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Recycling insight into the ceramic tile manufacturing industry

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ABSTRACT

The ceramic tile industry is one of the most important industrial sectors in Italy, with almost 90% of the whole production located in the Emilia-Romagna region. In this paper, the waste management and recycling practices in force among Italian ceramic tile manufacturers are reported and discussed on the basis of performance indicators determined thanks to the elaboration of a large amount of industrial data collected in the period 2013–2020. In particular, parameters such as annual water consumption (C_w) and demand (D_w), recycling factor of solid waste (R_{sw}) and water (R_w) and different kinds of waste generated in the process have been monitored for three different production layouts. Such indicators exhibit that recycling is a well-established practice in Italian ceramic tile production and only a minor amount of hazardous waste (exhausted lime) is land-filled.

1. Introduction

The increasing global population together with the over exploitation of non-renewable resources by industrial production are making waste generation a worldwide issue not to be avoided any longer [1,2]. All the industrial sectors shall be pushed to provide a second life chance to waste generated by their production processes, decreasing in this way natural resources and landfilling exploitation [3]. The concepts of circular economy have been proposed to help any economic system to sustain itself, becoming more autonomous and avoiding an overweight on environment and society [4].

During the last two decades, such approach, especially prompted by governmental institutions, has resulted in a vast scientific literature regarding the production and utilization of main exploited materials worldwide, under both economic and environmental point of view [5–8]. The European Union, for example, has conceived the Material System Analysis (MSA) [9]. This is a vast map of the economic flow of 33 different materials (e.g., iron, natural gas, cement, and paper amongst the others) reporting a complete mapping of extraction, import, export, production, and consumption channels, together with information on current supply and future demand. A similar approach is enforced also by numerous Material Flow Analysis (MFA) works regarding mainly plastics, rare earths, and common metals [10–12]. However, recycling aspects are often overlooked in MFA studies and recycling of materials is generally addressed more qualitatively rather than quantitatively.

The construction sector can be very interesting for a quantitative assessment of recycling strategies. In fact, due to the large number of raw materials involved in the production of concrete, steel, wood and ceramics, this sector has a great potential to benefit with the application of circular economy principles [13–15]. Ceramic tiles are building materials used in wall and floor coverings as well as ventilated facades and eventually in furniture (kitchen topcoat, tables, etc.). Almost the whole Italian tile production is located in Emilia Romagna region, where the 95% of the Italian manufacturing plants are present with a production of 435 millions of m^2 in 2021 [16]. Such high concentration of ceramic tiles industries has promoted technological advancements to reach not only innovative and high performing products, but also low environmental impacts [17–20]. Indeed, atmospheric pollution of porcelain stoneware tile production in Italy has recently been investigated [17] showing the all the gaseous emissions are well below the limits prescribed at European, national and region level.

A further concern is the issue of waste generated during the process, its quantification and the recycling strategies set up so far. The main raw materials involved in the production of porcelain stoneware tiles (i.e., clays, feldspars, and quartz) are widely abundant inside the Earth's crust [21–24]. However, the increasing aesthetic and technological features required by the market has pushed over the years towards the use of natural raw materials characterized by strict mineralogical compositions. Consequently, locally available raw materials have been replaced by purer or better performing resources coming from outside Italy. This

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is the case of albitite overmining in Turkey, a mineral employed as fluxing agent due to its large amount of sodium oxide [21,25]. Further, clays coming from Eastern-Europe [22,26,27] have been preferred to local clays thanks to the absence of iron impurities (Fe_2O_3). Such a strong dependence on imported raw materials has resulted as an increase in materials supply costs, especially when Ukraine stopped his exportations due to the recent political events [25].

Based on this background and the increasing relevance of sustainability policies, since 2013 the Italian ceramic tile industry has been engaged in a data collection regarding resources utilization and recycling of waste generated by ceramic tile production [19]. These data have been used in the present paper to determine and calculate key performances indicators such as annual water consumption, annual water demand, recycling factor for solid waste, recycling factor for water, internal and external recycling, and landfilling percentages, with the aim to discuss their trend versus time. The rationale of the work is to provide a portrait of the waste management in the Italian ceramic tile manufacturing sector. Although scientific literature so far largely covers topics such as ceramic tile recycling strategies [28–31], use of recycled raw materials [14], life cycle assessment of waste recycling [32–34], reuse of water and heat from productive plants [18,35,36], a comprehensive study with key indicators based on industrial data is currently lacking. This study results of great significance in describing the development of waste and resources management operated by the Italian ceramic tile sector. Moreover, as Italy is considered a leading country for ceramic tile production and technology, Italian tile waste management can be used as a model for other European and international countries involved in ceramic tile production.

