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TECHNO-ECONOMIC ANALYSIS IN THE SERVICE OF TRADITIONAL CERAMIC INDUSTRY. THE FIRST REVIEW

TEHNO-EKONOMSKA ANALIZA U SLUŽBI TRADICIONALNE KERAMIČKE INDUSTRIJE. PRVI PREGLEDNI RAD

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Abstract

The traditional ceramics industry uses large amounts of raw materials and energy while significantly contributing to the CO_2 footprint. The improvements, primarily in the first two areas, will contribute to sustainable development and answer the emerging questions of decreasing a gas-release footprint. These are topics of high importance considering European Union goals, and thus, on the contrary, there is yet only scarce available literature on the subject. This paper describes the state and future perspectives of the traditional ceramics industry through the techno-economic lens. Many options are detected that save resources (waste materials), energy consumption (reparation or modification of kilns, usage of dry pressing in ceramic tiles production, etc.), and control of flue gas composition (changing the fuel, etc.). Further intensified research is needed to widen the knowledge and compare the results. In the first place, the composition of flue gas should be determined by the same methods and presented using unified units. The lowest energy consumption and flue gas composition are determined in ceramic tiles production by the dry route. Using a downdraft gasifier of biomass in brick manufacturing increases the internal rate of return if a longer tunnel kiln is applied. The expected payback period is from 4 to 8 years.

Ključne reči
- tradicionalna keramička industrija
- tehno-ekonomska analiza
- ušteda potrošnje energije
- CO_2 otisak

Izvod

Tradicionalna keramička industrija koristi velike količine sirovina i energije, istovremeno značajno doprinoseći CO_2 otisku. Poboljšanja, prvenstveno u prve dve oblasti, doprineće održivom razvoju i odgovoriti na nova pitanja smanjenja otiska gasa. Ovo su teme od velikog značaja s obzirom na ciljeve Evropske Unije, ali je, naprotiv, literatura o ovoj temi još uvek oskudna. Ovaj rad opisuje stanje i buduće perspektive tradicionalne keramičke industrije kroz tehno-ekonomski objektiv. Otkrivaju se mnoge opcije koje štede resurse (otpadne materije), potrošnju energije (popravka ili modifikacija peći, korišćenje suvog presovanja u proizvodnji keramičkih pločica, itd.), i kontrolu sastava dimnih gasova (promena goriva itd.). Potrebna su dalja intenzivirana istraživanja da bi se proširilo znanje i uporedili rezultati. Na prvom mestu, sastav dimnih gasova treba da se odredi istim metodama i prikaže pomoću unificiranih jedinica. Najniža potrošnja energije i količina dimnih gasova su detektovani pri proizvodnji keramičkih pločica prema suvom postupku. Korišćenje gasifikatora biomase u proizvodnji opeke na nižem toku povećava internu stopu povrata ako se primeni duža tunelska peć. Očekivani period otplate je od 4 do 8 godina.

INTRODUCTION

Techno-economic analysis (TEA) holds immense significance in various industries for several reasons:

- Decision-Making: TEA helps make informed decisions on implementing new technologies or processes. While providing a comprehensive understanding of both the technical feasibility and economic viability of a project /1/, it also aids decision-makers in choosing the most efficient and cost-effective options.
- Resource optimisation: by evaluating different technological alternatives, TEA enables the identification of most resource-efficient solutions. It helps in optimising resource allocation, minimising waste, and maximising productivity /2/.
- Risk assessment: TEA assesses potential risks associated with adopting new technologies or processes. It allows for a thorough analysis of potential challenges, costs, and uncertainties, aiding in risk mitigation strategies /3/.
- Investment planning: it aids in estimating the investment required for implementing new technologies or projects /4/. Through financial metrics like the net present value (NPV), return on investment (ROI), internal rate of return (IRR), payback period (PBP), and production capacity (PC), TEA assists in determining the financial feasibility and potential returns on investment, /1, 5, 6/.
- Sustainability and innovation: TEA supports the evaluation of sustainable practices and innovations within industries /7/. It enables the assessment of technologies that align with environmental and social sustainability goals while maintaining economic feasibility.
- Continuous improvement: by regularly conducting TEAs, industries can continuously assess and improve their processes and technologies /8, 9/. It fosters a culture of innovation and optimisation, ensuring long-term competitiveness, and

- Ultimately, TEA serves as a crucial tool for aligning technological advancements with economic feasibility, fostering efficient decision-making, and facilitating sustainable growth in the industry, /6, 10/.

