U.Porto Journal of Engineering, 10:2 (2024) 81-99
ISSN 2183-6493
DOI: 10.24840/2183-6493_0010-002_002833

Received: 23 October, 2024
Accepted: 28 October, 2024
Published: 14 November, 2024

Valorization of Wastes from Wine Industry in the Production of Lightweight Clay Bricks

André Cruz
Departamento de Engenharia Química, Faculdade de Engenharia, Universidade do Porto, Rua Dr. Roberto Frias, 4200-465 PORTO, Portugal (up202008382@edu.fe.up.pt) ORCID 0009-0006-2840-2062

José Matos
Departamento de Engenharia Química, Faculdade de Engenharia, Universidade do Porto, Rua Dr. Roberto Frias, 4200-465 PORTO, Portugal (up202007166@edu.fe.up.pt) ORCID 0009-0005-0321-4295

Luís Marques
Departamento de Engenharia Química, Faculdade de Engenharia, Universidade do Porto, Rua Dr. Roberto Frias, 4200-465 PORTO, Portugal (up202005767@edu.fe.up.pt) ORCID 0000-0003-1001-1144

Rui Pereira
Departamento de Engenharia Química, Faculdade de Engenharia, Universidade do Porto, Rua Dr. Roberto Frias, 4200-465 PORTO, Portugal (up202008468@edu.fe.up.pt) ORCID 0009-0006-6946-311X

Author Keywords
Wine Waste, Circular Economy, Lightweight Clay Brick

Type: Research Article

Open Access
Peer Reviewed

Abstract
Lightweight clay brick is an idea that arose from the need to reduce waste by giving grape pomace, a waste product from the Portuguese wine sector, a new use, promoting a circular economy. Compared to ordinary building clay bricks, lightweight clay bricks have higher porosity, and consequently lower density and lower thermal conductivity, while maintaining good mechanical strength, allowing them to be used to build the inner walls in buildings. The production process for this brick, from obtaining the raw materials to manufacturing the brick itself, was studied using process simulation and an economic analysis. The latter led to the conclusion that the project is economically viable and profitable, with each tonne of bricks selling for €57.96.

1. Introduction

Nowadays, many companies and industries are increasingly investing in sustainable products and favoring a circular economy in order to promote environmental protection. At the same time, consumers are progressively preferring these products. Therefore, there is a growing need to develop sustainable products.

The Portuguese wine sector is a major contributor to the country's economic development. The large area of vineyards combined with a very high annual wine production makes Portugal the tenth largest wine producer in the world. As a result, there is also a high production of waste, such as vine shoots, stalks, grape pomace, and wine lees. These are usually disposed of in landfill sites, as is the case of grape pomace and wine lees. They can also be incinerated, especially the vine shoots, or deposited in the soil, such as the stalks which act as fertilizer (Contreras et al. 2022).

None of these processes is highly advantageous and all have significant environmental impacts. However, this waste is rich in bioactive compounds that can be utilized. With this in mind, this work was developed with the aim of using this waste as a raw material to produce a new value-added product that will satisfy market needs while reducing waste, thus favoring a circular economy.

Some examples of these new products are lightweight clay bricks, with grape pomace or wine lees incorporated in the clay, or biosurfactants, produced using vine shoots as a raw material.

2. State of the Art

Wine is a product with an extremely high demand worldwide and is even part of the cultural heritage of some countries, especially in the Mediterranean area. In 2022, 258 million hectoliters (MhL) of wine were produced worldwide. From the 85 producing countries that contributed to this result, 84% of the total production belongs to 10 countries. Among them are Italy, France, and Spain, solidifying their positions as the primary contributors to the world's wine production. Portugal, too, stands within this group of the main wine-producing countries (Roca 2023) as illustrated in Figure 1.

In Portugal, the wine industry is internationally recognized for its quality, and it is an important source of income for the country, as evidenced by the €940 million in exports in 2022. Notably out of the 6.8 MhL of wine produced in Portugal, a substantial 3.3 MhL was exported, which means that approximately 1 in every 2 bottles of wine produced are exported (ViniPortugal 2022; Roca 2023). Douro is the Portuguese region with the largest wine production with 1.46 MhL of wine produced in 2022, which corresponds to 21% of total national production (IVV 2023). Figure 2 shows the distribution of total wine production in Portugal by region in 2022.