2. Materials and methods

2.1. Analysis of the porcelain stoneware tile production process in light of its relevant waste

Porcelain stoneware tiles are made of a mixture of clays, feldspathic minerals and quartz shaped by pressing and fired at temperatures usually ranging from 1150 to 1250 °C [37]. The main steps of the typical manufacturing process of porcelain stoneware tiles are reported in Fig. 1 together with the main waste generated during the process.

During the milling stage, raw materials are mixed with water in rotating mills forming a slurry characterized by a density around 1700 kg/m^3. This slurry is then spray-dried by a heated cyclonic air stream (air temperature range: 400–600 °C) thus generating round-shaped and hollow granules (spray dried powder) with a residual humidity of 5–7 wt %, suitable for the following pressing step.

After pressing, the residual water is removed, by means of hot air drying with a temperature up to 250 °C. Pressing and drying steps generate waste because of the low mechanical resistance of unfired tiles (also named as green tiles) which can be easily broken during the process. This waste is defined as unfired scrap (S_{uf}). Before firing, decoration is carried out. This step involves the application of engobes and glazes on green tiles surfaces. Thanks to the increasing adoption of ink-jet technology, the deposition of the decoration is usually at micrometric level [37,38]. Firing in the temperature range of 1150–1250 °C allows sintering of green tiles, leading to microstructures based on crystalline phases (e.g., mullite, quartz, etc.) embedded in a new-formed amorphous phase [39]. Wrong tuning of firing conditions and unforeseen events during this step may lead to generation of some fired tiles waste, which is defined as fired scrap (S_f). During firing, gas emissions, mainly composed by O_2, H_2O, CO, CO_2, SO_x and NO_x, are released into the atmosphere and a specific abatement treatment of acidic emissions, using hydrated lime, is used [18]. Exhausted lime (EL) is thus generated as waste. This is a mixture of calcium oxide (CaO), together with other calcium-related salts, mainly calcium fluoride (CaF_2) [40]. Fired tiles may require some further treatments such as (I) the cutting operation to obtain tiles with different formats, (II) the squaring/rectification operation, involving tile edges abrasion to obtain gauged tiles; (III) the polishing operation, involving tile surface abrasion to obtain smooth surfaces characterized by an enhanced brightness (e.g., *lappato* and full *lappato* tiles). All these operations, when present, generate fired waste in sludge form. Finally, the concluding actions of the manufacturing process include packaging and logistic procedures.

Water is involved in several steps of the production process of porcelain stoneware tiles as well as in the generation of sludges occurring at milling, spray-drying, decoration, and post-firing steps. These sludges are usually treated inside ceramic tile production plants: a separation process is carried out generating water and a sludge suitable to be recycled directly in the milling step. Such latter material, defined as ceramic sludge (CS), is mainly composed of unfired or fired ceramic particles, depending on the source of wastewater, deriving from production steps ahead firing or after it. Usually, ceramic sludge is recycled in small amounts inside mills for the preparation of a new ceramic mix [18]. Unfired scraps coming from green and dried ceramic bodies are usually easily recycled as they are introduced in the rotating mills without any further treatment. Fired scraps, conversely, require mechanical milling for being recycled. However, their strong refractory behavior involves that their use in the raw materials mix is usually limited to less than 20 wt%. Finally, the hydrated lime adopted in flue gas cleaning produces waste (EL, exhausted lime) that is classified as dangerous waste, thus disposed of in proper landfills.