However, the main obstacle to conducting TEA in future processes is the inaccessibility of data needed for input parameters and also the unavailability of sophisticated computational tools for concise estimation. Thus, removing these limitations can be greatly aided by the integration of algorithms and data-driven technology, /6/.

Artificial intelligence is found as a very significant tool in many areas of study /11-13/ and is implemented in the same way to visualise the results and test the sensitivity of outputs to the changes in inputs. The inputs are often parameters related to the production process, materials shares, and, e.g., firing temperature, while the outputs are the data of interest in TEA: NPV, ROI, IRR, PBP, and PC, /14/.

TECHNO-ECONOMIC ANALYSIS IN CERAMICS MANUFACTURING

The traditional ceramic industry primarily uses clayey raw materials to manufacture clay bricks, clay blocks, roofing tiles, and ceramic tiles, while sanitary ware is excluded from this study. The production methodology is somewhat similar and includes raw materials preparation (mixing, milling), shaping (extrusion, or hydraulic pressing), drying, and firing. While the process is similar, some key differences exist, such as clay minerals' quantity and mineralogical composition, granulometry, necessary moisture, and firing regime and temperature. Additionally, the choice between a one- or two-step firing process and glazing can impact flue gas control and energy consumption.

European Commission`s Roadmaps for the ceramic industry set goals concerning resource efficiency, energy savings, and a low-carbon economy, /15/. The long-term target was set for 2050, /16, 17/, but there are also halfway milestones before 2030, /18/. TEA is a holistic approach, taking into account both technological and economic considerations. By considering both aspects, we can ensure that our decisions are well-informed and lead to the best outcomes. This is crucial in today's ever-evolving world, where the intersection of technology and economics is becoming increasingly complex.

Techno-economic advancements in the ceramic industry have primarily focused on improving production efficiency /19, 20/, reducing (optimising) energy consumption, optimising raw material usage /19, 21, 22/, and implementing advanced manufacturing techniques, /23/. Innovations in kiln design /24/, material formulations /23/, automation /19/, and waste reduction /25/ have been key areas of development, aiming to make the process more cost-effective and environmentally friendly. Additionally, research into alternative energy sources and sustainable practices has also gained attention in this industry, /26/.

Many factors must be followed in a comprehensive TEA. For example, in a TEA for a new ceramic product, several key factors should be estimated to assess its feasibility and profitability:

- Production costs: costs related to raw materials, labour, energy consumption, equipment, and facilities needed for manufacturing the new ceramic product are to be evaluated /19, 27/.
- Market demand: the potential market demand for the new product must be estimated - the sales volume, pricing strategy, and market trends to understand its commercial viability, /6/.
- Resource efficiency: the efficiency of resource utilisation, including energy, water, and raw materials should be assessed. The evaluation of the possible optimisation of the manufacturing process to reduce waste and resource consumption is to be considered, /19/. Resource efficiency is becoming extremely important, considering the recent concerns about the critical raw materials (including feldspars) availability and price, especially in ceramic tiles, sanitary ware, tableware, etc., production, /20/.
- Life Cycle Analysis: the environmental impact of the product from raw material extraction to disposal can be considered. The product's carbon footprint or environmental impact should be estimated to ensure sustainability, /28/.
- Profitability and ROI: the potential revenue generated against production costs should be estimated. ROI and PBP are to be calculated to determine the financial feasibility of the venture, /29/.
- Technology and Innovation: innovative technologies or manufacturing processes incorporated into production and their impact on efficiency, costs, and market competitiveness must be evaluated, /19/.

Conducting a comprehensive TEA helps in making informed decisions on whether to proceed with manufacturing the new ceramic product, considering both economic and environmental aspects.

However, research papers in the traditional ceramics field are scarce so this subject needs to be more widely investigated. The majority of studies explored the use of waste materials as raw materials /22, 23, 30, 31/, process energy consumption /22, 26, 31/, estimated the performance of different alternative fuels /5/, followed fuel gas analyses /5, 22, 26/, and tracked economic flows /5, 22, 23/. Economic analysis differentiates between novel product production processes utilising available machinery /2, 31/, and those requiring the introduction of new factories or machinery components, /32/.