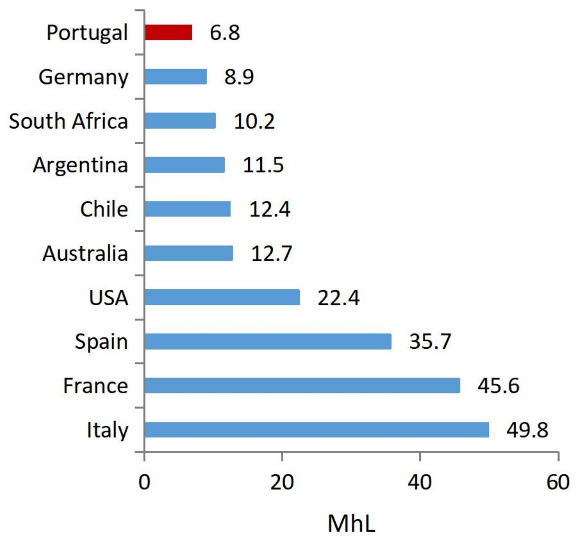


Figure 1: Total volume of the wine produced in 2022 by country (Roca 2023)

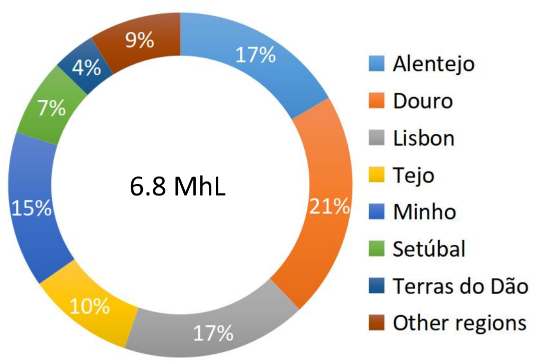


Figure 2: Percentage distribution of the total wine production in Portugal in 2022 (IVV 2023)

As wine is the end product of a series of processes that involve the production of waste, inevitably a large amount of waste is generated due to the sheer magnitude of production. The main wastes products that are formed during these processes are vine shoots that result from pruning the vines, stalks that result from pre-fermentation processes, pomace that consists of a solid matter obtained after crushing the grapes to extract the juice and lees that accumulate in the barrels after fermentation (Contreras et al. 2022).

The chemical composition of this waste is highly dependent on environmental factors such as the climate or the soil, and factors intrinsic to the winemaking activity itself, such as the grape variety, the fertilizers used or the grape processing techniques (Contreras et al. 2022; Silva et al. 2021).

Vine shoots and stalks have a similar composition and are essentially made up of cellulose, proteins, and lignin. In terms of practical applications, these residues can be used as fertilizers, as a carbon source for biological activity or for energy production through combustion (Contreras et al. 2022).

The lees contain traces of fermentation activity, such as yeast cells and ethanol, as well as cellulose, proteins, and tartaric acid. The recovery of tartaric acid is the main alternative to add some value to this waste (Contreras et al. 2022; Niculescu and Ionete 2023).

Pomace is the by-product with the greatest potential of valorization, both due to its composition and the quantity in which it is generated. Its rich content of polyphenols and other bioactive compounds makes it an interesting application in the pharmaceutical and cosmetics industries, as well as for use as food additives. Furthermore, pomace is also made up of cellulose and lignin due to the presence of pits, fibers and stalks left over from the grape-crushing process which enhance the pomace’s utility and versatility (Contreras et al. 2022; Silva et al. 2021; Niculescu and Ionete 2023).

Contreras et al. (2022) estimate that for every tonne of grapes obtained and destined for wine production, around 30-40 kg of stalks, 130-200 kg of pomace and 30-40 kg of lees are generated and, for each hectare of vineyard, approximately 1-2 t of vine shoots can be generated as a result of pruning the vines. In 2022, 888,000 t of grapes were harvested for wine production in Portugal (Eurostat 2023), which means that there is some potential for exploring valorization methods for these residues.

Consequently, seeking alternatives for the valorization of winemaking waste not only addresses environmental concerns but also presents an opportunity to create added value.

3. Chemical Product Design (CPD)

According to Moggridge and Cussler (2003), Chemical Product Design is divided into four stages: 1) Needs; 2) Ideas; 3) Selection; 4) Manufacture. In the first stage it is necessary to find out who the consumers are, what are the market needs, and convert them into specifications. In the 'Ideas' stage, several product ideas are designed to satisfy the market needs identified earlier. Criteria are then selected to evaluate each of the ideas so that only one is selected, thus concluding stage three. Finally, in the last stage, the production process for the idea selected in the previous stage is developed. This was the procedure adopted for the creation of a new product.

