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Review

# Exposed Clay Bricks Made with Waste: An Analysis of Research and Technological Trends

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**Abstract:** Properly disposal of industrial waste is a recurring issue due to its large volume and environmental impact. In turn, civil construction has shown itself to be a potential consumer of waste and can contribute to expanding the circular economy. Clay matrix materials have been a focus of interest for absorbing waste, with the possibility of varying their aesthetics, depending on the waste, as an exposed clay brick. Therefore, it is necessary to understand the research and technological trends on the topic to truly meet the demands of the market and society, in an innovative and sustainable way. To this end, a bibliometric review was carried out considering articles published in journals and an analysis of patent trends was carried out. The use of industrial waste was considerably influential in the growth of research on clay bricks. However, while the scientific community focuses on understanding the impact of industrial waste on clay brick properties, inventors focus on processes and methods for synthesizing clay particles associated with contaminants. The existence of gaps to be explored was identified, such as the aesthetic evaluation of clay bricks. The need to further study the properties of bricks made with waste, optimizing production processes and evaluating the life cycle of these materials are some of the challenges for future research.

**Keywords:** industrial waste; clay; exposed bricks; review

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## 1. Introduction

The incorporation of waste into the construction supply chain is aligned with environmental sustainability. It promotes the reduction in consumption of natural raw materials, allows the recycling and reuse of waste and ensures its proper disposal [1–5]. Some additional benefits are the commercial valorization of discarded materials, reduction in energy expenditure in transformation processes, reduction in the volume of materials sent to landfill areas and compensation for the imbalance in local sustainability [1,2,6].

The generation of solid waste is understood as a serious problem in the modern world. A study conducted by the United Nations Environment Program (UNEP) and the International Solid Waste Association (ISWA) in 2024 highlights the need to increase waste management capacity for both public and private entities. This study presents data on municipal solid waste generation, in addition to the amount of uncontrolled or unmanaged waste for the year 2020. Control, in this context, is associated with appropriate waste disposal.

South America had a controlled waste generation rate of approximately 100,000 thousand tons/year. Uncontrolled generation was estimated at 75,000 thousand tons/year. North America, with greater economic power and a higher level of industrialization, has a controlled waste generation rate of about 310,000 thousand tons/year. No data are available regarding waste without management processes. Oceania, with its main representatives Australia and New Zealand, has the lowest waste generation rates. The rate of managed waste is less than 50 thousand tons/year [7].

Regarding waste quantification in Brazil, data mainly originates from business associations, the National Sanitation Information System (SNIS), and the National Solid Waste Management Information System (SINIR) established by the National Solid Waste Policy, linked to the federal government. The SNIS and SINIR databases do not use the concept of waste generation, but rather per capita collected mass for the urban population, which includes the amount collected through selective collection by all executing agents (public agents, private agents, waste pickers' associations or cooperatives, and other executing agents). However, the use of the term "generation" is not entirely inaccurate, since Brazil has a high waste collection rate (98.8%).

It is estimated that waste collection in 2019, in Brazil, reached an annual amount of 65.11 million tons, equivalent to 178.4 thousand tons per day [8,9]. The year 2019 was chosen due to the complexity of the studies conducted up to that year. It is believed that data collection and processing in subsequent years were impacted by the COVID-19 pandemic.

Brazil still falls short of its potential for reuse or recycling, according to the data presented in Table 1. The value of 1.67% corresponds to the Waste Recovery Index or IRR, quantified by the sum of reused, recycled, and energy recovery waste divided by the total waste generated in the country. This value exposes the challenges that must be faced in Brazil regarding this issue [8].

**Table 1.** Waste recycling index and absolute value of waste recycled in Brazil.

| Year | IRR % | Recycled Waste (Thousand Tons/Year) |
|---|---|---|
| 2019 | 1.67 | 928.96 |
| 2018 | 1.75 | 923.2 |
| 2017 | 1.70 | 890.08 |
| 2016 | 1.65 | 842.5 |
| 2015 | 1.90 | 1020 |
| 2014 | 1.60 | 937.28 |

Source: [8,9].

Specifically, regarding industrial waste, Table 2 presents data on generated/collected waste, categorized by type of industrial activity and hazardousness to human health and the environment, available on the SINIR platform. The sectors classified as industrial mainly encompass waste originating from filter media, scrap metal and slag, scrap/used tires, fly ash from coal and zinc combustion, sugarcane bagasse, and waste containing hydrocarbons. Among mining waste, dust and particulate matter, waste contaminated with hydrocarbons, packaging, gravel, and rock fragments are noteworthy. The column labeled "Other Activities" encompasses various activities; however, the most frequently cited waste materials include ash, slag, and boiler dust, wood waste, sludge from urban effluent treatment, and caustic waste.

**Table 2.** Mass of industrial waste collected in Brazil.

| Type | Industry (Thousand Tons) | | Mining (Thousand Tons) | | Other Activities (Thousand Tons) | |
|---|---|---|---|---|---|---|
| **Year** | **Hazardous** | **Non-Hazardous** | **Hazardous** | **Non-Hazardous** | **Hazardous** | **Non-Hazardous** |
| 2019 | 28.60 | 2200.00 | 4.00 | 898.00 | 99.70 | 4400.00 |
| 2018 | 16.30 | 157.00 | 3.40 | 366.40 | 135.30 | 940.60 |
| 2017 | 26.40 | 118.00 | 3.90 | 24.50 | 187.10 | 1100.00 |
| 2016 | 39.50 | 60.00 | 3.50 | 33.20 | 854.90 | 2800.00 |
| 2015 | 23.10 | 2200.00 | 10.30 | 12.80 | 70.30 | 4100.00 |
| 2014 | 15.80 | 40.90 | 44.90 | 134.00 | 53.00 | 3700.00 |

Source: [8,9].

Civil construction presents itself as a consumer of waste from other industries, contributing to the circular economy. One possibility that has been studied is the use of waste in the production of ceramic pieces, such as exposed brick, which is widely used in masonry systems. Exposed brick is a parallelepiped solid piece, made of clay, and obtained by extrusion. It is dried and burned under high temperatures to obtain important properties, such as resistance and durability. Its sides are full of material and can have different finishing characteristics on both or one of the sides, making it visible without the need for layers of coating. This brick forms a unique aesthetic expression related to the Brazilian architectural tradition. Notable examples include the Convent of São Francisco in São Paulo and the Church of São Francisco de Assis in Belo Horizonte, where the exposed brick is not only a structural material but also a decorative element [8,9]

Among the various waste materials studied as additions or substitutes for clay raw materials, those rich in aluminum stand out due to the high recyclability and control of aluminum-based products in Brazil, and the affinity of aluminum oxides with the clay mixture. Aluminum industry filter dust was used as a raw material for the manufacture of clay bricks, at a content of 20% by mass, producing bricks with higher bulk density and compressive strength, and water absorption similar to reference bricks [10]. An aluminum-rich sludge, produced from anodizing or surface coating processes, was utilized for the fabrication of refractory ceramic bodies with high thermal inertia and mechanical strength [11]. An abundant residue in Brazil that has also been studied as an addition in the manufacture of ceramic bricks is sugarcane bagasse. Studies show that the mechanical and physical properties of bricks made with sugarcane bagasse are better than conventional ones [12].

Therefore, considering the need to conserve traditional construction materials and expand their possibilities of use, there is an effort to search for alternative raw materials. Given the different possibilities for incorporating industrial waste into ceramic products, this study sought to identify the existing gaps on the subject, focusing on the preservation of the raw material (natural clay), possibilities for reducing energy consumption for production and the need to improve the properties of mechanical resistance, water absorption, porosity, linear shrinkage and aesthetic appearance [6,13]. To this end, a bibliometric review was carried out on the recycling of waste in the production of exposed bricks, covering the main patents and published articles. It is expected to contribute to the advances in the compatibility of clay with mining, petrochemical and sewage treatment industry waste, due to its importance in the Brazilian scenario [14–16].

## 2. Materials and Methods

The ProKnow-C (Knowledge Development) method, a systematic approach for preparing review articles, was used, which aims to ensure the careful selection of data. This method is structured into four main steps (Figure 1).

