firing to 800, 900, 1000, 1100 °C at the ramp of 200 °C/h; 2 hr soaking time	Water absorption; compressive strength; freeze-thaw resistance; crystalline phases; porosity; density	[113]
13	Biosolids (<1.1 mm/25%)	Cylinder: 100 in. diameter and 50 in. height	Mixing; moulded and compacted under 240 kPa; air-drying for 24 hrs; oven-drying at 105 °C for 24 hrs; firing to 1100 °C for 3 hrs	Compressive strength; density; water absorption; initial rate of absorption; loss on ignition; shrinkage; thermal conductivity	[114]
14	Rice husk ash (RHA) and wood ash (WA) (<0.1 mm/0, 10, 20, 30%)	60 * 30 * 10	Mixing; pressed under 54.5 MPa; firing to 900, 1000 °C at the ramp of 3 °C/min for 4 hrs	Shrinkage; water absorption; porosity; density; compressive strength; microstructure; thermal conductivity; leaching behaviour	[100]
15	Red mud (–/0, 10, 20, 30%)	5 * 5 * 5, 190 * 90 * 57	Mixing; moulded and compacted; curing at 60 °C and 99% relative humidity for 3, 7 and 28 days	Compressive strength; porosity; microstructure; leaching behaviour; water absorption	[115]
16	Waste absorbents: Thermally treated laterite (TTL); acid-base treated laterite (ABTL); aluminium oxide/hydroxide nanoparticles (AHNP) (–/0, 10, 20, 30%)	60 * 33 * 27	Mixing; pressed and moulded; air-drying for 2 days; oven-drying at 105 °C for 24 hrs; firing to 800, 900, 1000 °C at the ramp of 10 °C/min; 1 hr soaking time	Density; water absorption; shrinkage; compressive strength; efflorescence; leaching behaviour	[116]
17	Mine tailings: dried and ground (<0.074 mm); mine gangue) 0.425–0.85, 0.85–1.18, 1.18–2, 2–2.36, 2.36–4 mm) (Gangue/tailings: 6/4, 7/3, 8/2, 9/1)	200 * 100 * 50	Mixing at 10% moisture content; pressed under 2 MPA; oven-drying at 100 °C for 12 hrs; firing to 1140, 1160, 1180, 1200, 1220 °C at the ramps of 2.5 °C/min below 750 °C and 3 °C/min beyond 750 °C; 45 min soaking time	Permeability; compressive strength; porosity; water absorption; microstructure	[117]

the higher strength [112]. Also, Zhao et al. [105] found that higher forming and autoclaved pressures could improve the CS. Regarding WA, it was found that these CSH based samples had lower WA compared to ordinary fired bricks [91,105]. It should be noted that no CSH-related studies examined the SK of their samples.

Other characteristics involved in these papers were flexure strength [102,104,118], strength of masonry structure made of the samples [119], thermal conductivity [120], durability [76,91,104,105,112], fire resistance [91], crystalline phases [112]. Some interesting findings were mentioned in these papers. The first one is that the strength of masonry structure made of the samples was acceptable [119]. Another one is that few new crystalline phases were formed during the CSH-curing process [112]. Again, there is only one study, which is in partial industrial-scale.

Table 10
Recent studies on calcium silicate hydrate based bricks.