3.1. Needs and Ideas

By-products from the wine sector can satisfy some of the market's needs, such as the demand for sustainable products with compounds of natural origin or renewable carbon sources. In addition, the search for enriched foods that promote the consumer's physical well-being, using the polyphenols present in selected raw materials, has been increasing. All these market needs make it possible to fulfill the objective of this work: the valorization of waste resulting from wine production.

To meet these needs, more than 20 ideas were considered. Some of these were immediately excluded because they were not easily feasible, as they had limitations in their applicability, such as natural dyes because they do not easily bind to the fabrics (Phan et al. 2021), or due to extremely strict legislation, as is the case of pharmaceutical products. After eliminating replicated ideas, the 10 most promising ideas remained: transdermal patches, production of bioethanol or biosurfactants, weight loss drinks, furan resins, pills to treat hangovers, grape seed flour, natural additives and preservatives, pesticides, and lightweight clay bricks.

Transdermal patches would be produced using lactic acid obtained from the hydrolysis and fermentation of vine shoots or grape pomace. These transdermal patches would be used for controlled release of drugs over time (Sousa et al. 2019). Biosurfactants would also be obtained through the processes of hydrolysis and fermentation of vine shoots, and with these, shampoos or detergents could be produced (Contreras et al. 2022). Bioethanol would result from the fermentation of the organic matter that constitutes the waste, and could then be used to produce disinfectants, perfumes or after-shaves (Rodrigues, Gando-Ferreira, and Quina 2022). Gallic acid, extracted from grape pomace or vine shoots, using ethanol as a solvent, can be used as a food preservative (Kalli et al. 2018) or in the production of drinks to help with weight loss (Dludla et al. 2018). In addition, other polyphenols can be extracted from grape pomace to be used as natural additives and preservatives (Ferrer-Gallego and Silva 2022), thanks to their anti-inflammatory and antioxidant properties. The production of succinic acid from waste as a raw material allows it to be used in pills to treat hangovers (The Times 2004). The idea of furan resins is based on the fact that vine shoots contain furfural which, once extracted, can be converted into furfuryl alcohol, essential for the production of these resins (Rivas et al. 2021). The flour would be produced from grape seeds present in the grape pomace (Oprea et al. 2022). These seeds contain valuable compounds such as flavonoids and resveratrol, known for their antioxidant, anti-inflammatory, antiviral and antibacterial properties. Grape pomace or wine lees can also be mixed with clay to create bricks with greater porosity, maintaining good physical and mechanical properties, while reducing thermal conductivity and mass (Taurino et al. 2019). Finally, vinasse can be used as an organic pesticide (Santos et al. 2008).

3.2. Selection

In order to select three of the ten ideas presented, the selection matrix shown in Table 1 was used. For this purpose, six criteria were selected, each assigned a specific weight. For each idea it was given a score from 1 to 10 for every criterion. The three ideas with the highest overall scores were then selected.

The six criteria chosen were innovation, ease of implementation of the production process, market needs, maturity of the production process, existing competition in the market and production cost.

The criterion that was given the highest weight (30%) was market needs. This decision is justified by the fact that the aim of this work is to obtain a product capable of satisfying market needs and, as such, is essential in the market. The greater the ability of the product in addressing the market needs, the higher the score given to the idea in this criterion.

Ease of implementation of the production process and cost of production have an equal weight (20%). It is important to maximize the value of wine production waste through a product that is easy to develop and whose production process is not too expensive. Some of the ideas require production processes with several, often complex, steps, resulting in a lower score for the criterion of ease of implementation of the production process. Also, a higher cost of a product's production process is reflected in a lower score given in the cost of production category.

The other criteria all have the same weight, equal to 10%. As far as the innovation criterion is concerned, the more innovative an idea and the product that results from it, the higher the score. Some of the processes involved in making the above-mentioned ideas possible have been around for a long time and there is a lot of knowledge about them, which results in a higher score being awarded to these ideas for the maturity criterion. Finally, the last criterion is market competition. This is assessed based on the existence on the market of products with the same objective as the one being developed. A product's score in this category diminishes as the level of competition within its market increases.

	Criteria	**Innovation**	**Implementation**	**Need**	**Maturity**	**Competition**	**Cost**	
	Weight %	10	20	30	10	10	20	**Final Score**
Ideas	Transdermal patches	8	5	8	6	6	6	6.6
	Bioethanol	6	6	7	6	5	4	5.8
	Biosurfactants	8	6	8	5	7	5	6.6
	Weight loss drink (Gallic acid)	9	5	8	2	2	6	5.9
	Furan resins	3	8	1	10	2	8	5.0
	Pills to treat hangovers (Succinic acid)	6	4	9	6	1	2	5.2
	Grape seed flour	6	7	5	5	8	7	6.2
	Natural additives and preservatives	2	6	7	7	4	7	6.0
	Lightweight clay bricks	8	9	6	7	5	7	7.0
	Pesticides	5	8	7	5	5	7	6.6

Table 1: Selection Matrix to evaluate ideas

A look at the previous table shows that the ideas with the highest final scores are transdermal patches, biosurfactants and lightweight clay bricks.