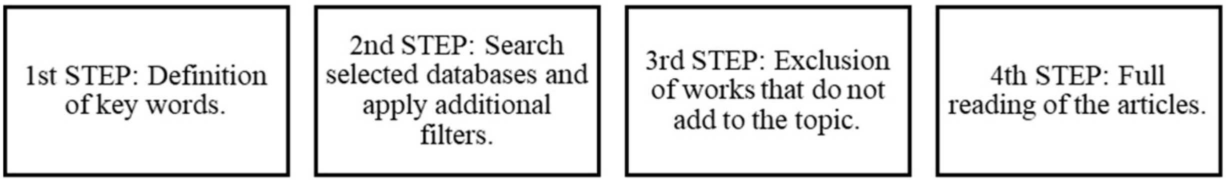

**Figure 1.** Description of the ProKnow-C method used to prepare the systematic review.

The Scopus database was used to search for scientific articles, while the Lens.org database was used to search for patents. The keywords used in each database were different, as indicated by the ProKnow-C method, to obtain as many works related to the topic as possible (Figure 2). Among the key words, the Boolean operator "AND" was used. Additionally, the Boolean operators "NOT" or "ANDNOT" were used for the word cement, aiming to exclude works on bricks with Portland cement.

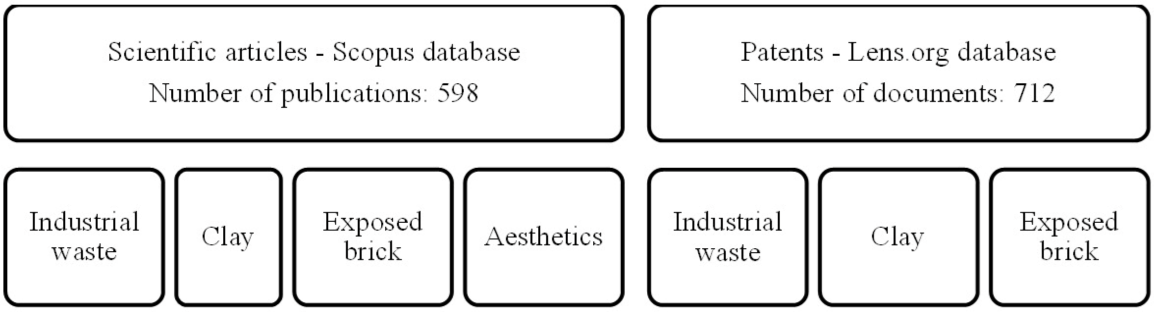

**Figure 2.** Keywords selected to apply the data collection method.

For scientific articles, the period between 2013 and 2023 and the types of publications (only articles published in journals) were used as filters. Also, Biblioshiny and Bibliometrix (software package for the R language, version RStudio 4.4.2) were used for analyzing the data.

Biblioshiny, the graphical interface for the Bibliometrix package in the R language, offers a comprehensive suite of tools for bibliometric analysis. These tools facilitate complex analyses of bibliographic data, even for users without extensive R programming expertise. The interactive interface allows for dynamic exploration of results, simplifying data interpretation and the identification of patterns and trends. The combined use of these tools enables the extraction of metadata from renowned databases such as Scopus and Web of Science, the generation of bibliometric indicators including H-indices, co-authorship networks, and bibliographic coupling, and data visualization through network graphs and word clouds.

For the global analysis of patents, the tool available on the Lens.org platform was used. To analyze the most found words in patents, the VOSViewer (2023) tool, version 1.6.20, was used because the Bibliometrix tool proved to be ineffective in analyzing the data generated through the Lens.org platform.

Thereby, a robust bibliometric analysis was carried out, highlighting information regarding the number of publications per year, authors, countries and institutions. Through a complete reading of reference articles and patents, the main industrial waste and their interference with the properties of exposed brick were discussed. In this way, it was possible to identify gaps in studies and topics of greatest interest to society related to exposed bricks.

## 3. Results and Discussion

### *3.1. Bibliometric Review Based on Articles Published in Journals*

The number of articles on clay bricks with industrial waste showed an increasing trend between 2017 and 2019, reaching a maximum of 93 publications (Figure 3) in that period. Between 2019 and 2021 there was again a new interest in the topic with 148 publications. Since then, a decrease has been observed, with 56 productions recorded in 2023. However, in recent years the number of publications has effectively grown, which indicates a search for compatibility between the construction materials industry and the waste generators and possibilities to validate the recycling of their waste.

The 598 publications were separated into conference articles (7.78%), review articles (16.68%) and research articles (75.54%). This result shows that there is still space for more research on clay bricks with industrial waste. It also justifies the focus of this study and of debates and publications at conferences, fundamental for the dissemination and debate of the topic.

There was a total of 225 authors who published about incorporating industrial waste into the composition of clay bricks. The 10 researchers with the most publications are presented in Figure 4. The author considered first in the volume of publications was Aeslina Abdul Kadir, with 25 articles. The focus of her research is the different burning temperatures of clay bricks with waste in their composition, as well the use of waste with the presence of heavy metals, bodywork mill sludge and quarry dust.

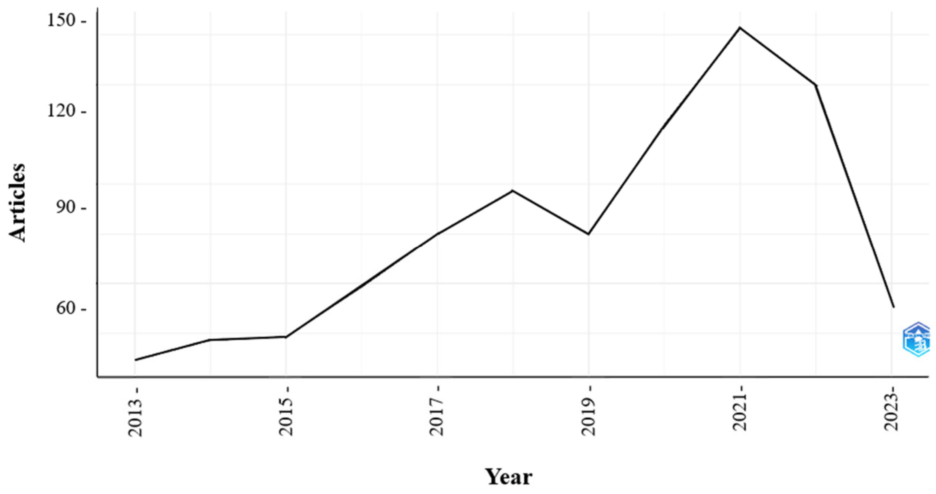

**Figure 3.** Scientific production on clay bricks with industrial waste from 2013 to 2023.

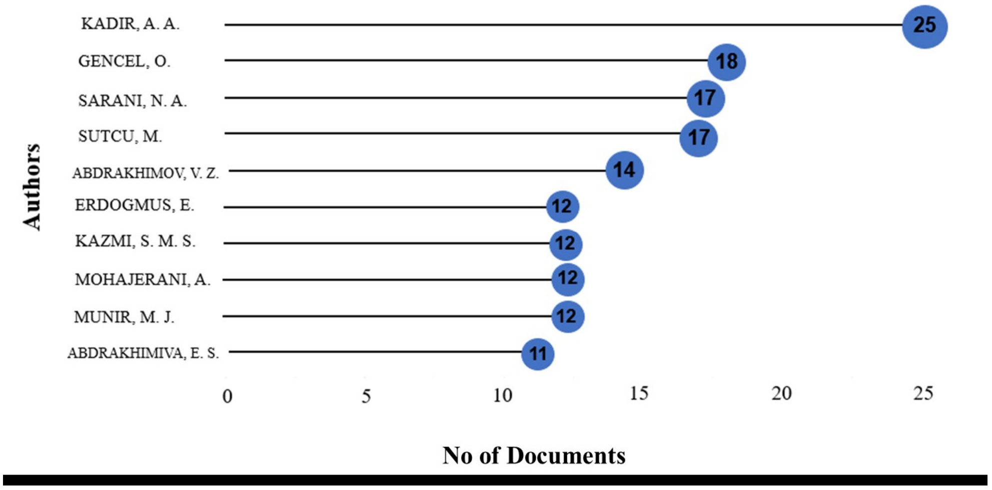

**Figure 4.** The 10 authors with the highest number of publications.

In total, 41 countries were identified researching clay bricks, and the 10 countries with the highest frequency of publications are presented in Table 3.