No.	Mixture matrix (size/wt%)	Specimen dimensions (mm)	Shaping/drying/firing/curing conditions	Characteristics examined	Reference
1	Sand (<0.2 mm), fly ash (<1 mm), hydrate lime (8, 10, 12, 14%)	Cylinder: 45 in. diameter, 100 g in weight	Mixing; moulded at 0.5, 10, 20, 25, 30 MPa; pre-curing at room temperature for 24 hrs; autoclaved curing at 0.5, 1, 1.5, 2 MPa for 3, 6, 9, 12 hrs	Compressive strength; water absorption; thermal conductivity	[120]
2	wood sawdust and limestone powder (<1.18 mm), cement (376 g)	105 * 90 * 75, 105 * 225 * 75	Mixing at water/cement ratio of 0.5; moulded and pressed under 17, 8, 4, 2 MPa for 4 hrs, respectively; demoulded; curing at room temperature for 24 hrs; curing in lime-saturated water at 22 °C for 28 days; drying at 105 °C for 24 hrs for testing	Compressive strength; flexure strength; absorption; UPV	[102]
3	Cotton waste, limestone powder waste, waste glass powder, cement (376 g)	105 * 90 * 75, 105 * 225 * 75	Mixing; moulded and pressed under 2, 5, 10, 20, 40 ton for 1 min; demoulded; curing at room temperature for 24 hrs; curing at 22 °C in the lime-saturated water for 28 days	Water absorption; compressive strength; flexure strength; density; UPV	[118]
4	Clay (<5 mm), granulated furnace blast slag, lime, cement	215 * 102 * 65	Cast through a hydraulic press under 15 MPa; curing in a plastic container at 20 °C for 7, 28, 56, 90 days	Water absorption; compressive strength; voids; resistance to freeze and thaw; microstructure; energy consumption and emissions	[76]
5	Phosphogypsum (original and autoclaved), fly ash, sand, lime	240 * 115 * 53	Mixing; pressed under 20 MPa; steam autoclaved at 0.8 MPa for 4 hrs	Compressive strength; flexure strength; durability	[104]
6	Low-silicon tailings, alkali-activated slag/fly ash	240 * 115 * 53	Mixing; pressed under 12–23 MPa; sealed curing for 6 hrs; autoclaved at 0.75–1.75 MPa for 8 hrs	Compressive strength; freeze–thaw durability; water absorption	[105]
7	Cement (400, 450, 500 kg/m3), sand, expanded polystyrene	100 * 100 * 100, cylinder: 150 in. diameter and 300 in. height, 240 * 390 * 720, 390 * 290 * 240	Mixing; moulded; curing at room temperature for 24 hrs; demoulded; curing at 20 °C and 95% relative humidity for 7 and 28 days	Compressive strength; stress and strain behaviour	[119]
8	Red clay brick waste (<0.021 mm), sand, NaOH, Na_2SiO_3	N/A	Paste sample: mixing for 4 min, moulded, sealed curing at 65 °C; mortar sample: mixing with sand, moulded and vibrated for 4 min, curing at 65 °C and relative humidity of 90–95% for 3, 7 days	Compressive strength; porosity; microstructure; weight loss	[112]
9	Fly ash and bottom ash (<10 mm), cement (25, 35, 45%)	200 * 90 * 60	Mixing bottom ash with cement in dry state for 2 min; adding fly ash and mixing for another 2 min; adding water and mixing; pouring into mould; curing at 22 °C and 95% relative humidity	Compressive strength; ultrasonic pulse velocity (UPV); modulus of rupture; water absorption; initial rate of suction; fire resistance; durability	[91]

4.2. Geopolymer based

The term of "Geopolymer" was firstly introduced in the latter of the 20th century, referring to the inorganic polymers synthesised from aluminosilicate materials [121,122]. The "geo" implies the constitutive relationship between geopolymer and naturally geological materials. Currently, there are generally two types of geopolymer as per the synthesis routes; they are alkali-activated and acid-activated geopolymers. Amongst the reviewed geopolymer-related studies, only one study employed acid medium to produce geopolymer samples [123]. The precursor materials used in these papers include clay [89,96,123–125], calcined clay [123–126], sand [126,127], fly ash [36,85,89,96,124,128,129], mine tailings [111], tuff [130], ground granulated blast furnace slag (GGBFS) [87], glass waste [36], metakaolin [131], red mud [131], borax [128,129], high calcium wood ash [127], and calcined water potabilization sludge [126]. The particle sizes of these precursors ranged from<0.036 mm to<0.6 mm. One common characteristic among these materials was the abundance of SiO_2 and Al_2O_3 as well as being amorphous in the X-Ray Diffraction test. These were the basic conditions for geopolymerisation. Table 11 illustrates the experimental design and results of these geopolymer-related studies.