Transdermal patches were considered innovative since there is not a wide variety of them in the market. The same applies to biosurfactants and lightweight clay bricks. As for the ease of implementation of the production process, bricks are the easiest to produce, as they do not require a large number of steps of extraction or purification processes. The same does not apply to the other two ideas. For the same reason, the cost of production is lower for bricks, which corresponds to a higher score. The brick production process has been carried out for several years and is therefore well developed, unlike the transdermal adhesives and biosurfactants production processes.

Due to the wide variety of bricks on the market, a lower score in the need category was awarded. Transdermal patches and biosurfactants, obtained from natural products, have a large demand, and therefore received a higher score.

Finally, as far as competition is concerned, there are several products on the market with the same purpose of the highlighted products, which is why the scores given were not high.

For each of these ideas, a set of useful, essential, and desirable needs was defined, which are shown in Table 2.

Ideas	Essential needs	Desirable needs	Useful needs
Transdermal Patches	Good adhesion to skin Effective medicine liberation	Comfortable Water-resistant	Easy application
Biosurfactants	Water soluble Reduce surface tension	Functional on a wide temperature range Biodegradable	Skin irritation free
Lightweight clay bricks	Good mechanical properties Lightweight Good processability	High durability Low thermal conductivity	Low cost Fire resistant

Table 2: Essential, desirable and useful needs for transdermal patches, biosurfactants and lightweight clay bricks

4. Product

From the idea selection process, the conclusion drawn was that the production of a lightweight brick was the alternative with the highest probability of success, largely due to the less complex industrial processes that would be involved. The aim is to produce a brick that mechanically guarantees the necessary properties to be eligible for the same functions as a brick made simply from clay, but at the same time acquires other physical properties that are more advantageous for its application, such as a lower density and a greater thermal insulation capacity. At the same time, this product reduces clay consumption and gives value to the waste generated from the wine industry.

The inclusion of an organic additive in the paste that forms the brick is instrumental in creating a lightweight product post-firing. The high temperatures achieved during the firing process burn all organic matter, resulting in the formation of pores. When it comes to forming pores, organic wastes are generally cheaper than inorganic materials and also have the advantage of contributing to the heat required during the firing process (Crespo-López et al. 2023).

Muñoz el al. (2014) and Rubia-García et al. (2012) reported clay compositions constituted mainly of oxides, with calcite, illite and quartz as the main constituents of the brick. These compositions are shown in Table 3.

Chemical composition	**wt %**	**Chemical composition**	**wt %**
SiO_2	43.82-46.56	CaO	7.43-20.12
TiO_2	0.67-0.80	Na_2O	0.39-0.76
Al_2O_3	12.67-19.03	K_2O	2.56-2.82
Fe_2O_3	4.12-4.89	$CaCO_3$	13.57-15.49
MgO	2.07-2.22		

Table 3: Clay chemical composition (Muñoz et al. 2014; Rubia-García et al. 2012)

Regarding the characteristics of the product in question, we can see from Table 4 that, compared to a reference brick in which only clay was used in its manufacture, the use of the additive influences the characteristics of the final product.

Properties	Clay (reference)	95% Clay + 5% Lees	95% Clay + 5% Pomace
Loss on Ignition (%)	14	14.1	14.8
Linear Shrinkage (%)	7.4	7.6	4.8
Density ($kg·m^{-3}$)	1650-1700	1460	1560
Water Absorption (%)	16	24	17
Mechanical Strength (MPa)	16.84	12.02	12.5
Thermal Conductivity ($W·m^{-1}·K^{-1}$)	0.7	0.574	0.610
Mass Reduction (%)	-	11.5-14.1	5.4-8.2

Table 4: Thermal and mechanical properties of the different bricks (Taurino et al. 2019; Muñoz et al. 2014)

Loss on Ignition (LoI) is a parameter that assesses the reduction in mass caused by the firing process. All bricks suffer a reduction in mass at this stage. However, in the case of the specimens with an organic additive in their composition, the LoI is higher due to the presence of organic waste. The maximum limit for LoI is 15% (Taurino et al. 2019) and Table 4 shows that the presence of the additive does not exceed this limit.