2.2. Database and key performance indicators

All the data elaborated in this work are representative of Italian ceramic tile manufacturers. The data were collected anonymously by analyzing the compliance to the Integrated Environmental Authorization (IEA) document yearly filled by ceramic manufacturers in agreement with the Integrated Pollution and Prevention Control (IPPC) directive [41,42]. Data collection and elaborations have been carried out in the framework of a collaboration between Emilia-Romagna region

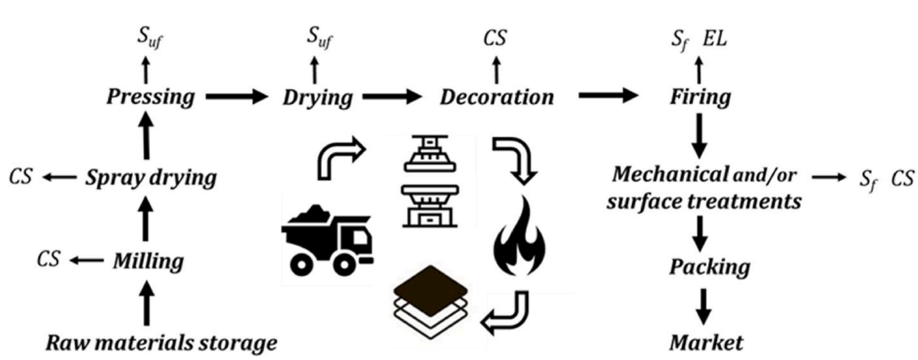

Fig. 1. Main steps of porcelain stoneware tile production process with related waste production. CS: ceramic sludge; S_{uf}: unfired scrap; S_f: fired scrap; EL: exhausted lime.

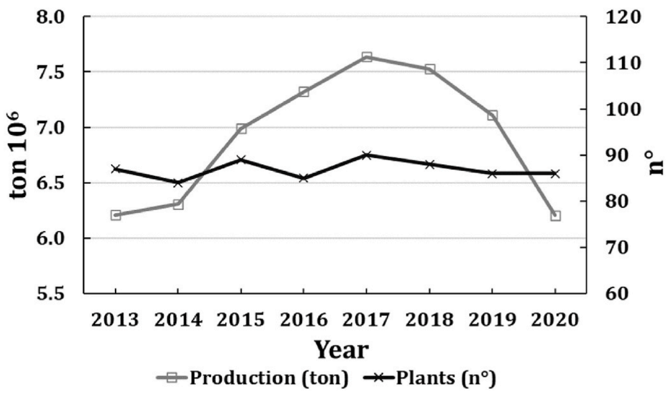

Fig. 2. Annual Italian production of ceramic tiles (ton) and number of factories involved in this investigation as function of the year (time period: 2013–2020).

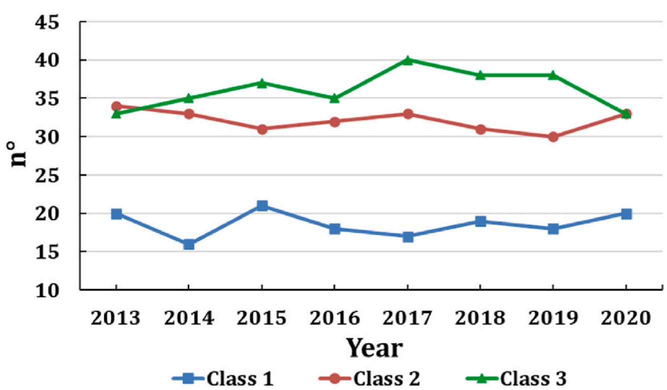

Fig. 3. Number of factories belonging to the three different classes in the period 2013–2020.

(Italy) and the Italian ceramic industry association (Confindustria Ceramica). The annual Italian production of ceramic tiles in the period 2013–2020, as well as the number of factories considered in this investigation is reported in Fig. 2.

The number of factories examined in the period 2013–2020 is comprised in a strict range between 84 and 90, thus it can be considered constant over the years. Conversely, the annual production of ceramic tiles shows an increasing trend up to 2017, followed by a slight decrease in production from 2017 to 2019 and then by a quick drop in 2020 due to the lockdown caused by Covid-19 pandemic.

In order to cluster data regarding companies with similar production layouts, dimensions, and level of technology, ceramic tile factories have been divided into three different classes:

– class 1: factories with complete production cycle (as reported in Fig. 1);
– class 2: factories with complete production cycle, but also involved in the production of spray-dried powder for other parties;
– class 3: factories with a production cycle that does not involve raw material preparation and spray-drying procedure.

Factories belonging to class 3, with a partial production cycle, are usually smaller than companies belonging to class 1 and 2. Fig. 3 reports the number of factories belonging to each class in the period from 2013 to 2020. Class 1 is the less represented one, with industrial plants ranging between 16 and 21. These are medium-sized companies that never had the opportunity to expand by opening additional plants. Firms belonging to class 2 and 3 are by far more represented, being the latter more diffuse than the former ones.