Most geopolymer-related studies prepared their samples in the shape of cylinder. Only two of these papers produced ordinary-size brick specimens [85,89]. These samples were shaped by two ways: moulding [87,123–126,128,129,132] or pressing [36,85,89,96,111,127,130]. The forming pressures ranged from 0.5 to 35 MPa, and the curing temperatures ranged from the ambient temperature (20–30 °C) to as high as 140 °C. It should be noted that the heat-curing usually last for 6–24 h. Sukmak et al. [89] extended this period to 168 h to investigate the effect of heat-curing time. It was found that nearly all the geopolymer-brick papers adopted sealed- or moist-curing, while Ahmari and Zhang [111] chose to uncovered- and dried-cure the samples and argued that this was better for development of geopolymer.

The alkali and acid mediums play a vital role in geopolymerisation. Most reviewed papers introduced mixed solutions of NaOH and $NaSiO_3$ as the medium. The concentration of NaOH ranges from 4 to 17 M, but most studies employed 8–10 M NaOH solutions. The weight ratio of $NaSiO_3$ to NaOH ranges from 0.4 to 9.0. Regarding the introduction ratio of alkaline solution, the review papers introduced it in different manners. Some papers used the ratio of liquid content to solid content to describe the content of the mediums, while some used the ratio of liquid to one precursor to denote [36]. It is worth noting that several studies only used alkali metal hydroxide, eliminating silicate [111,125,130]. And there is only one reviewed study employing acid medium, phosphoric acid, to produce geopolymer samples [123].

The most common examined property is Compressive strength in these geopolymer-related studies. Many reviewed studies found that addition of the NaOH with higher concentrations could lead to higher strength [111]. But it is worth noting that this did not mean

Table 11
Recent studies on geopolymer based bricks.