METHODOLOGY

Traditional ceramics industry is the subject of various studies accessible through literature databases as SCOPUS, Web of Science, and Google. These studies primarily focus on potential energy savings, flue gas analyses, and economic calculations. Most of the research in the ceramic industry concerns the utilisation of different agricultural and industrial waste as a partial substitute for raw materials /33/. However, there is a lack of in-depth studies on the subject. This study comprehensively reviews the literature, evaluates the results obtained, and synthesizes the key findings. Various approaches are analysed and compared to address future challenges and suggest recommendations for further research.

RESULTS AND DISCUSSION

Raw materials and energy consumption

In the creation of ceramics, the first essential element is the availability of raw materials which account for a significant 39.6 % of total cost, /34/. According to the literature, producing 1 m^2 of ceramic tiles requires 20-22 kg of solid raw materials /35, 36/. Additionally, a substantial amount of water is necessary, the quantity of which depends on the slurry density. Water usage ranges from 3.4 to 95 %, as reported /24, 35-37/. This data emphasizes the critical nature of this phase of the ceramic production process, offering opportunities for savings through the implementation of waste materials. This aspect has been extensively analysed in previous studies, /31/. The European Union has recently introduced a groundbreaking proposition aimed at promoting sustainability through eco-design, /38/. This initiative focuses on encouraging manufacturers to adopt an environmentally friendly approach while designing their products. The proposed guidelines are set to establish sustainable practices as the new norm, with the ultimate goal of reducing waste and minimising the environmental impact of consumer goods. European Union has published a novel proposition for an eco-design of the products while insisting on sustainable products as a norm, /10/.

The optimal utilisation of thermal and electric energy is a crucial factor that contributes to 20-30 % of the total production cost in the ceramic industry /17, 21, 38/. To ensure that the units are obtained and compared on a standardised basis, it is assumed that 1 m^2 of tiles weighs 19 kg. The diagram in Fig. 1 shows that wall ceramic tiles production process is the most energy-intensive, followed by the floor tiles /26, 39/. The preparation of raw materials is more costly in the case the wet route is applied to produce floor ceramic tiles, /36/. The firing process is the most energy-intensive step in the production of wall ceramic tiles /38/, whereas there are lower temperatures applied for brick and roofing

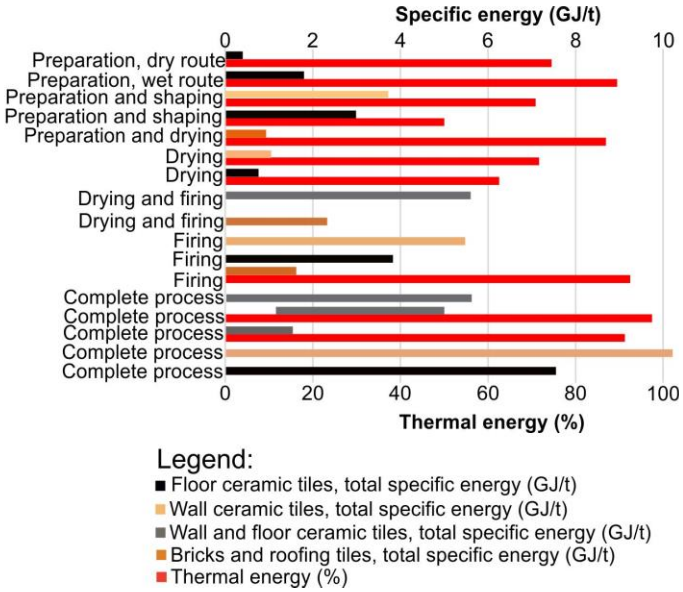

Figure 1. Total specific energy requirements and percentage of thermal energy employed in traditional ceramics production /20, 26, 35, 36, 39, 41/.

tile production, making them less energy-intensive. To reduce the consumption of energy, different methodologies have been implemented, resulting in significant savings. By adding waste mud from paper production as a raw material, up to 3 % of energy can be saved, which can be increased up to 30 %, /17/. Similarly, switching from normal to zig-zag stacking of products in brick production can save approximately 30 % of energy, /40/. Besides, the extension of tunnel kilns is reported to provide an energy savings of 18 %, /40/. Thermal energy is the primary energy source required, accounting for up to 97.62 % of energy-related needs in the ceramics industry /21, 40/. It has been noted in the Best Available Techniques report that while thermal energy savings in drying and firing may occur, it can increase electricity consumption, /35/. However, an analysis of the period from 1990 to 2020 shows that energy consumption in the ceramic tile industry has reduced by 50 %, /17/.