The collected data have also been used to determine different key performance indicators specifically addressed to highlight the recycling factor for water and solid waste. Solid waste includes unfired (S_{uf}) and fired (S_f) waste, exhausted lime (EL) and ceramic sludges (CS) coming from water depuration, as depicted in Fig. 1. The considered indicators are calculated following the equations reported in Table 1.

where:

$R_{sw,i}$: amount of recycled solid waste [%] for the i-factory;
$R_{w,i}$: amount of recycled water [%] for the i-factory;
$W_{out,i}$: amount of waste produced [ton] by the i-factory;
$C_{w,i}$: annual water consumption [m^3] for the i-factory;
$D_{w,i}$: annual water demand [m^3] for the i-factory;
n: total number of factories for each year.

The results for the solid waste management were illustrated by reporting for each waste source (S_{uf}, S_f, EL, CS) the weighted average of the amount of waste produced per ton of produced tiles (kg/ton), according to the total amount of tiles (ton) produced by each factory. As an example:

– S_{uf}: production of unfired scrap [kg/ton], obtained as weighted average of values reported by factories, according to the total amount of tiles produced by each factory (TP_i). These values were obtained using the following equation:

$$S_{uf} = \frac{\sum_{i=1}^{i=n} S_{uf,i} TP_i}{\sum_{i=1}^{i=n} TP_i}$$

where:

$S_{uf,i}$: amount of unfired scrap [kg/ton] produced by the *i*-factory;
TP_i: tile production [ton] for the *i*-factory.

Finally, the different end-of-life pathways of each source of waste (S_{uf}, S_f, EL, CS) were expressed by reporting the percentage of internal or external reutilization or landfilling of waste calculated on the arithmetic

Table 1
Definitions and equations of the key performance indicators considered in this study.

Key performance indicators	Definition	Equation
C_w [10^3 m^3/year]	Annual water consumption obtained as arithmetic mean of values reported by factories	$C_w = \frac{\sum_{i=1}^{i=n} C_{w,i}}{n}$
D_w [10^3 m^3/year]	Annual water demand obtained as arithmetic mean of values reported by factories	$D_w = \frac{\sum_{i=1}^{i=n} D_{w,i}}{n}$
R_w [%]	Water recycling factor obtained as weighted average of values reported by factories, according to annual water consumption of each factory ($C_{w,i}$)	$R_w = \frac{\sum_{i=1}^{i=n} R_{w,i} C_{w,i}}{\sum_{i=1}^{i=n} C_{w,i}}$
R_{sw} [%]	Solid waste recycling factor obtained as weighted average of values reported by factories, according to the total amount of waste produced by each factory ($W_{out,i}$)	$R_{sw} = \frac{\sum_{i=1}^{i=n} R_{sw,i} W_{out,i}}{\sum_{i=1}^{i=n} W_{out,i}}$

mean of the total amount of waste recycled internally or externally or landfilled by factories in the period 2013–2020.

As an example:

$$- \ Internal\,Use = \frac{\sum_{2013}^{2020} IU_{Suf}}{8}; External\,Use = \frac{\sum_{2013}^{2020} EU_{Suf}}{8}; Landfilling = \frac{\sum_{2013}^{2020} L_{Suf}}{8}.$$

where:

IU_{Suf}: amount of unfired scrap [ton/year] internally recycled by the whole sample of factories for each year calculated as follows:

$$IU_{Suf} = \sum_{i=1}^{i=n} IU_{Suf,i}$$

EU_{Suf}: amount of unfired scrap [ton/year] externally recycled by the whole sample of factories for each year calculated as follows:

$$EU_{Suf} = \sum_{i=1}^{i=n} EU_{Suf,i}$$

L_{Suf}: amount of unfired scrap [ton/year] landfilled by the whole sample of factories for each year calculated as follows:

$$L_{Suf} = \sum_{i=1}^{i=n} L_{Suf,i}$$

where:

$IU_{Suf,i}$: amount of unfired scrap [ton/year] recycled internally by the *i*-factory.

$EU_{Suf,i}$: amount of unfired scrap [ton/year] recycled externally by the *i*-factory.