No.	Mixture matrix (size/wt%)	Specimen dimensions (mm)	Shaping/drying/firing/curing conditions	Characteristics examined	Reference
1	Bafoundou tuff (0.25 mm/80%), NaOH (4, 8, 12 m/20%)	Cylinder: 2.5 in. diameter and 5 in. height	Mixing; pressed under 10 MPa; soaking overnight; curing at 40 and 80 °C for 7, 14, 28 days, and 120 °C for 0.25, 0.5, 1 day	Compressive strength; stress-strain behaviour; crystalline phases; microstructure; leaching behaviour	[130]
2	Copper mine tailings (<0.12 mm), cement kiln dust (<0.036 mm), NaOH (10, 15 m)	Cylinder: 33.4 in. diameter and 72.5 in. height	Mixing; pressed under 0, 0.5, 25 MPa for the moisture content of 20, 16, 12%; demoulded; uncovered curing at 90 °C for 7 days	Compressive strength; water absorption; durability	[111]
3	Municipal solid waste incinerator ash, coal fly ash, Na2SiO3 (1.15 m), NaOH (10, 17 m), Na2SiO3/NaOH = 1	Cylinder: 30 in. diameter and 60 in. height	Mixing; pouring into mould; heat-curing at 60 °C for 3 days under 100% relative humidity; curing at 25 °C for 1, 3, 7, 14, 28 days	Compressive strength; microstructure; amount of reacted sodium silicate and water; leaching behaviour	[87]
4	Coal fly ash (<0.1 mm), clay, (<0.1 mm), mixture of Na2SiO3 and NaOH (10 m) at the ratio of 0.4, 0.7, 1, 1.5, 2.3	Cylinder: 50 in. diameter and 100 in. height	Mixing at the liquid to fly ash ratio (L/FA) of 0.4, 0.5, 0.6, 0.7; pressed; kept at 27–30 °C for 24 hrs; heat-cured at 65, 75, 85 °C for 24, 48, 72 hrs	Compressive strength; leaching behaviour	[96]
5	Coal fly ash (<0.1 mm), clay, (<0.1 mm), mixture of Na2SiO3 and NaOH (10 m) at the ratio of 0.4, 0.7, 1, 1.5, 2.3	Cylinder: 50 in. diameter and 100 in. height; 230 * 90 * 75	Mixing at the liquid to fly ash ratio (L/FA) of 0.4, 0.5, 0.6, 0.7; pressed; kept at 27–30 °C for 24 hrs; heat-cured at 55, 65, 75, 85, 120, 130, 140 °C for 24, 48, 72, 120, 168 hrs	Compressive strength; microstructure	[89]
6	Sediment clay (raw and calcined), ground granulated blast furnace slag (0, 30%), NaOH (5, 7, 10 m), Na2SiO3	Cylinder: 21 in. diameter and 50 in. height	Mixing; moulded; sealed curing at 60 °C and 100% relative humidity for 3 days; demoulded; curing at room temperature until 28 days	Compressive strength; crystalline phases; microstructure	[124]
7	Fly ash (30%), Glass waste (<4.75 mm/70%), mixture of Na2SiO3 and NaOH at 90/10, 70/30, 50/50, L/FA: 0.25, 0.375, 0.5, 0.625, 0.75	Cylinder: 50 in. diameter and 100 in. height	Moulded and compacted; 3–7 days at a low curing temperature of 50C	Compressive strength, microstructure	[36]
8	Red mud (<0.125 mm/25%), metakaolin (75%), NaOH (10 m), Na2SiO3, alumina powder	N/A	Mixing; moulded; sealed curing at 40 °C and 65% relative humidity; demoulded; curing at room temperature until 28 days	Compressive strength; water absorption; leaching behaviour; density; porosity	[131]
9	Fly ash, borax, NaOH (8 m), Na2SiO3, NaOH/Na2SiO3/Borax: 50/50/0, 54/45/5, 65/35/15, 75/25/25, 85/15/35, 95/5/45	50 * 50 * 50; cylinder: 50 in. diameter, 100 in. height	Mixing; moulded; sealed curing at room temperature for 24 hrs; demoulded; curing at 70 °C for 2 hrs; curing at room temperature for 5 days	Compressive strength; modulus of elasticity	[128]
10	Fly ash, ground granulated blast furnace slag, borax, NaOH (8 m), Na2SiO3, NaOH/Na2SiO3/Borax: 50/50/0, 54/45/5, 65/35/15, 75/25/25, 85/15/35, 95/5/45	50 * 50 * 50; cylinder: 50 in. diameter, 100 in. height	Mixing; moulded; sealed curing at room temperature for 24 hrs; demoulded; curing at 70 °C for 2 hrs; curing at room temperature for 5 days	Compressive strength; microstructure	[129]
11	High calcium wood ash (<0.6 mm), pulverised fuel ash, sand (<5 mm), Na2SiO3 (0, 1, 2, 3, 4, 5%), wood ash/fuel ash: 6/4, sand/binder: 2.25, water/binder: 0.3	290 * 140 * 100	dry-mixing; wet-mixing; pressed as the compression ratio of 1.48; curing at 28 °C for 24 hrs; curing in lime-saturated water or sealed moist curing for 7, 28, 90 days	Compressive strength; flexure strength; UPV; water absorption; porosity; intrinsic air permeability	[127]
12	calcined kaolin, calcined natural clay, phosphoric acid, solid/liquid: 1/1, Si/P: 1.75/1	N/A	Mixing; vibrating; sealed curing at room temperature for 2 hrs; sealed curing at 60 °C for 24 hrs; sealed curing at room temperature for 28 days; demoulded	Crystalline phases; dielectric analysis	[123]

that adding more NaOH solution could result in higher strength. The similar effect was found in terms of curing temperatures and durations. Adopting higher curing temperatures or longer curing time would not certainly increase the CS of samples [89,130]. Sukmak et al. [89] argued that the heating energy, depending on the curing temperature and duration, was the key to the development of geopolymerisation. Other factors tending to increase the strength include the amount of $NaSiO_3$ and whether the precursor is calcined. It was found that calcined materials could result in higher strength than non-calcined materials [124].

Other important properties tested by these papers are leaching behaviour and crystalline phases. All the reviewed papers examining leaching behaviours found the geopolymer samples could meet the requirement of standards [87,96,130,131]. Regarding the question of laboratory or industry, there is only one reviewed paper [126] that is based in partial industrial scale.