Flue gas

The information presented in Table 1 highlights the potential environmental impact of traditional ceramics production and emphasizes the need to adopt more sustainable production practices. Table 1 provides a comprehensive list of the wastes and chimney gases that are generated during the traditional ceramics production process, which are not frequently reported. The results in the table are calculated based on dry samples, with an O_2 correction factor of 3 % for combustion plants to convert them to mg/Nm^3. The limits set in Europe refer to the plants built not earlier than 2014, for combustion of solid, biomass and gas fuel /42/. The total organic carbon (TOC) content is rarely discussed in the relevant literature /21, 42, 43/. However, it has been found that when paper pulp waste is used as a raw material, the TOC content remains within acceptable limits. On the other hand, when petroleum coke is used as fuel, the TOC content exceeds the allowable limits /42, 45/. Black carbon, which is a part of TOC and indicates incomplete combustion, can be significantly reduced by improving the kiln stacking methodology during brick production, /40/. Particulate matter (PM) limits are exceeded in some brick traditional plants, /40/. As for the ceramic tiles industry, rare literature presents PM content per 1 m^2 of tiles, which is not comparable to the legislative limits. The detected contents vary from 0.27 kg/m^2 for PM10 /35/ to 1.87 kg/m^2 /33/ for total PM. PM10 yearly quantity reported in Serbia in 2014 was, for comparison, higher about 30 %, than the quantity in Belgium determined during 2020, /44/.

There are no defined limits in Europe for HF (hydrogen fluoride) and HCl (hydrogen chloride) in the ceramics industry. The reported values for these chemicals are presented per 1 m^2 of tiles /36/, which makes it difficult to compare to the limits set in Serbia, /44/. In addition to this, wastewater is an important factor in the production of ceramic tiles, with 4.5 l/m^2 /36/. This is a significant amount of wastewater that needs to be considered.

All the reported results on the concentrations of NO_2 and NO_x were within the required limits /42, 45/. However, there is an issue with non-unified reporting regarding the form of nitrogen oxides, and the unit of measurement used in the production of ceramic tiles is often per 1 m^2 of the product.

Table 1. Some of the waste gases and materials in the traditional ceramics industry.

Parameter	Industry	Detected	Reference
TOC	Brick (with waste)	0.30 mg/Nm^3	/21/
TOC	Brick (petroleum coke as fuel)	22.43 mg/Nm^3	/43/
TOC	LIMIT in Serbia	20.00 mg/Nm^3	/42/
TOC	LIMIT in Europe	10.00 mg/Nm^3	/45/
Black carbon	Brick, traditional	48.7 mg/Nm^3	/40/
Black carbon	Brick, Induced ZigZag	3.2 mg/Nm^3	/40/
PM2.5	Brick, traditional	509.1 mg/Nm^3	/40/
PM2.5	Brick, Induced ZigZag	172.3 mg/Nm^3	/40/
PM10	Ceramic tiles	0.27 kg/m^2	/35/
PM10	Ceramic industry in Serbia	97600 t/year	/44/
PM	Brick (with waste)	54.8 mg/Nm^3	/21/
PM	Brick (petroleum coke as fuel)	14.80 mg/Nm^3	/43/
PM	Ceramic tiles	1.87 g/m^2	/34/
PM	LIMIT in Serbia	20 mg/Nm^3	/42/
PM	LIMIT in Europe	10-30 mg/Nm^3	/45/
HF	Ceramic tiles	0.003 kg/m^2	/36/
HF	LIMIT in Serbia	5.00 mg/Nm^3	/45/
HCl	Ceramic tiles	0.009 kg/m^2	/36/
HCl	LIMIT in Serbia	30.00 mg/Nm^3	/42/
Wastewater	Ceramic tiles	4.5 l/m^2	/36/
NO_2	Brick (with waste)	32.7 mg/Nm^3	/21/
NO_x	Brick (petroleum coke as fuel)	31.99 mg/Nm^3	/43/
NO_x	Ceramic industry in Serbia	107,000-127,000 t/year	/44/
NO_x	Ceramic tiles	0.01 kg/m^2	/36/
NO_x	Ceramic tiles	6.19 g/m^2	/34/
NO_2	LIMIT in Serbia	500 mg/Nm^3	/42/
NO_x	LIMIT in Europe	100-450 mg/Nm^3	/45/
SO_2	Brick (with waste)	1.10 mg/Nm^3	/21/
SO_2	Brick (petroleum coke as fuel)	291.93 mg/Nm^3	/43/
SO_2	Brick, traditional	648 ppm	/40/
SO_2	Brick, Induced ZigZag	27 ppm	/40/
SO_x	Ceramic industry in Serbia	20,500 t/year	/44/
SO_x	Ceramic tiles	0.02 kg/m^2	/36/
SO_2	Ceramic tiles	2.37 g/m^2	/34/
SO_2	LIMIT in Serbia	500.00 mg/Nm^3	/42/
SO_2	LIMIT in Europe	200-400 mg/Nm^3	/45/
CO	Brick, traditional	15.0-26.8 %	/5/
CO	Brick, traditional	2349 ppm	/40/
CO	Brick, Induced ZigZag	718 ppm	/40/
CO	Brick (with waste)	23.3 ppmV	/21/
CO	Ceramic tiles	0.005 kg/m^2	/36/
CO	LIMIT in Europe	100 mg/Nm^3	/45/