Linear Shrinkage (LS) is a phenomenon that occurs during the drying and firing stages and eventually results in the accumulation of internal strains in the brick. These internal strains increase the likelihood of cracks and/or other defects in the bricks after production. Table 4 shows that the presence of the additive represents an advantage in this respect compared to the reference brick since the LS decreases in these cases due to the greater stability of the organic matter in the drying stage (Taurino et al. 2019).

Thermal conductivity is an important property from an application point of view because one of the objectives of this type of product is to ensure that the thermal insulation of buildings is as efficient as possible. Bricks that use organic additives in their manufacture have lower thermal conductivity. Therefore, they are more suitable for thermal insulation.

Mechanical strength is also a factor to be considered, as it is an indicator of whether the brick is suitable for the function for which it was designed. In this case, the bricks presented are classified as C62, according to the Brick Industry Association (2007), which means that they are building bricks intended for use in both structural and nonstructural masonry where appearance is not a requirement, with no weathering conditions and most likely to be used to make inner walls in buildings. Although there is a decrease in this resistance for the bricks that incorporate organic waste, the values presented are above the limit for the intended application.

Water absorption is also a useful parameter to understand whether the brick meets all the criteria for its intended application. The importance of this property is defined by the weather the bricks will face. So, in this case, since the lightweight bricks are used in the interior walls of buildings, water absorption is an insignificant factor (Taurino et al. 2019).

In addition, Table 4 shows that the density is lower when there is an organic additive present in the brick production process. Therefore, the bricks produced using organic waste will have a lower mass.

It is possible to conclude that there is a benefit in using organic waste to produce lightweight bricks as the brick performance is not compromised. As outlined by Contreras et al. (2022), wine pomace is generated in greater quantities than wine lees, which means that from the point of view of the applicability of this project, using pomace as an organic additive emerges as the most viable alternative.

5. Manufacture

The previous section presented the lightweight brick, which reused waste from the wine industry as an additive in the manufacturing process, often yielding improved physical properties in the final product. This section provides a comprehensive overview of the entire production process, from the collection of the raw materials to the attainment of the final product.

The production process can essentially be divided into two different sections: preparation of the raw materials and production of the lightweight bricks. The detailed flowsheet describing the manufacturing process of lightweight clay bricks is presented in Figure 3.