**Table 3.** The 10 countries with the highest frequency of publications.

| Region | Frequency |
|---|---|
| Brazil | 62 |
| Spain | 52 |
| India | 23 |
| Turkey | 19 |
| Chile | 16 |
| France | 11 |
| Australia | 10 |
| Italy | 10 |
| USA | 10 |
| Greece | 9 |

Brazil is the country with the largest number of studies on the destination and recycling of industrial waste into clay products with a frequency of 62 publications, in absolute numbers.

Next is Spain, with a frequency of 52 articles, and India with 23. It is understood that Brazil's leadership can be associated with the incentives of associations regarding the disposal of solid waste. Furthermore, the occurrence of landslide flood disasters in industrial areas of Brazil was considered a reason for implementing waste management policies [17]. Spain and India follow the same perspective and are countries that seek to invest and develop innovation and technology aiming at waste management with a great possibility of reuse [18,19].

The National Solid Waste Policy, enacted in Brazil in 2010, provided a crucial framework for waste management guidelines, facilitating research and technical analyses. Furthermore, Brazil holds a prominent position in research on clay bricks incorporating waste materials, due to its tradition of self-supporting masonry with solid clay bricks, a legacy largely influenced by Portuguese colonization. However, the emergence of new products (different types of blocks and wall systems) has been diminishing the competitiveness of bricks within the sector. The incorporation of waste materials in bricks emerges as a promising solution to address this challenge.

By reducing the extraction of raw materials and waste generated in brick production, companies in the sector can not only mitigate their environmental impacts—a primary effect of implementing more sustainable practices—but also generate substantial economic benefits. Optimizing production processes and seeking innovative solutions can result in secondary impacts such as reduced production costs, new job creation, and the stimulation of technological innovation, configuring a virtuous cycle of sustainable development.

The 10 institutions, from 212, with the most publications and research development in clay bricks and the compatibility of industrial waste are presented in Figure 5. Although Brazil has been identified as the country with the highest frequency of publications (Table 3), the research on this subject is of interest to a large group spread across the globe. Bartin University, Tun Hussein University and RMIT University, located in Turkey, Malaysia and Australia, respectively, are the most relevant in the development of studies on the topic covered in this article.

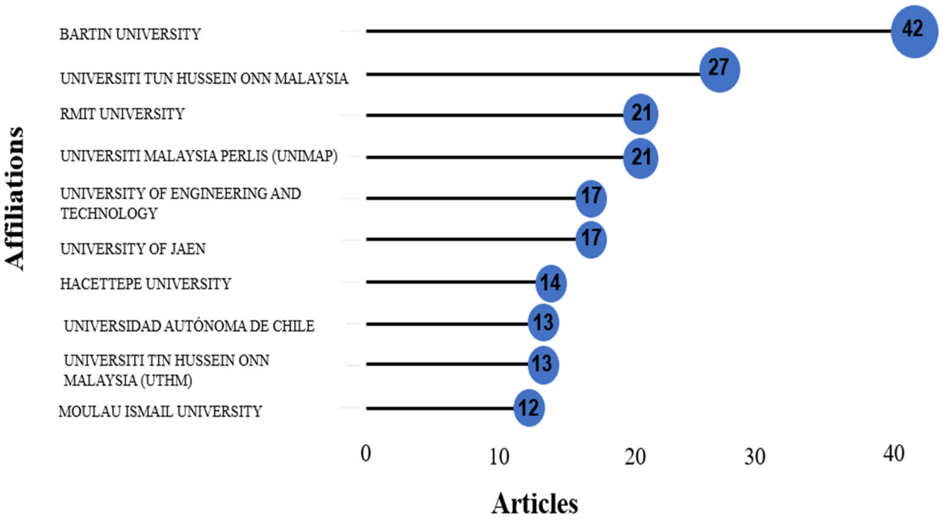

**Figure 5.** Institutions that publish the most on the topic.

Another important aspect to be analyzed is the choice of journals for publication. Figure 6 lists the 10 (out of 60) most relevant journals regarding the impact factor, which considers the number of publications and citations per year. Construction and Building Materials stand out with the maximum number in the index. Next, there is the Journal of Cleaner Production, with an impact index of 8, and in third place the Journal of

Building Engineering, with an index of 6. These are the main journals on the recycling of industrial waste in construction materials. However, they are seen as multidisciplinary because they publish research on materials engineering, civil construction, the chemistry of materials, clean production, waste management and treatment and energy efficiency in production processes.

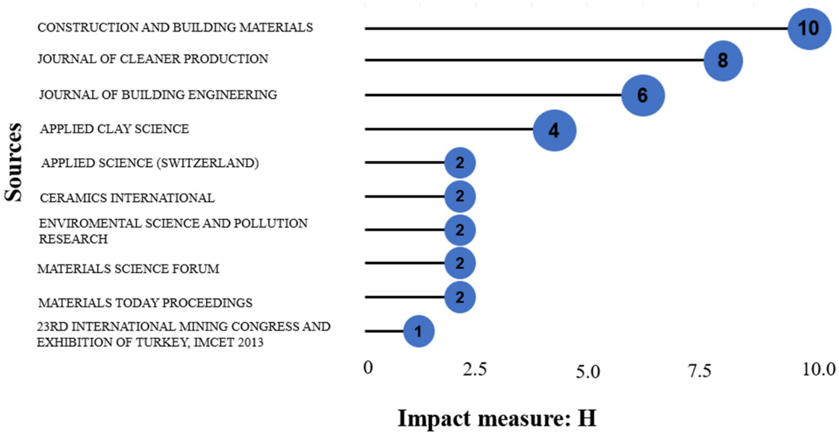

**Figure 6.** Measurement of the indexing number of the 10 most relevant journals.

The evaluation of keywords was carried out through the visual representation of the word cloud, where the font size determined the relevance of the topic in the searches on the database. Among the 50 words mapped and used in Figure 7, it was observed that the themes with the greatest research relevance are focused on the words bricks, with 504 repetitions, clay, with 206, ceramic materials, with 113, and recycling, with 99 repetitions. The most relevant properties under study were resistance to variation, with 504 repetitions, water absorption, with 235 and thermal conductivity, with 113.

**Figure 7.** Word cloud referring to the 50 most frequent keywords.

The other keywords had a frequency of repetition lower than 113 times, thus having less relevance and frequency of use in searches. The keywords referring to waste topics, such as industrial waste, had 68 repetitions in the articles found. Furthermore, words such as firing temperature, sintering and particle size were also found, however, with a minimum amount of frequency. In view of this analysis, it is possible to see that the panorama of studies about the recycling of industrial waste is still a subject in development. It also showed an increase in consolidated research areas, like clay bricks, and possibilities to combine industrial waste into ceramic pieces [20,21].

When collecting keywords, it was identified that there was no high frequency of the words aesthetics and texture. Those are important properties to be studied in exposed bricks, since one of the functions of the product is to compose the masonry system and be exposed in facades, forming the composition and aesthetics. Therefore, this topic is a knowledge gap for future research.

A thematic map of niches (Figure 8) was developed, addressing themes that are relevant and under development. In the quadrant referring to "basic" themes, the most frequent themes are about clays, ceramics and energy conservation, as they are underdeveloped due to their consolidated concepts.