Regarding SO_2 released from ceramic industries, the reported values were mostly within the limits. If petroleum coke is used as fuel, the flue gas may contain more SO_2 than is allowed. However, the use of this type of fuel fuel is mainly limited to brick factories, /41/. Besides, some brick factories reported the results in ppm which were above the limits /42, 45/. Similarly, the values for SO_2 emissions are also reported per 1 m^2, or yearly releases are presented.

Reporting CO emissions is a complex issue because of the use of different units and measurement methods. Again, some traditional brick factories reported high CO flue gas contents with decreased values while inducing ZigZag technology, which was still above the limits, /40/.

According to the Ceramic Roadmap to 2050 /17/, the development of the ceramic industry will be directed towards lowering process emissions, net zero CO_2 indirect emissions, and carbon removal and utilisation technologies.

The available results concerning CO_2 release per 1 t of the ceramic goods (Fig. 2) show the same trend as with the consumption of energy which is expected since the majority of this gas is released by the fuel used, including some quantities that originate from raw materials. Thus, the highest CO_2 footprint is detected during wall and floor tile production, being between 233 and 475 kg/t /33, 39/. The lowest footprint of 16-20 kg/t is determined in a dry-route ceramic tiles fabrication /36/, since significantly lower energy is needed in the drying process. In the brick and roof tiles industry, around 74 % of the footprint is released during the firing process, while in the ceramic tiles, the same is among 61-65 %, /39/. When compared to the measured values with the plan set for 2025, 58 kg/t in ceramic tiles and 106 kg/t in facing bricks /26/, a significant further reduction of CO_2 release must be achieved. The data related to the ceramic industry in Italy shows the release of 1.7-2.5 Mt CO_2eq/year, /26/. Given that some of the European countries like the Netherlands included the taxes of 47 €/tCO_2 /39/, this is a significant sum.

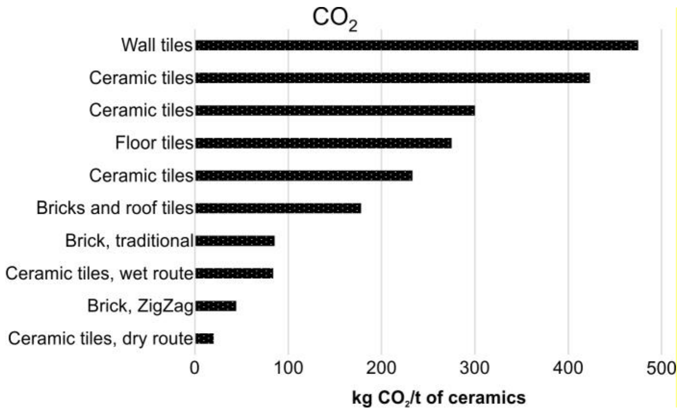

Figure 2. CO_2 footprint of the ceramic industries /33, 35, 36, 39-41/.

In conclusion, although there are currently no limits related to CO_2 release, there is a net-zero aim for all industries. The taxes could be a problematic issue for the survival of ceramics industries. In addition, an initiative to count the CO_2 released from the electricity used in the process makes this challenge even more worrying. However, since global warming must be slowed down, these activities are more than necessary.