$L_{Suf,i}$: amount of unfired scrap [ton/year] landfilled by the *i*-factory.

n: total number of factories for each year.

3. Results and discussion

3.1. Water management

The production of ceramic tiles involves the use of water in different parts of the process. Water is used to prepare the slurry needed for the spray-drying process and in glazes preparation to provide suspensions characterized by a proper rheology, tuned according to surface decoration machineries such as engobes and glaze applicators. Water is also extensively used to wash out ceramic powder present in some specific areas such as to spray-drier locations. In addition, water is also used as a working fluid in machineries for mechanical squaring and smoothing of fired tiles. Fig. 4 reports the annual demand (D_w) and consume (C_w) of water in the period 2013–2020 for the 3 different classes. The demand of water is the quantity of water involved in the whole production process of ceramic tiles. The consume of water, instead, represents the amount taken from water reservoirs.

For each class, the difference between water demand and consume values represents the quantity of water internally recycled. The consume, on the other hand, is related to the amount of water used to restore the amount lost in the environment through evaporation in the spray-drying and drying steps and during tile decoration. It can be noted that the three different classes, according to different production layouts, require different amounts of water. Generally speaking, factories with complete production cycle and involved in the production of spray-dried powder for other parties (class 2) exhibit the highest water demand, the highest consume and the highest recycling. On the other hand, factories with a production cycle that does not involve raw materials preparation and spray-drying procedure are characterized by the lowest values. The overall trend for the water demand data seems to agree with the production data reported in Fig. 2, which exhibit a progressive increase until 2017, followed by a marked decline after the same year. However, some minor inconsistencies can be noticed. In 2018 and 2019, in fact, water demand and consume slightly increased despite the decrease in tiles production. This behavior is probably because water demand is also strictly related to finishing operations carried out after firing, which are in turn strictly related to market requirements. Thus, even if the production decreases, the highest request of rectified ceramic tiles and *lappato* ceramic tiles by the market explains the high demand of water. Luckily, such raise is also followed by the increase in water recycling, thus highlighting that the attention for the environment is a well assessed practice. Data of 2020 are also affected by Covid-19 pandemic which forced factories to lockdown for about one month.

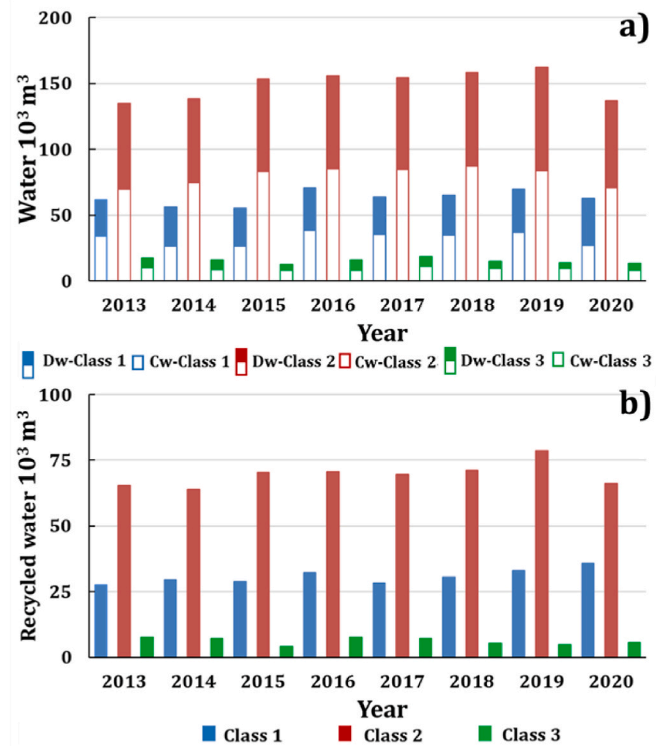

Fig. 4. (a) water demand (D_w) and consume (C_w); (b) amount of water recycled in the three production classes during 2013–2020 period.

3.2. Solid waste management

As solid waste, unfired (S_{uf}) and fired (S_f) ceramic waste, exhausted lime (EL) and ceramic sludges (CS) coming from water depuration and mechanical surface treatment operations are considered for all the three different production classes and their trends in the period 2013–2020 are reported in Fig. 5.