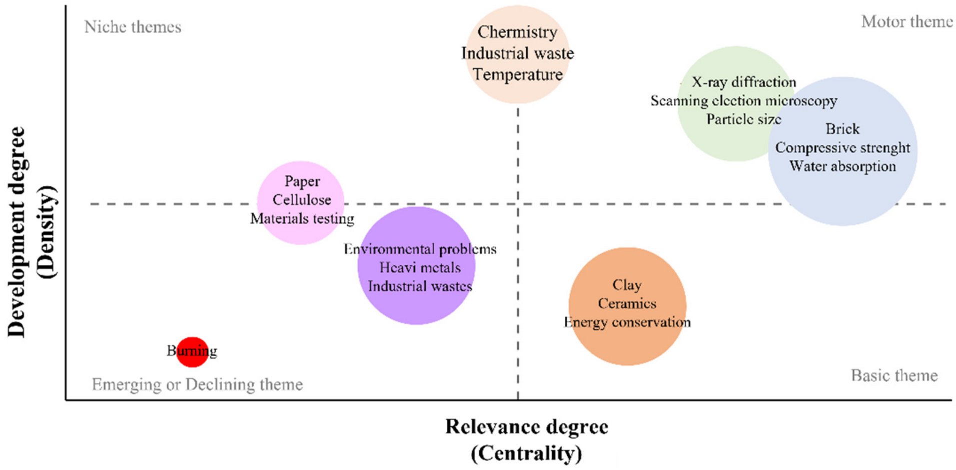

**Figure 8.** Niche themes chart about the relevance of themes and the development of publications.

In the second quadrant are the "motor" themes, which have continuous relevance and are currently featured in the research and publications found. Considering only clay bricks, compressive strength and water absorption are words with great relevance in the point cloud and, according to the studies, there is a search for improvements and enhancement of these properties. Studies have also been developed on X-ray diffraction (XRD), scanning electron microscopy (SEM) and particle size, which are fundamental for understanding the physical and mineralogical characteristics of types of waste, influencing compatibility with clay matrices.

The topics about chemistry, industrial waste and temperature are seen as "central" and highly relevant in analysis and discussions. These themes are the ones that are most underdeveloped. It shows a need to consolidate scientific studies and methodologies to advance the manufacturing of products, achieving the necessary requirements.

Topics considered "emerging or declining" are presented in the fourth quadrant. It includes paper, cellulose, materials testing, environmental problems, heavy metals and industrial waste. There has been a growing number of publications in the last 10 years about them, which are themes for studies that have emerged (or can still be considered as emerging); however, there is still low production, and there may be advances.

Considering a general view, research has shown that there is a great interest of the construction industry in unraveling studies on the characteristics of the types of industry waste and consolidating methodologies for its application and inclusion in clay matrices.

### 3.2. *Types of Industrial Waste and Their Influence on the Properties of Clay Bricks*

Table 4 contains the articles pre-selected by the ProKnow-C method, in which, based on the author's interpretation, we sought those that are most closely aligned with the theme studied and the types of industrial waste most used. This was carried ou by reading the abstracts and titles. These articles (Table 4) were read in full and in detail. The table was organized according to the type of waste evaluated, whether there was a need for treatment for application and what the influence was on the properties of the clay bricks.

**Table 4.** Industrial waste and the influence on the properties of clay bricks.

| n° | Waste | Preparation | Properties | Percentage | References |
|---|---|---|---|---|---|
| 1 | Marble slurry residue | N.T.S (not specified) | Mass loss; Decrease in compressive strength; Increase in water absorption; Reduction in thermal conductivity; Increase in apparent porosity; larger open pore size after firing; Irregular and interconnected pores | 5, 10, 15, 20 and 25 wt% | [22] |
| 2 | Sulfide Mining Waste | Flotation and comminution | Lower porosity; lower water absorption; greater retraction; higher modulus of elasticity; greater efflorescence; high arsenic leaching | 20 and 40 wt% | [16] |
| 3 | Fly ash | N.T.S | Decrease in compressive and flexural strength; lower efflorescence; less mass; higher porosity; higher water absorption; | 5, 10, 15, 20 and 25 wt% | [23] |
| 4 | Fly ash | N.T.S | Decrease in plasticity index; Increase in compressive strength; lower water absorption; higher porosity; higher water absorption | 50, 60, 75, 80 wt% | [24] |
| 5 | Kraft cellulose pulp residue | Dried to a uniform weight and then dissolved in water | Increase in water requirement to confer plasticity; increase in shrinkage; increase in apparent porosity; decrease in density; increase in water absorption; decrease in compressive strength | 0, 2.5, 5 and 10 wt% | [25] |
| 6 | Electroplating sludge (10 wt%) + Glass residue | The sludge and pulp were dried at 105 °C for 24 h, then the glass was ground to 74 µm. Everything was mixed in powder form until homogeneity was obtained | Reduction in open porosity; reduction in the surface area of the bricks; increase in compressive strength; higher density; reduction in heavy metal leaching | Content of electroplating sludge of 10 wt% and 5, 10 15, 20, 25, 30 wt% of waste glass powder | [26] |
| 7 | Coconut husk | Dried in an oven, ground and classified | Greater mass loss on firing; increase in porosity; increase in water absorption; decrease in compressive strength; decrease in apparent density; decrease in thermal conductivity; decrease in shrinkage, decrease in sintering temperature | 0, 10, 20, and 30 wt% | [27] |
| 8 | Urban sewage treatment sludge | Anaerobic reactor, anoxic filter, drum filter, secondary and tertiary decanters and calcium hydroxide | Greater mass loss, decrease in compressive strength, decrease in sintering temperature, increase in porosity, increase in water absorption, increase in plasticity | 15 wt% sludge | [28] |
| 9 | Contaminated glass powder | N.T.S | Decrease in firing temperature, decrease in shrinkage, increase in compressive strength, increase in thermal conductivity, increase in density, decrease in porosity, decrease in water absorption, lower leaching index | 5, 10, 15, 25 wt% | [29] |

**Table 4.** *Cont.*

| n° | Waste | Preparation | Properties | Percentage | References |
|---|---|---|---|---|---|
| 10 | Water treatment plant sludge | Sieved at 60 mesh, drying at 70 °C for 24 h | Increase in porosity, decrease in flexural strength, increase in water absorption, increase in mass loss, decrease in apparent specific mass | 5, 10, 15, 20 and 25 wt% | [30] |
| 11 | Silica sand | Drying at 105 °C for 24 h, Comminution up to 1.2 mm, mixed with water for extrusion | Decrease in plasticity, decrease in flexural strength on drying, decrease in shrinkage, decrease in thermal conductivity, decrease in flexural strength, increase in water absorption, decrease in density | 11 wt% | [31] |
| 12 | Sawdust | Drying at 105 °C for 24 h, Comminution up to 1.2 mm, mixed with water for extrusion | Increase in plasticity, decrease in flexural strength on drying, decrease in shrinkage, decrease in thermal conductivity, decrease in flexural strength, increase in water absorption, decrease in density | 3.7 wt% | [31] |
| 13 | Bauxite residue | Drying at 105 °C for 24 h, Comminution up to 1.2 mm, mixed with water for extrusion | Decrease in plasticity, increase in flexural strength on drying, decrease in shrinkage, increase in thermal conductivity, increase in flexural strength, increase in water absorption, increase in density | 3 wt% | [31] |
| 14 | Dolomitic limestone | Drying at 105 °C for 24 h, Comminution up to 1.2 mm, mixed with water for extrusion | Increase in plasticity. Decrease in flexural strength on drying, decrease in shrinkage, increase in thermal conductivity, decrease in flexural strength, decrease in water absorption, increase in density | 25 wt% | [31] |
| 15 | Paper sludge | Drying at 105 °C for 24 h, Comminution up to 1.2 mm, mixed with water for extrusion | Increase in plasticity, increase in flexural strength on drying, increase in shrinkage, decrease in thermal conductivity, decrease in flexural strength, increase in water absorption, decrease in density | 8 wt% | [31] |
| 16 | Iron scrap | Drying at 105 °C for 24 h, Comminution up to 1.2 mm, mixed with water for extrusion | Decrease in plasticity, increase in flexural strength on drying, increase in shrinkage, decrease in thermal conductivity, decrease in flexural strength, increase in water absorption, decrease in density | 15 wt% | [31] |
| 17 | Coal | Drying at 105 °C for 24 h, Comminution up to 1.2 mm, mixed with water for extrusion | Increase in plasticity, decrease in flexural strength on drying, decrease in shrinkage, decrease in thermal conductivity, decrease in flexural strength, increase in water absorption, decrease in density | 8 wt% | [31] |
| 18 | Olive stone | Drying at 105 °C for 24 h, Comminution up to 1.2 mm, mixed with water for extrusion | Increase in plasticity, increase in flexural strength on drying, decrease in shrinkage, decrease in thermal conductivity, decrease in flexural strength, increase in water absorption, decrease in density | 20 wt% | [31] |