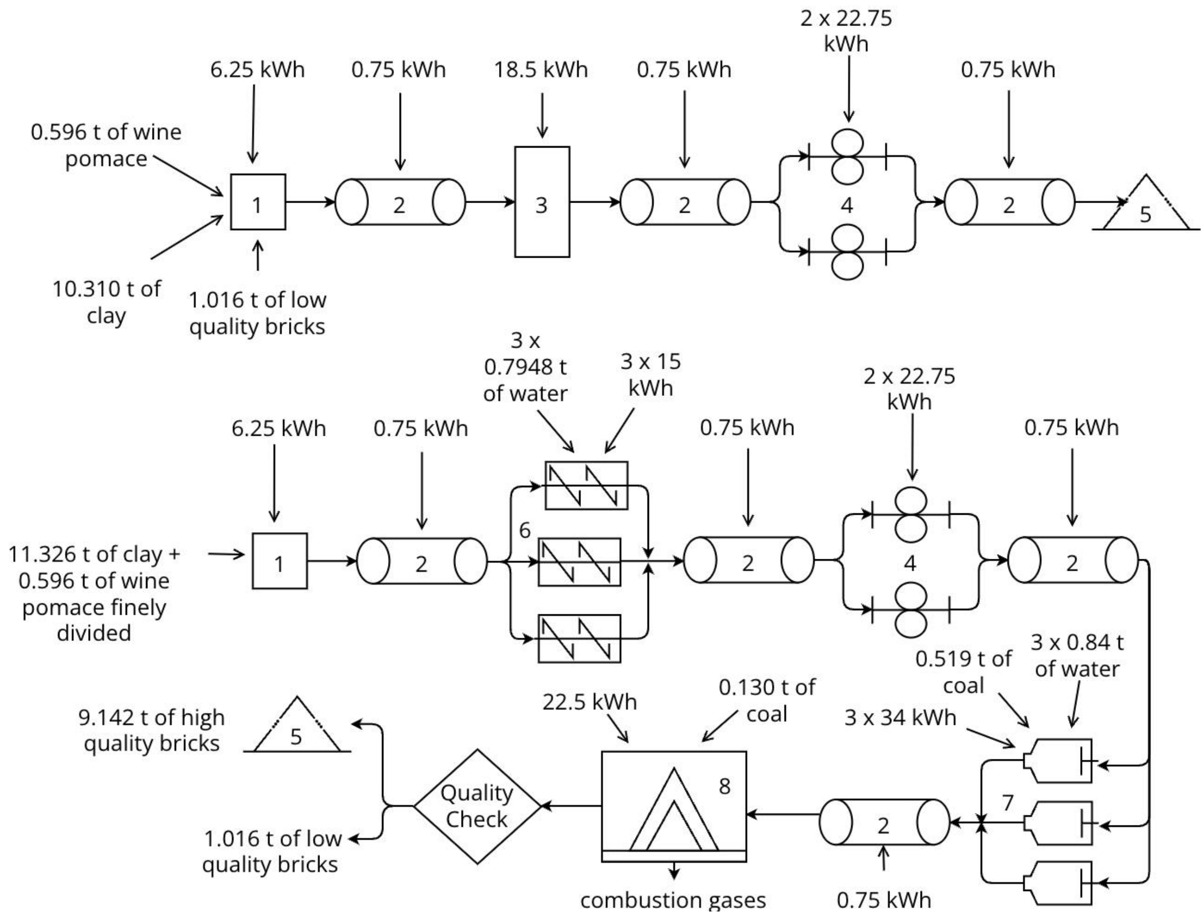


Figure 3: Flowsheet of the manufacturing process of lightweight clay bricks. Key: 1 – Linear dosing device, 2 – Conveyor belt, 3 – Disintegration of clay and pomace, 4 – Rolling mill, 5 – Open bulk storage, 6 – Mixer, 7 – Extruder, 8 – Tunnel kiln. The values presented were calculated for an hour of brick production

Commencing with the purchasing of clay and wine pomace, these materials are transported to the factory by company vans for initial storage and drying. Subsequently, the clay and the wine pomace are loaded into the linear dosing device responsible for regulating the flow of raw materials. The power consumption of this device is 6.25 kW boasting a maximum capacity of 25-35 t/h (Alves 2015). To achieve the desired composition of 5% wine pomace in the bricks, 0.60 t of wine pomace and 11.33 t of clay (comprising 10.31 t of newly arrived clay and the recycling of 1.02 t of low-quality bricks) are required per hour. Conveyor belts were employed to transport materials from one unit process to another. It is estimated that this machine's power rating is about 0.75 kW (Engineering ToolBox 2009). The raw materials are then transported by a conveyor belt to a unit process where large blocks of clay and wine pomace are disintegrated into smaller grains. It will be spent 18.5 kWh of electricity per hour to execute this process and the maximum capacity of this device is 15-20 t/h (Alves 2015). To reduce the size of the grains of clay and pomace, the materials go through a rolling mill. To better control the size of the grains produced, there is a machine attached to the rolling mill that controls the height of the cylinder. The rolling mill has a power consumption of 22.75 kWh and a maximum capacity of 5.5-9 t/h (Alves 2015). Therefore, it is needed two rolling mills to be able to process 11.92 tonnes of raw material per hour. After the materials leave the rolling mill, they are transported through a conveyor belt to an open bulk storage site where they are stored awaiting transfer to the lightweight brick production facilities.

A wheel loader will transport the prepared raw materials from the open bulk storage site to the linear dosing machine. After this step, the materials are transported by a conveyor belt to the mixers. In the mixer, a certain amount of water must be added to the mixture to increase its workability. Workability is a key factor for brick manufacturers since it influences the extrusion and drying process as well as the geometry that may be achieved without the clay body cracking (Taurino et al. 2019). In the brick factory, the amount of water will be set at 20% (calculated on a dry basis) which is below 22% (the plastic limit for clay mixtures) (Taurino et al. 2019). This means that per hour it is needed to add to the clay and pomace mixture 2.384 m^3 of water. Each mixer has a power rating of 15 kWh. It will be necessary 3 mixers, as one unit can only process at most 5-6 t/h (Alves 2015). After the mixing of the raw materials, these must pass through the extruder. This machine gives the clay body the desired brick shape by forcing the clay mixture through a narrow channel with multiple iron rectangular blocks that mimic the shape of the final brick voids. At the end of this machine, there is a mechanized cutter to give the bricks the appropriate length. Each extruder is also equipped with a vacuum pump that removes all the excess air that may cause defects in the production of the bricks. This vacuum pump has a power rating of 4 kW and uses 14 L/min of water for refrigeration (Alves 2015). The extruder has a power consumption of 30 kW and a maximum capacity of 5 t/h, which will require the usage of 3 extruders to process all the materials needed for the desired brick production (Alves 2015).