4.3. Other process innovations

Table 12 provides information of three studies of other process-oriented innovation. Galan-Marin et al. [132] investigated bricks stabilised with natural polymer alginate extracted from algae with clay as the main material. They used alginate to bind the clay particle together to gain the strength and the substitution ratio of alginate was up to 19.5 wt%. The samples were extruded and cured at 50 °C for 24 h, not subjected to firing. The compressive and flexural strengths of the samples were examined. It was found that addition of alginate increased the compressive strength of samples compared to the control samples of pure clay cured at the same conditions, while it did not improve the flexural strength. The flexural strength improved by introducing both the alginate and wool fibres. In addition, the natural fibre prevented bricks from drying cracks and sudden failure.

Espuelas et al. [133] explored the possibility of producing unfired clay bricks with addition of magnesium oxide (MgO) waste. The samples with the addition of MgO ranging from 0 to 18 wt% were prepared by pressed-moulding at 5 kN. These samples were subsequently sealed-cured for 1–90 days. A control group using hydrated lime was also prepared as the reference. The results showed that addition of MgO led to high strength until the substitution ratio was over 15 wt%, and resulted in low water absorption within the testing range.

Soussi et al. [134] researched from a direction differing from all the other reviewed papers. This study tried to mitigate the impact of brick industry by improving the efficiency of tunnel kilns. It was found that recovering the hot air in the cooling area of kiln to firing

Table 12
Recent studies on other process innovation based bricks.

No.	Innovation point	Specimen dimensions (mm)	Shaping/drying/firing/curing conditions	Characteristics examined	Reference
1	Stabilised by alginate (0, 19.5, 19.75 wt%), mixed with natural fibre, lignum and wool	160 * 40 * 40	Mixing; moulded; oven-drying at 50 °C for 24 hrs; demoulded	Compressive strength; flexure strength	[132]
2	Stabilised by MgO waste (0, 3, 6, 9, 12, 15, 18 wt%)	Cylinder: 65 in. diameter and 75 in. height	Mixing; pressed at 5 kN; demoulded; sealed curing for 1, 7, 28, 56, 90 days	Density; compressive strength; water absorption	[133]
3	Improvement on energy use of kilns	300 * 200 * 150	N/A	Energy consumption	[134]

area could conserve a considerable amount of energy. Most importantly, this improvement did not require special and large investments.

5. Opportunities and challenges

This review categorised the brick-related publications into two groups according to the direction of innovation – Material orientation and process orientation. From these papers, a general route of how a research project coming up can be drawn. Fig. 2 illustrates a general process of a typical brick-related study. There are three key parameters, which need to be determined. Both first two elements, the waste type and manufacturing process, are interrelated. The waste type influences the determination of suitable manufacturing process, and similarly the manufacturing process is able to reversely affect the selection of waste materials. Regarding the characteristics to be examined, physical and mechanical properties of bricks are the main aspect, but other properties, such as thermal and acoustic performance and leaching behaviour, are also important since these properties are related to the comfort of users. This point was also mentioned by Velasco et al. [12] that leaching behaviour was especially important for the bricks containing waste materials as well as geopolymer based bricks because possible leaks of heavy metals and alkaline substance might occur in these types of bricks. It is necessary to ensure the leaching behaviour of bricks is acceptable.

Amongst these reviewed studies, the optimum incorporation ratios of different waste materials varied (see Fig. 3). It can be found that the optimal addition ratios of sludge and ash had wider ranges. This could be attributed to the large variance in chemical compositions of sludge and ash sourced from different places. In addition, compressive strength and water absorption were two of the most common characteristics examined. Compressive strength determines the workability of bricks and water absorption determines the durability. While shrinkage was also rather common, it was only for the research projects based in firing process. Most CSH or Geopolymer based studies did not mention the shrinkage of the samples. This may be due to the changes of CSH or Geopolymer based samples in volume are minor compared to the fired samples. However, it should be noted that the volumetric control of bricks is rather crucial for the practical brick manufacturing. Hence, the shrinkage should also be examined for future research of CSH or Geopolymer bricks.