**Table 4.** *Cont.*

| n° | Waste | Preparation | Properties | Percentage | References |
|---|---|---|---|---|---|
| 19 | Hausmannite | N.T.S | Decrease in water absorption, no change in drying rate, lower mass loss in freeze–thaw test, decrease in mass loss in crystallization test, little change in porosity: more interconnected pores | 15 wt% | [32] |
| 20 | Industrial ceramic sludge | N.T.S | Greater pore interconnectivity, increase in water absorption index, increase in drying rate, Greater mass loss in freeze–thaw test, Mass gain in salt crystallization test, little change in porosity: greater number of open pores | 10 wt% | [32] |

According to Table 4, mining, water and sewage treatment waste, glass, fly ash and biomaterials were used in the last research. Mining residues are wastes from the industrial processing of ores and, as they have a composition closer to the raw material used in bricks, they are the first to be investigated and considered ideal additives. Industrial ceramic waste is an example of application, as it has a majority composition of aluminum-silicon and has a chemical composition similar to that of the clay used to manufacture bricks, influencing the reduction in defects [6].

Researchers [22] studied the marble mud waste, rich in calcite, and observed an increase in apparent porosity, a larger pore size and irregular and interconnected pores. The results were influenced by the combustion of calcite that decomposes into $CO_2$, creating pores in the brick structure and CaO prone to expansion, forming pores. Porosity allows the brick to be lighter and provides better thermal insulation.

Other identified wastes were silica sand, bauxite residue, dolomitic limestone, iron scrap and coal [31]. Bricks using silica sand, bauxite residue and iron scrap showed a decrease in plasticity and a reduction in flexural strength during drying and in the product. Those with bauxite residue had a higher flexural strength. These wastes influenced shrinkage positively, reducing the risk of defects; however, the use of scrap residue had the opposite effect. Bricks with dolomitic limestone and coal achieved plasticity with better processing conditions and an increase in thermal conductivity proportional to the increase in density. All samples, except for the one with dolomitic limestone, had an increase in water absorption.

The incorporation of industrial ceramic sludge waste [28] and waste from the production of iron alloys and manganese oxide batteries (hausmannite) [32] was also considered. The samples with ceramic sludge showed greater pore interconnectivity, resulting in a higher water absorption rate and better drying rate. The samples with hausmannite had a decrease in water absorption, while the drying rate remained almost the same.

Water treatment and sewage industries' sludge is a mixture of organic and mineral waste, presenting pollution risks for rivers and other bodies of water. The biggest concern when it comes to incorporating this waste is its toxicity and risk to human and environmental health. The presence of heavy metals and other metals is considered toxic but during the burning process, the organic matter combusted and released enough energy to cause the inclusion of these metals in the crystalline structure of the brick. This combustion process helped with the energy efficiency of burning, increasing the temperature inside the brick. Properties such as linear retraction were not influenced, however, water absorption increased, and compressive strength reduced. The incorporation of water treatment sludge interfered with the loss of mass during burning [19], influencing the pores and reducing the density of the material, which caused thermal insulation and the reduction in mechanical resistance. However, even with the lowest mechanical resistance, the bricks with up to 15% incorporation of this residue were in accordance with Brazilian safety standards [30].

Glass waste is considered a flow agent and directly influences the reduction in the sintering temperature, with the introduction of a liquid phase filling the pores and densifying the brick during firing. Research shows that this material immobilizes heavy metals through the vitrification process, being able to reduce or eliminate the leaching of these metals in bricks. The glass was able to fuse, acting as an encapsulation of metallic atoms, called spinels. Once the glass creates the liquid phase, it fills the pores, increasing density and mechanical resistance. A study showed that this addition reduced porosity, burning temperature for sintering, and shrinkage. It also caused an increase in compressive strength and density, in addition to reducing water absorption and the leaching rate [26–29].

Fly ash, a waste identified among the 50 keywords in the word cloud presented in Figure 7, comes from the combustion of coal in thermoelectric plants. A study incorporated 50%, 20% and 25% of fly ash in the clay composition and identified different responses regarding compressive strength [23,24]. However, more studies are still needed to establish a pattern.

Biomaterials are classified as organic matter wastes and are considered combustible agents, reducing the energy and temperature required for sintering. Due to the cause of combustion, it is common to identify the formation of pores and a lower density. The addition of Kraft cellulose pulp waste [25], in ratios of 2.5%, 5% and 10%, increased the clay brick porosity. However, the greater the content of the waste, the density, water absorption and compressive strength were more negatively affected. Another modified property was plasticity, increasing the need for water in the extrusion process.

The use of coconut shells, and other biomaterials, in clay matrices was evaluated and there was a greater loss of mass during burning due to the combustion of the material [27]. The result of this is increased porosity, thermal conductivity and water absorption and lower density and compression resistance. This combustion effect caused internal centers of high temperature, reducing the sintering temperature. Sawdust waste, paper sludge and olive pits have also been studied and in all cases, there is an increase in plasticity, porosity water absorption, and a decrease in thermal conductivity and flexural strength [31].

## 4. Technological Prospection

The research began with the selection of keywords to be inserted into the database Lens.org. Table 5 lists the attempts made. The set of words that provided the greatest number of patents should be the chosen one. However, by reading part of the texts, the Boolean operator "NOT" was included due to the large number of works that use Portland cement as a binder, which is not the focus of this study.

**Table 5.** Key words used to search the database Lens.org.

| Key Words | Results |
|---|---|
| Faced Brick AND Exposed AND clay AND industrial waste AND aesthetic ANDNOT cement | 62 |
| Exposed Brick AND clay AND industrial waste AND aesthetic | 79 |
| Faced Brick AND clay AND industrial waste NOT cement | 435 |
| Exposed Brick AND clay AND industrial waste NOT cement | 712 |
| Exposed Brick AND clay AND industrial waste | 2211 |

The word "faced brick" provided a satisfactory number of documents, however, most patents were related to the production of refractory bricks for the manufacturing industry, and not for the construction of walls. The final selection was exposed brick AND clay AND industrial waste NOT cement, totaling 712 patent texts, as listed in Figure 2.

Figure 9 shows the number of patents linked to the topic over the years, together with the equation obtained from the simple regression analysis.

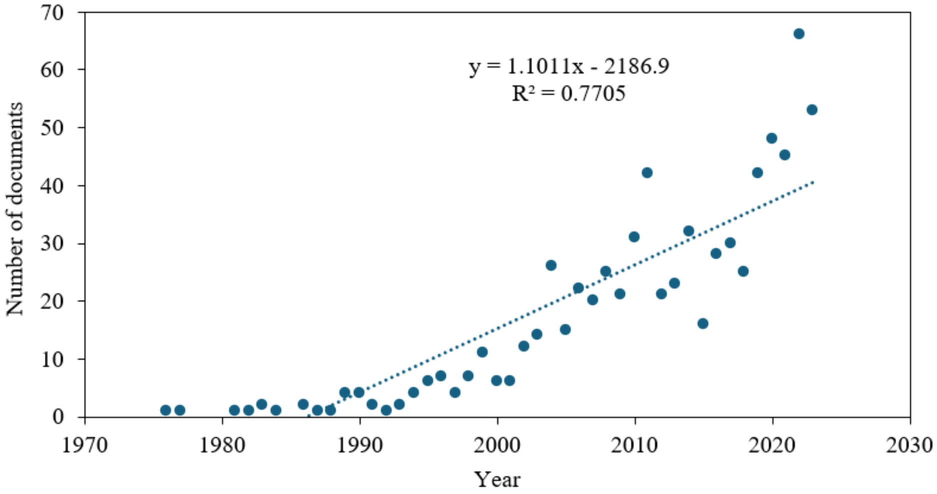

**Figure 9.** Number of patents linked to the topic, throughout the years.

The analysis yielded an $R^2$ value of 77.05% with a significance level of 5%. The *p*-value for the "year" variable was lower than the significance level ($5.213 \times 10^{-15}$), indicating that the variable has a significant effect on the number of patents. Despite this, we concluded that to accurately forecast the number of patents based on the year, a larger dataset should be analyzed. This is because the residuals exhibited in Figure 9 show a certain trend up to the year 2000, with greater dispersion observed after that year. The seemingly parabolic trend suggests that the relationship between the variables may be nonlinear. In other words, the number of patents does not increase at a constant rate over time, but rather with a variable growth rate.