There are many different kilns that can be used to fire the bricks such as the vertical shaft brick kiln, zig-zag kiln, the fixed chimney bulls trench kiln, the down-draught kiln, and the tunnel kiln. Ultimately, we chose the tunnel kiln as the most appropriate type of kiln for our operation. The tunnel kiln is the safest kiln available because workers are less exposed to the heat generated in the kiln when compared to other types of kilns (Maithel et al. 2012). Besides that, it has a good environmental performance, and it the best kiln for quality brick production (Maithel et al. 2012). Also, the advantage of this technology lies in its ability to fire a large variety of products. Has a large production volume (up to 25 million bricks per year), good control over the firing process and it is mechanized (Maithel et al. 2012). Finally, it saves a considerable amount of energy since it uses the hot combustion gases from the firing section to dry the green bricks in the drying section (energy integration) and thus it is avoided the investment in a dryer (Maithel et al. 2012). The firing kiln has a large capital cost of about 1 million US dollars and needs 1.47 MJ per kg of brick for the drying and firing process (Maithel et al. 2012).

To operate this type of kiln is necessary to use coal as the internal and external fuel (Maithel et al. 2012). The internal fuel constitutes around 80% of the total fuel consumption (Maithel et al. 2012) and it involves mixing 0.52 t of coal per hour with the clay mixture in the extruder. The clay and the pomace mixed with coal are loaded into cars that firstly enter the drying section, then go through a preheating section, followed by the firing section, and finally exit through the cooling section where cold air is drawn from the car's exit at the end of the tunnel, cooling the newly fired bricks. Two fans with a power consumption of 22.5 kW are used to draft the hot combustion gases from the cooling section to the drying section (Maithel et al. 2012). The external fuel used is fed into the tunnel kiln through fire holes on the roof of the kiln in the firing section by firemen depending on the firing shrinkage and kiln's temperature (Maithel et al. 2012) and amounts to 0.13 t of coal per hour of production. The flue gases from the drying section are expelled through a chimney. It may be needed to treat these flue gases using for example a lime water scrubber (Maithel et al. 2012).

Despite the tunnel kiln efficiency, it is expected that only 90% of the fired bricks have the quality intended (Maithel et al. 2012). Therefore, the fired bricks must be inspected to separate the low-quality bricks from the high-quality ones. The low-quality bricks can be recycled and be reused in the beginning of the process. The high-quality bricks are loaded into pallets containing 198 bricks and are transported by forklift to the storage site awaiting selling to the final customer.

In order to produce 9.14 t of high-quality lightweight bricks per hour, it is necessary 0.60 t of wine pomace, 11.33 t of clay, 296.75 kWh of electricity, 4.90 m^3 of water, and 0.65 t of coal. These values were calculated assuming a yearly production of 15 million bricks with each weighting 4.9 kg and assuming that the factory works nonstop 8040 h per year, the loss on ignition is 14.8% (Muñoz et al. 2014), and the coal used has a calorific power of 5500 kcal/kg (IEA 2023). The amount of wine pomace needed to produce the desired quantity of bricks depends on the water content within the pomace. The pomace needed ranges from 15% to 49% of the total pomace generated in the region of Lisbon and Tejo combined (IVV 2023; Contreras et al. 2022), considering a water content in pomace between 55% to 75% (García-Lomillo and González-SanJosé 2017).

6. Process Simulation

Since the power needed for the operation of most of the equipment was available, it was not needed to use any process simulation software to model them. However, for the tunnel kiln it was used Aspen Plus V12.1 to check whether the energy consumption value in the firing kiln reported by Maithel et al. (2012) was appropriate. To model the firing of the bricks, it was determined the amount of heat necessary to increase the temperature of the bricks up to 980 °C, the estimated maximum temperature achieved in the firing process (Muñoz et al. 2014; Taurino et al. 2019). Besides that, it was used the equations present in APPENDIX A to compute the mass and energy balance for the drying process. For this step, Aspen Plus V12.1 was also used to calculate the average specific heat of the clay and pomace mixture when heated from 20 °C to 95 °C (Muñoz et al. 2014). The main advantage in using Aspen Plus is its extensive database, which encompasses the specific heat for various components of clay and cellulose.