While unfired ceramic powders are fully recycled in ceramic body preparation stage, fired ones can be recycled only in limited amounts. In fact, it is well known that the sintering of ceramic materials during firing leads to alteration of raw materials mineral phases, breaking down the aluminum silicate reticule of clays and creating new phases as, for example, mullite, characterized by high hardness and refractory behavior [43]. Solid residues of CS may contain unfired and fired ceramic waste and their recycle is allowed only if the amount of fired waste is previously determined. Exhausted lime is by far less abundant than S_{uf}, S_f and CS, differing by two orders of magnitude, as shown in Fig. 5. In fact, lime is not a raw material intended for tiles production, but it is produced in fumes purification from kilns. These fumes contain acidic compounds, (e.g., hydrochloric (HCl) and hydrofluoric acids (HF)) due to impurities naturally present in clays and shall be purified before their emission into the atmosphere. The purification of acidic emissions, mainly performed by using lime, is mandatory in Italy [44]. Such purification treatment generates exhausted lime that is classified as hazardous waste and needs to be disposed of in landfills. The possibility

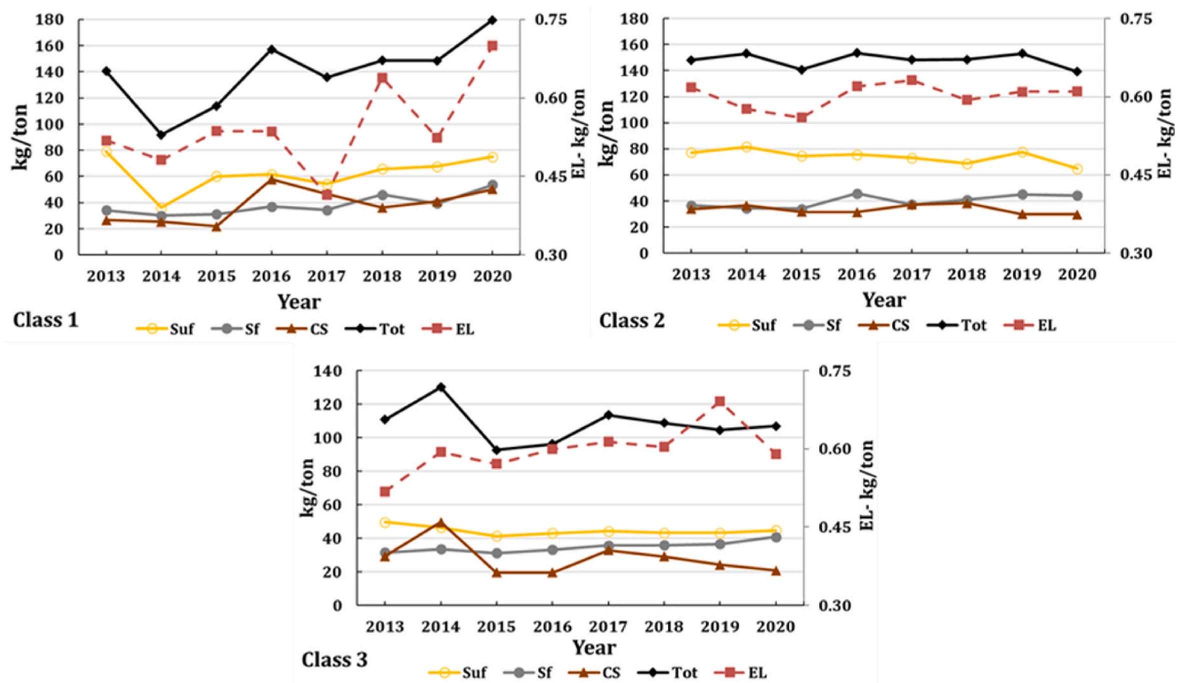

Fig. 5. Solid waste production in 2013–2020 for class 1, 2, and 3 (S_{uf}: unfired scrap; S_f: fired scrap; CS: ceramic sludges; EL: exhausted lime; Tot: total amount of waste produced (S_{uf} + S_f + CS + EL).

to recycle exhausted lime is currently investigated only at scientific level. In particular, some examples from the literature report the possibility of recycling lime waste inside glass-ceramics making use of waste glass, which is able to lower the sintering temperature, and kaolin, stabilizing the fluorine ions inside the newly formed reticule [45,46].