There has been a considerable increase since the early 1990s, coinciding with the growing global interest in the preservation of natural resources and sustainable development. It is important to mention the ECO-92 event (or Earth Summit), held by the United Nations Conference on Environment and Development in the city of Rio de Janeiro, in 1992. This conference is understood as a milestone, helping to consolidate and expand the concept of "sustainable development", making it a central part of the international development and environmental agenda [33]

Comparing the results shown in Figures 3 and 9, it is possible to observe that the growth patterns of scientific research and technological work are similar after 2013. In both cases, the production peaks occurred in 2021, during the pandemic. Thereby, the production of clay bricks incorporating industrial waste has become a topic of interest to the scientific and technical community, also evidenced by the increase in concessions and patent applications related to the topic (Table 6). The COVID-19 pandemic has underscored the urgent need to re-evaluate and modify existing production and consumption models, prompting a heightened focus on sustainable practices and the exploration of alternative materials. In this context, the incorporation of industrial waste in brick manufacturing emerges as a solution with dual benefits: it reduces reliance on natural resources, such as virgin clay, and contributes to effective waste management, thereby minimizing the environmental impact of the construction industry.

Figure 10 presents the jurisdiction of the patents identified in this study. American patents fall under the jurisdiction of the United States Patent and Trademark Office (USPTO), which guarantees intellectual property rights granted by the U.S. government. These patents provide protection concerning sale, use, and manufacturing for the domestic market, as well as importation into the U.S. This protection is time-limited (typically 20 years) in exchange for public disclosure of the invention upon patent grant [34]. The European Patent Office (EPO) has enhanced its collaborations with major foreign corporations such as Bosch, Toyota, Nissan, and Phillips, among others. The EPO's patent network is a more globalized and interconnected framework [35]. The World Intellectual Property Organization (WIPO) serves as the global forum for services, policies, information, and cooperation in the field of intellectual property. The WIPO became a specialized agency of the United Nations in 1974. This entity comprises various sectors responsible for administering numerous international treaties and ensuring protection for inventions across multiple countries [35].

**Table 6.** Number of patents granted and patents applications per year.

| Year | Granted Patent | Patent Application |
|---|---|---|
| 2016 | 9 | 19 |
| 2017 | 12 | 18 |
| 2018 | 11 | 14 |
| 2019 | 15 | 27 |
| 2020 | 12 | 36 |
| 2021 | 15 | 30 |
| 2022 | 23 | 42 |
| 2023 | 25 | 28 |

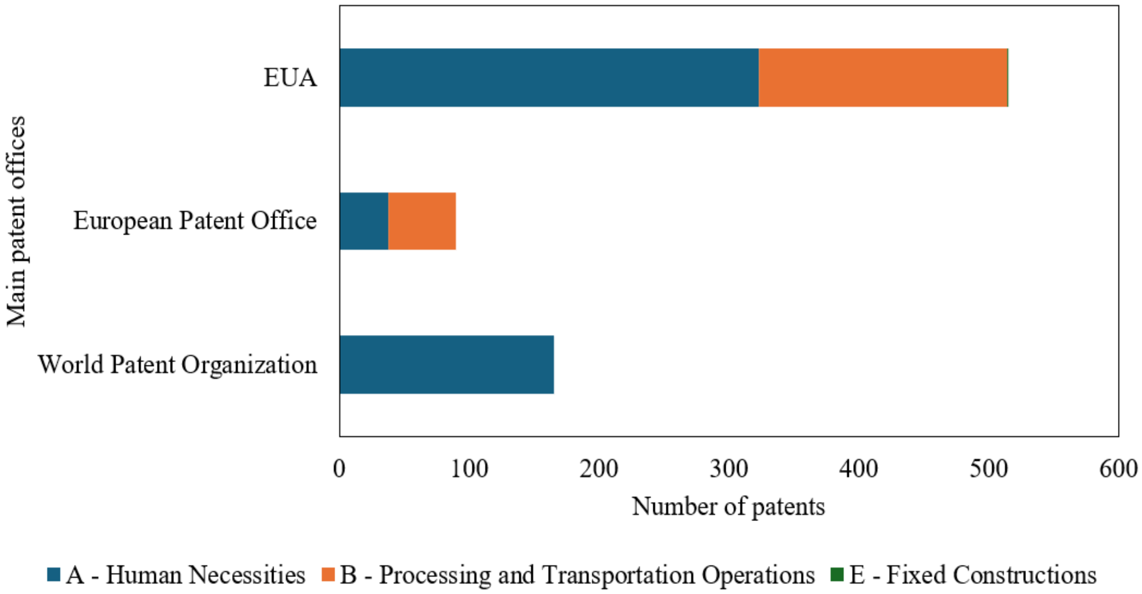

**Figure 10.** Number of patents according to their jurisdiction and IPC classification.

The results presented in Figure 10 differ from those from Table 3. The countries with the most scientific research on exposed clay bricks with waste are not the ones that develop the most technology with this material.

The nationality of inventors matches the country that has the most patents (Figure 11). However, when comparing the data obtained in the survey of articles, there is a difference in the results. At least part of the top 10 researchers are known to be non-American (Figure 4), even though the USA is the country with the most patent inventors.

Despite the significant number of American inventors, many patent holders are Japanese and Canadian entities. These organizations hold exclusive commercialization rights for these inventions (Figure 12. Number of patents according to the nationality of the patent holders).

The main corporations holding patents are shown in Figure 13. The different areas in which the companies operate can also be seen. The patents associated with the keywords selected are focused on water treatment and the uses of clay materials as thickeners or rheology modifiers [36]. For example, the company Boral Industries INC., a construction company, holds a patent that use clay materials to manufacture polyurethane composites filled with light fillers [37]. However, we also identified patents for different uses than listed as those held by the Fluid Energy Group, a Canadian company. Their patents are related to fine particle technology for different industrial applications [38].