Economic observations

Of the economic aspects in ceramics production, mainly IRR and PBP were analysed (Fig. 3).

Regularly, a 15 % internal rate of return is considered as a minimum that justifies introducing changes to a factory /23/, while IRR after 20 years of implementation of 10 % is satisfactory, /5/. The results obtained in the extruded ceramic tiles production containing ornamental rock waste of 16.82 % were found satisfying, /5/. While producing traditional bricks in small-scale factories, while using a downdraft gasifier of biomass, a 12.01-24.35 % IRR is determined, which is increased by the improved kiln capacity. The highest IRR is found for the capacity of 100,000 pieces daily. Among the tested biomass, rubber seed kernel shells showed the best results concerning the rate of investment return /5/, which was caused by the lowest capital and running costs.

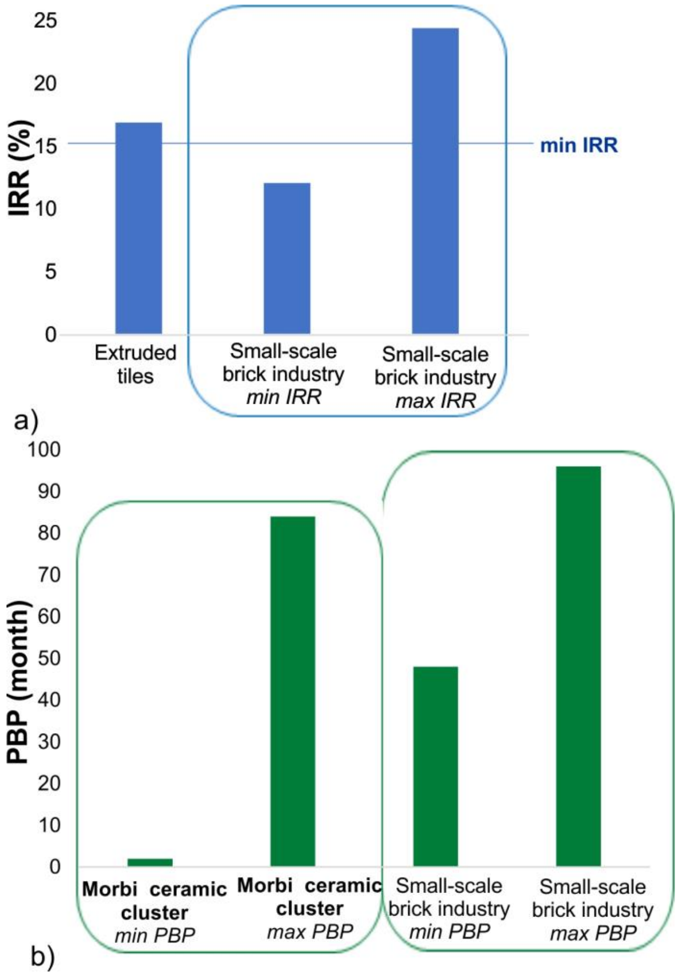

Figure 3. a) Internal rate of return (IRR), and b) Payback period (PBP) in the ceramics industry, /5, 20/.

A payback period varied from 2 to 96 months /5, 20/. While inserting improvements in the Morbi ceramic cluster in India, the UN found a PBP of between 2 and 84 months, while improving certain parts of the process, from the installation of a control system in the agitator motor to the solar-wind system, /20/. A PBP of 4-8 years is determined in the case of small-scale red brick industry while using biomass as a fuel /5/. Minimum PBP, after implementation of gasifier, is found while using rubber seed kernel or coconut shells as a cheap fuel. PBP is also influenced by the capacity of kiln, being shorter if the longer tunnel kilns are applied, /5/.

CONCLUSION

The literature showing techno-economic analysis in the ceramics industry is scarce. Available studies are considered, and the summed conclusion is presented. Within the analysis, it is seen that often traditional brick manufacturers having old types of kilns produce most flue gas that contains chemicals above the set limits. Although a higher firing temperature is required in ceramic tiles production, the flue gas composition reported is cleaner. The situation is vice-versa when CO_2 footprint is considered, being the lowest in dry-route ceramic tiles manufacturing. This kind of ceramic tile production is also a better option when considering energy consumption. Further analysis is needed to include the flue gas results obtained by the same method and expressed in the units comparable to existing legislation.

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