With a mean value of 44.4 kg/ton over the whole examined period, class 3 exhibits the slightest production of S_{uf}, followed by class 1 and class 2, with 62.4 and 74.1 kg/ton, respectively. This trend is totally consistent with the differences in manufacturing processes of the three classes. Indeed, class 2 factories handle higher loads of raw materials compared to factories belonging to class 1, due to a larger production of spray-dried powder also for the third parties and consequently generating a higher amount of Suf. On the other hand, factories belonging to class 3, which do not include milling and spray-drying processes, are characterized by the lowest production of Suf. Concerning Sf, all the three classes display similar average values equal to 38.2, 39.8, 34.8 kg/ton for class 1, 2 and 3, respectively (Fig. 5), being the firing process and final operations substantially equal for all the three classes. Same behavior occurs for EL, where an average value ranging between 0.54 and 0.60 kg/ton has been determined. Finally, CS exhibit a trend which is influenced by the production cycle, as Suf. Indeed, CS is mainly generated by factories belonging to class 1, with an average value of 38.2 kg/ton, followed by class 2 and class 3, with average values of 33.5 and 28.1 kg/ton, respectively. The lowest CS production for class 3 is due to the absence of milling and spray-drying steps, which give an important contribution in generating this type of waste.

3.3. *Recycling paths for solid waste and wastewater*

Fig. 6 reports the recycling factor for solid waste (R_{sw}) and water (R_w) determined for the Italian ceramic tile manufacturers involved in this study. These two indicators represent the total amount of water and solid waste recycled inside (close-loop recycling) and outside (open-loop recycling) ceramic factories, thus giving a clear indication about the recycling capacity of the sector. No preference for neither close- or open-loop recycling is suggested here. In fact, such distinction is often abused by attributing benefits and drawbacks to a particular recycling perspective only according to the general premises and assumptions from circular economy, whereas any specific case should be treated separately, avoiding any preconceived preference for a close- or an open-loop recycling [47].

Generally speaking, all the three classes exhibit values of R_{sw} and R_w higher than 100% indicating the capability to recycle inside production cycles higher amount of waste than those produced.

Class 2 displays the highest values for the two indicators. Indeed, the production of spray-dried powder for the market gives the opportunity to use high amount of recycled-based raw materials (including water) also coming from external producers and thus explaining the R_{sw} and R_w

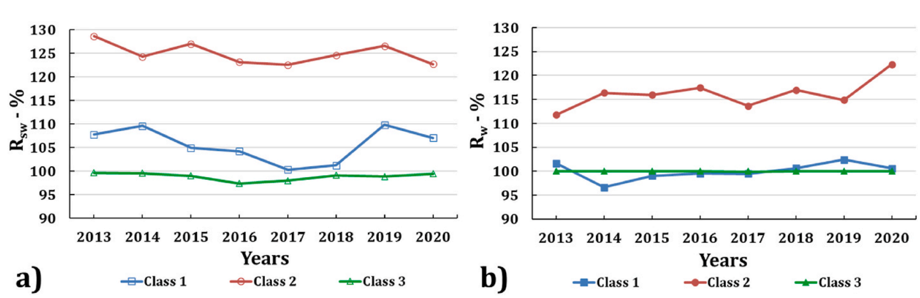

Fig. 6. Recycling factor for (a) solid waste R_{sw} and (b) water R_w for the three classes in the period 2013–2020.

Table 2
Recycling paths of annual total amount of waste production [%] from ceramic tile factories. S_{uf}: unfired scrap; S_f: fired scrap; CS: ceramic sludges; EL: exhausted lime. Values are expressed as average values for the period 2013–2020.

	Internal Origin – Internal Use [wt%]				Internal Origin – External Use [wt%]				Landfilling [wt%]			
	S_{uf}	S_f	EL	CS	S_{uf}	S_f	EL	CS	S_{uf}	S_f	EL	CS
Class 1	68.5	20.8	8.8	59.9	31.5	77.8	2.7	39.0	0.0	1.4	88.6	1.1
Class 2	89.2	16.9	2.6	54.3	10.8	82.5	1.8	44.0	0.0	0.6	95.6	1.7
Class 3	2.9	0.1	0.0	1.2	97.1	98.4	17.2	97–0	0.0	1.5	82.8	1.8

values higher than 100%. Class 3 reaches 100% for R_w and R_{sw}, but the possibility to overcome this value is limited by the production layout, which allow a lower versatility compared to the other two classes. Indeed, most of waste generated in Class 3 factories are externally recycled. For class 1 an important increase in R_{sw} is evident in the recent years, reaching the maximum value of 109.8% in 2019. Such increase is consistent with the growing tendency to use recycled-raw materials for further strengthen the sustainability of the sector and following the criteria of ISO 17889-1 [48]. Water recycling factor for class 1 is always around 100% in the investigated period.