Amongst all the publications above, it was found that the majority focused on the fired bricks. As Fig. 4 shown, there are

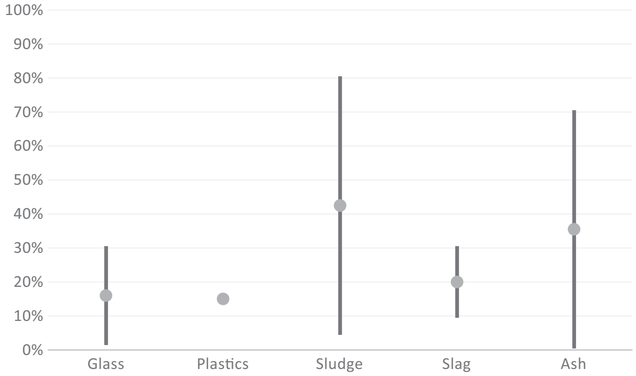

Fig. 3. Optimum incorporation ratio ranges by five main waste material types.

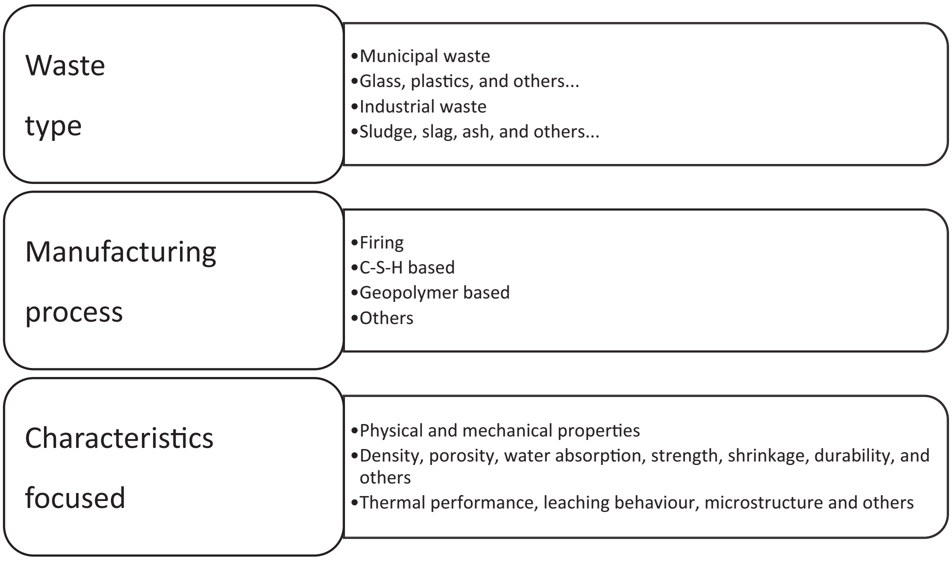

Fig. 2. A general developing route of a typical brick-related study.

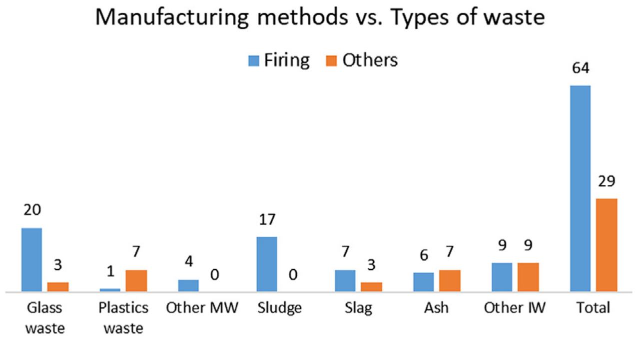

Fig. 4. Summary of literature distribution against manufacturing methods and types of waste.

93 reviewed papers in the category of material-oriented innovative studies. 64 out of the 94 projects were firing based, and other methods based studies were only 29. In some groups, the disparity was even larger, such as glass waste, sludge and slag. In particular, all the papers regarding sludge were based in the firing method. Although many successful attempts have been found to produce fired waste-added bricks that possessed comparable even superior properties, the use of firing method still means enormous energy consumption and carbon footprint. Thus, this review suggests that future efforts should be made to the studies on incorporating waste materials into bricks based on CSH or geopolymer. However, it should be noted that it is not preferable to use cement or lime to manufacture CSH bricks since the production process of cement and lime are also energy-intensive and has large carbon footprint.