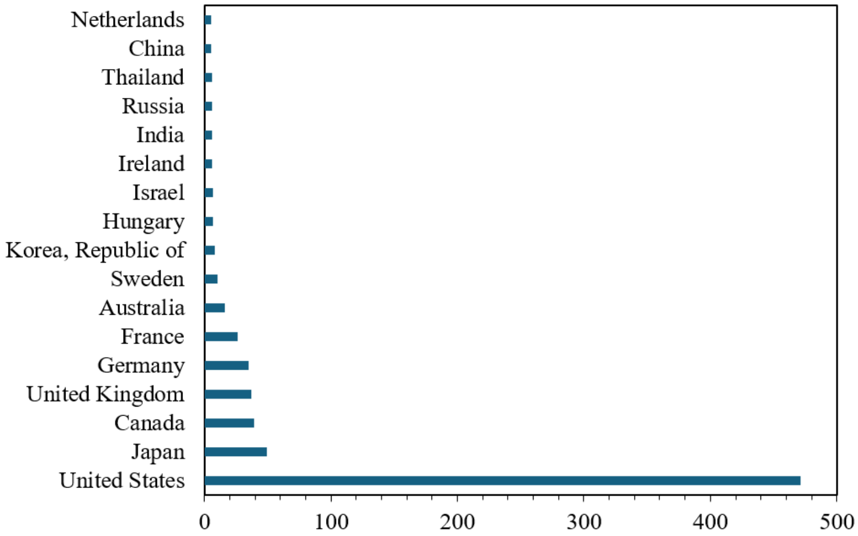

**Figure 11.** Patent numbers according to the nationality of the inventors.

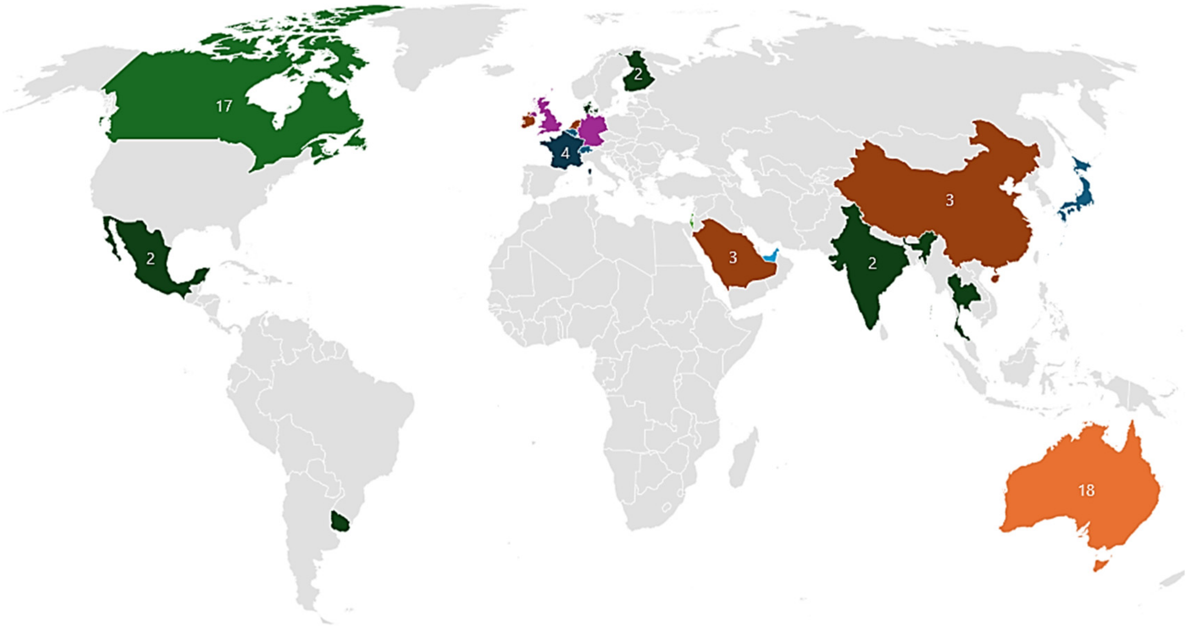

**Figure 12.** Numerical distribution according to the nationality of patent holders.

Regarding the relevance of the study, the citation was also considered as a research variable. Figure 14 demonstrates the growing interest in this topic over recent decades, as evidenced by the numerous citations of the documents selected for this study. Patents classified under section A (Human Needs) are more prevalent. However, this category encompasses various purposes. Examples include adsorbent ceramic particles [39]; processes for the chemical binding of heavy metals from sludge into the silicate structure of clays and shales for building manufacturing material [40]; a method for forming bricks, tiles, and similar products by treating clay, shale, or other clay ceramic raw materials containing pyrite [41]; and a formula for sintered brick with red mud [42].

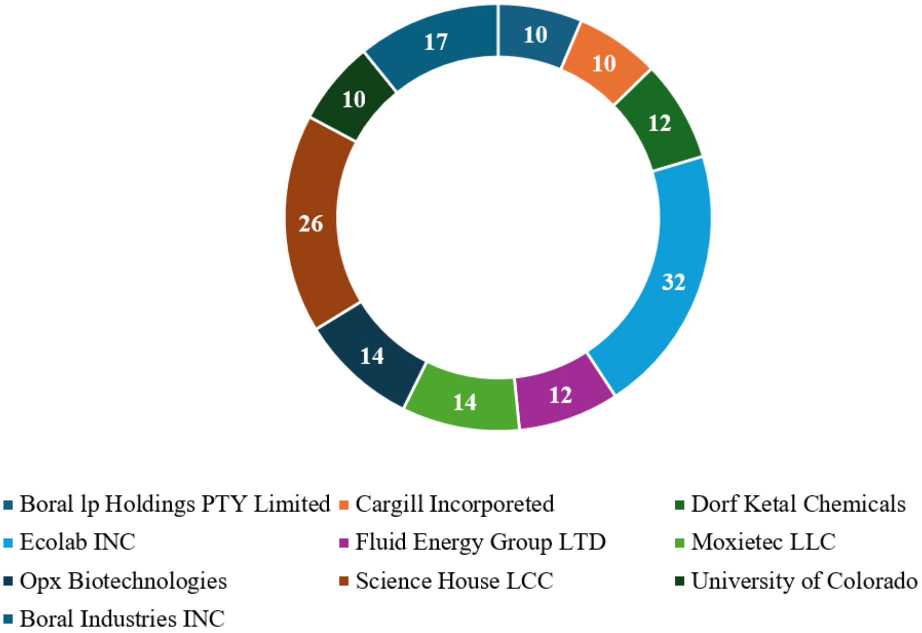

**Figure 13.** Major patent-holding corporations.

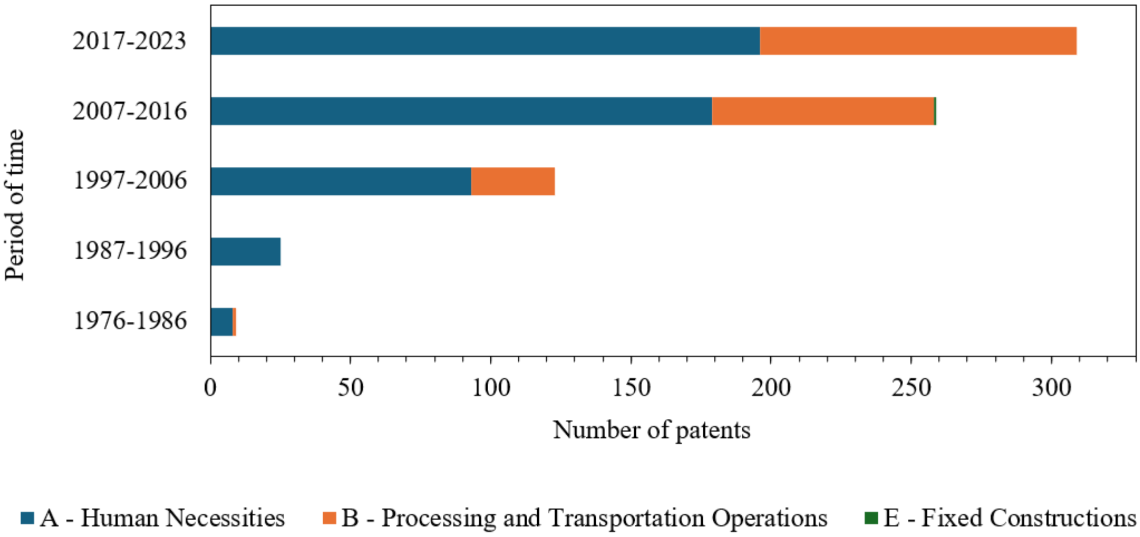

**Figure 14.** "Cited by Patents" tab as an indicator of the relevance of articles according to the IPC classification.

Among the most relevant patents in class B are those that propose advancements in raw material processing, material recovery in effluent and waste treatment, and the synthesis of new materials. Examples include the composition and manufacturing process of building bricks and tiles [43], clay fiber filtration tubes containing flocculant wound on a mandrel [44], linear hearth kiln system and related methods [45], and method for processing clay ceramic materials [41].