However, the water and solid waste recycling trends reported in Fig. 6 do not distinguish between internal and external recycling. Actually, such distinction is quite essential. In fact, even if external recycling can involve important savings of natural raw materials in other sectors and a second life chance for waste is still awarded, this type of recycling can often lead to higher costs in terms of environmental impacts (e.g., further treatments, transport to other companies, low yields, etc.) than close-loop recycling.

In Table 2 the total amount of solid waste coming from ceramic factories, expressed as average percentages by weight of each specific waste in the period 2013–2020 is reported as function of the different end-of-life pathways, identified as landfilling or internal and external recycling.

Factories can efficiently recycle S_{uf}, as proven by the data reported in the Table 2. Factories of class 1 recycle internally almost 70 wt% of waste, while those of class 2 almost the 90 wt%. For class 3, recycling is almost entirely external as the operations related to ceramic body preparation are missing. The small amount of solid waste recycling for class 3 is probably due to glaze and frits preparation. EL is almost totally landfilled since it is classified as hazardous waste, as previously stated. The few tons declared for recycling are probably intended as reuse in hot fumes depuration. Sf and CS (containing also fired ceramic powders) are only partially internally recycled and mainly externally recycled in the building sector (filler for concrete, pozzolanic addition, etc.). A more detailed presentation of the data differentiated by internal/external recycling and landfilling is reported on yearly basis as function of the different classes in Fig. 7. All the solid waste produced within ceramic tile factories has been considered for this evaluation.

Fig. 7. Weight percentages of the solid waste for the three production classes as function of final destination (internal and external recycling and landfilling). Reference period: 2013–2020 (Int Orig – Int Use: internal origin – internal use; Int Orig – Ext Use: internal origin – external use).

The first thing to note is how fundamental is the presence of the operations related to ceramic body preparation for internal recycling of resources. In fact, factories belonging to class 3 rely almost entirely on external recycling paths, committing waste to other ceramic factories or transferring them to be recycled in a different industrial sector. However, class 3 still shows very low percentages of landfilling. As regards factories belonging to class 1 and 2, percentages of internal recycling are quite similar over the years, with a slightly higher tendency for class 2. However, the amount of waste addressed to landfilling is quite low over the whole period considered in this assessment. Indeed, these data well demonstrate all the efforts performed by the Italian ceramic tile sector over the years to aspire to an ever-increasing sustainability of industrial production processes.

4. Conclusions

This paper provides a portrait of waste management of the Italian ceramic tile sector. The collected data, covering the period between 2013 and 2020, allow to draw specific trends in waste production and its management according to the three classes considered for describing different production cycle layouts. The following conclusion can be drawn:

- class 1 (complete production cycle) and 2 (complete production cycle + production of spray-dried powder for other parties) are the production layouts involving both the highest consume of water and waste production. This is mainly related to spray-dried powder production, the most impacting step of the whole manufacturing cycle in term of resource consumption. However, both class 1 and 2 also allow the highest recycling factor for solid waste and water and the highest percentage of internal recycling of all the different investigated solid waste types.
- Class 3 (production cycle without raw material preparation and spray-drying) is the production layout characterized by the highest external recycling. To be competitive in terms of environmental impact, such factories shall be located close to class 2 factories to generate an efficient exchange of spray-dryer powder and recyclable wastes.
- Exhausted lime is currently the only waste totally landfilled among the ones generated during the ceramic production process. Being a hazardous waste, its recycling is more difficult even if some studies are currently running in this direction.

The continuous monitoring of the Italian ceramic tile manufacturers represents a unique approach in the European ceramic and building sector. The results of this monitoring action are strategic to develop future actions addressed toward sustainability and recycling, avoiding inefficiencies due to blind environmental policies. Indeed, Italian ceramic tile industry has reached a high level of maturity in waste management and recycling, thus it can be considered a model for other tiles manufacturing countries.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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