Although it was mentioned by many researchers that bricks based on alkali-activated binders conserve considerable energy compared with the bricks produced by firing or using cement or lime [10], few studies conducted the cost and benefit analysis to find out how much energy and emissions are consumed and generated, respectively. Further research should be performed regarding this aspect to validate the argument. It should be noted that the energy consumption and emissions for producing NaOH and Na_2SiO_3 particularly need to be considered, in addition to the consumption and emissions during manufacturing process.

This review in particular indicated that nearly all these examined research projects were based in laboratory-scale. Despite many successful attempts, few studies took trials of innovative bricks in the industrial-scale, not to mention introducing it into practical brick production. This is the key challenge to the application of innovative bricks into practical industry. There is only one study that was applied in the practical production: Okuno and Takahashi [60] in Japan among all the papers covered in this review. Similar results were also found by Zhang [10] and Velasco et al. [12]. It was explained that the rather low rate of commercial applications may be caused by the large difference of manufacturing processes between the laboratory- and industrial-scale, lack of standards and regulations, and low public and industrial acceptance due to the concerns for environment. Thus, in future, research should try to adopt industry-alike conditions to produce brick samples. For example, it is recommended to use extrusion method to shape samples into ordinary size other than cylinder samples. In addition, government should externally establish regulations to limit landfilled waste; therefore, these waste materials can be diverted to brick manufacturing. A prime example is the application of recycled materials, such as plastic and glass, in pavement in Victoria, Australia [135]. The specifications endorsed by government played a key role in the implementation.

In fact, there is another vital reason for the low industrial acceptance. It is the concern for economic benefits. Schumpeter [136] defined the product and process innovations, mentioning that the outcome of innovations should be the increase in quality or reduction in cost. Although nearly all the reviewed brick-related studies claimed that their attempts were successful and it is viable to produce bricks with waste materials or using new manufacturing processes, few studies provided quantitative measurements demonstrating the benefits. Less revealed benefits result in lower industry acceptance. Therefore, it is necessary to include cost and benefit analyses in future research.

An insight into the trend of future innovative brick research can be gained based on this review. Firstly, it should be noted that waste materials are also a kind of limited resource for the global brick industry, though it is abundant in reserve. A prime example is the coal combustion products, which are one of the most plentiful waste materials among all the waste. Its annual global production was estimated at 777 million tonnes in 2010 [137], and the total brick production was estimated at 1500 billion units annually [2]. Assuming the average weight of a brick is 3.5 kg, the total weight of produced bricks was 5250 million tonnes per year. Clearly, the coal combustion products only accounted for 14.8% of the total brick production by weight. This suggests that it is not practical to completely substitute the raw material with only one type of waste material for brick manufacturing, so clay still needs to play the role as one of the most crucial materials for the brick industry. Hence, the future research could focus on investigating the clay-based geopolymer bricks, considering the low energy consumption and emissions. While the viability of using calcined clay for geopolymerisation has been verified, calcining is still an energy-intensive process. So, the key objective and challenge of the future research should be to produce the clay-based geopolymer by a less energy-consuming measure.

6. Conclusions

Extensive brick-related studies have been reviewed in this paper. The key findings are shown as below:

- There are two types of innovative bricks, namely material-oriented and process-oriented bricks.
- Firing is the most common method to produce bricks, while this process involves enormous energy consumption and carbon footprint.
- Cement and lime based calcium-silicate-hydrate bricks are also not sustainable.
- Geopolymerisation is a preferable way to produce bricks, but corresponding cost and benefit analyses need to be conducted to reveal the opportunities.
- Demolishing the scepticism of brick industry toward innovative bricks is the key challenge to the future research in bricks.
- Clay-based geopolymer bricks could be one of the focuses of future brick-related research, and the key challenge is to produce the clay-based geopolymer in a less energy-intensive way.

Conflict of interest

The authors declare that they have no conflict of interest.

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