The legal status of the surveyed patents is in Figure 15. It is evident that even patents filed over 20 years ago remain active, reflecting the ongoing interest of the holders. Notably, there is a significant number of patents with pending filing confirmations. Specifically, between 2017 and 2023, there are 121 patents awaiting filing confirmation. Again, a confirmation of the interest of the industry and the market on the use of waste in exposed clay bricks.

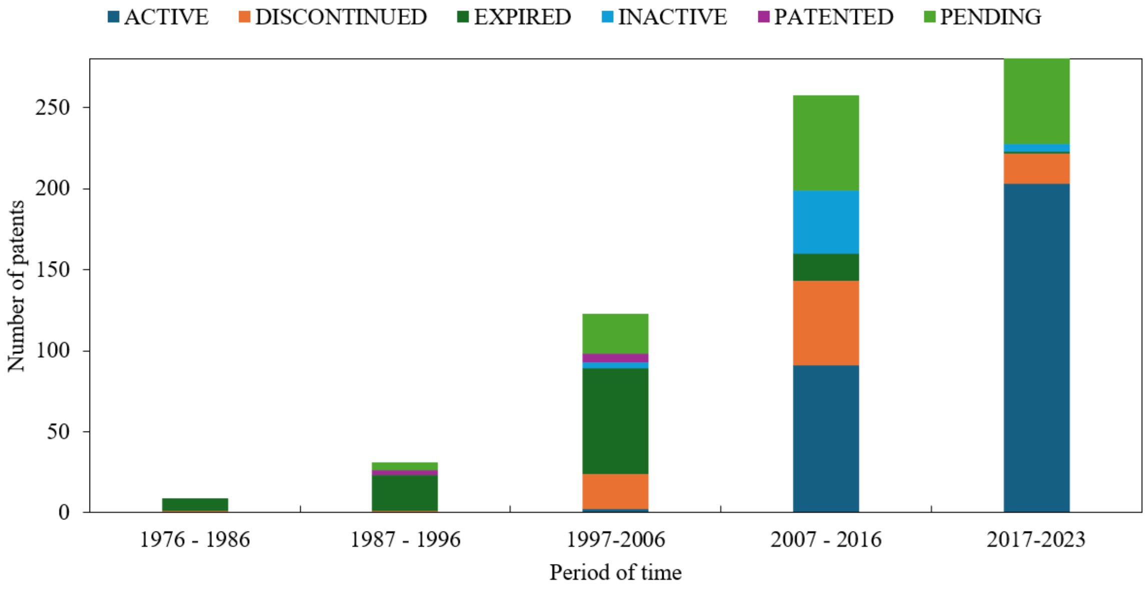

**Figure 15.** Number of patents over the years according to their legal status.

The recurring keywords found in the patent abstracts are shown in Figure 16. The words "embodiment", "chemical product", "article", "mixture" and "coating" highlight the focus of the patents: the search for optimized processes and compositions. These keywords are strongly connected. From this central core, connections radiate to more specific areas of research. For example, the term "mixture" is linked to "catalyst" and "chamber", suggesting that the patents explore chemical reactions in controlled environments to create innovative mixtures.

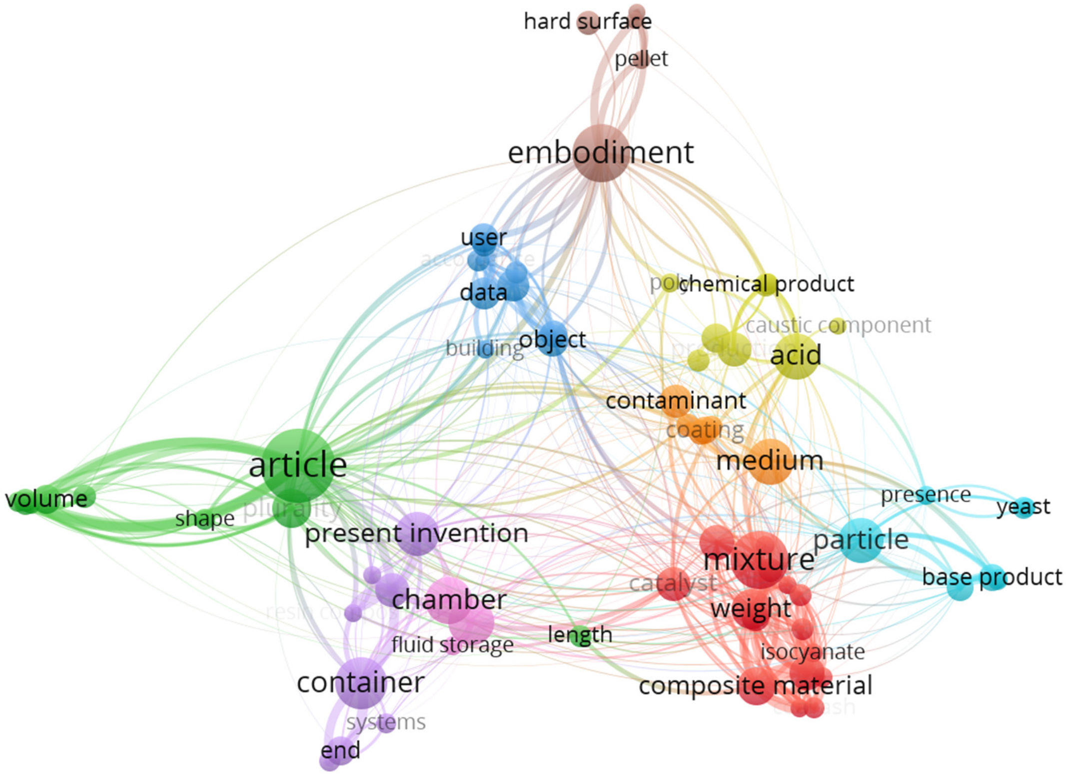

**Figure 16.** Most frequent words and their connections.

The connection between “mixture” and “particle” and “weight” indicates the investigation of the impact of particle size and proportion on the composition of clays. The presence of the term “contaminant” connected to “mixture” and “coating” highlights the concern with the safety and sustainability of the inventions.

The word “contaminant” is most strongly connected to “amount”, “pellets” and “particle”, which are believed to represent inventions about the synthesis of particles to the encapsulation of contaminating substances. The pellets produced are then incorporated into the manufacturing of bricks or other building materials.

It can be observed that the scientific community, regarding the production of clay bricks, seeks to understand the impact of the incorporation of different types of industrial waste on the properties of the brick, with emphasis on compressive strength. However, from the analysis of the selected patents, the inventors focus on the processes of transformation of clays as a mineral and on the creation of methods that allow the synthesis of clay particles associated with contaminants [46,47]. For example, the US patent 4882067 [40] discusses the chemical bonding of heavy metals from sludge in the silicate structure of clays and shale for the manufacture of construction materials.

## 5. Conclusions

This study has revealed a diverse range of research over the last decade on the incorporation of waste materials in clay bricks, highlighting a growing trend in publications and patents. This field demonstrates significant potential for promoting sustainability within the construction industry, driven by increasing interest in waste recycling and reuse.

Analysis of the most cited keywords in scientific articles has shown a focus on the properties of water absorption, strength, and thermal conductivity of bricks incorporating waste materials. Various industrial wastes, such as those from mining, water treatment, glass, and fly ash, have proven promising for this application, significantly impacting brick properties such as plasticity, shrinkage, and water absorption. However, the impact on these properties varied according to the waste studied, as shown in Table 2. This is associated with the variation in the chemical and mineralogical composition of the waste materials.

Patent analysis has revealed trends and opportunities for innovation in the field, particularly highlighting the use of waste contaminated with pyrite, red mud, and ash from various sources.

An interesting point identified was the divergence of interests between academia and industry. While academic research focuses on the influence of waste on brick properties, the industry seeks to optimize production processes. This divergence points to the need for greater alignment between research and development, aiming to accelerate innovation and the application of new technologies.

Finally, the study identified a knowledge gap regarding the aesthetics of bricks incorporating waste materials, both in scientific articles and patents. Future research could explore the impact of sustainability and the use of clean energy on the aesthetics of bricks, in addition to investigating the life cycle of these materials.

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