To model the clay mixture, it was used the compositions present in Table 3 and it was assumed that the dry pomace was 100% cellulose. Using the clay composition reported by Muñoz et al. (2014), it is spent 0.91 MJ/kg of fired brick in the drying process and 1.34 MJ/kg of fired brick in the firing operation, whereas using the clay composition reported by Rubia-García et al. (2012), it is also spent 0.91 MJ/kg of fired brick drying the green bricks but only 1.28 MJ/kg of fired brick in the firing kiln. It can be concluded that the total energy needed for the drying and firing process is in the range of 2.19 to 2.25 MJ/kg of fired brick.

As said before, it is needed 1.47 MJ/kg of fired brick to operate the tunnel kiln which incorporates firing and drying of the green bricks in the same unit process. This value is slightly higher than the value simulated for the energy consumption in the firing process (1.28-1.34 MJ/kg of fired brick) because when performing the computer simulations, it was not considered neither the energy losses through the wall, nor the heating of the surrounding air in the firing zone. Also, the energy used in the tunnel kiln is much lower than the simulated energy consumption for the drying and the firing processes done separately because there is energy integration in the tunnel kiln as the hot combustion gases drafted from the firing zone are used in the drying process. It can be stated that the values obtained in the simulations are in accordance with the energy consumption value reported by Maithel et al. (2012) for the operation of the firing kiln.

7. Economic analysis

A Gantt diagram is a type of chart that illustrates a project schedule. It shows tasks and events displayed against time in which a darker color represents a higher involvement. Table 5 encompasses the Gantt diagram for the first four years of our project combined with the different stages of the Chemical Product Design methodology previously mentioned: Needs, Ideas, Selection and Manufacture. From the fourth year forward, the involvement and intensity in each task remain constant.

In the first stages of the CPD process, R&D is of relevance to establish the needs of the market and to turn them into ideas. After the selection of the final idea, it is necessary to intensify the research and development, engineering and investment facets in order to develop a production process that leads to a high-quality product. Although the aim is to mainly create a business-to-business company, marketing is still relevant during the earlier stages of the business so as to divulge the product and to establish a market share.

Year	**1**				**2**				**3**				**4**			
Trimester	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
CPD Stage	**N** **I**	**S**			**M**											
R&D																
Marketing																
Investments																
Engineering																
Production																
Sales																

Table 5: Gantt Chart considering a four-year time span. Key: N - Needs; I - Ideas; S - Selection; M – Manufacture

From the second year onward, production and sales will begin. It is expected that each year production and sales will increase until they stabilize from year four onwards. Investments will also decrease since all heavy machinery and equipment were purchased during the company´s first year.

The production will start in the second year with 40,000 t of bricks at €0.284 per brick or €57.96 per tonne of bricks (Preceram 2023). During the third and fourth years, production will rise to 60,000 and 73,500 t of bricks respectively, while the price remains the same.

To achieve these levels of production, an initial investment of about 3.5 million euros is required. This figure includes €330,000 for the cost of 11,000 m^2 of land in Leiria, selected due to its proximity with clay extraction sites, €1,000,000 for the cost of a 5000 m^2 building (APX Construction Group 2023), €1,769,770 for the necessary equipment and €407,047 in working capital. Table 6 summarizes the equipment and machinery necessary to obtain the desired product.

Equipment	Quantity	Price per unit (€)
Linear Dosing Device	2	27,500
Conveyor Belt	7	5,000
Disintegration Device	1	27,100
Rolling Mill + Rectifier	4	22,900
Mixer	3	24,900
Extruder	3	82,790
Vacuum Pump	3	1,000
Tunnel Kiln	1	1,000,000
Wheel Loader	1	135,000
Forklift	2	10,000
Transport Truck	2	40,000
Total		1,769,770

Table 6: Cost of equipment and machinery (Alves 2015)

In addition, it was deemed necessary to employ 34 employees distributed among the management, administrative, commercial, and operational sectors of the company. The operational sector would be constituted by 30 members, the commercial by two members while the other sectors would each possess one employee. This results in an annual charge of €613,827.

Production costs must also be taken into account. It was considered that the pomace is obtained free of charge (Crespo-López et al. 2023). Considering the figures presented in the flowsheet of the manufacturing process, it is possible to obtain the total cost of energy and water per tonne of final product. The cost of electricity, coal and water necessary to produce one tonne of bricks were estimated at €4.38, €8.17, €0.76 respectively, while the price of clay was estimated at €20 per tonne of clay in accordance to (Youssef, Lafhaj, and Chapiseau 2020).

In order to assess the economic feasibility of this project it is crucial to take into account some financial parameters such as net present value (NPV), internal rate of return (IRR), payback period and the overall cash flow of the company. A ten-year financial assessment, considering an average cost of capital of 10%, was conducted obtaining a NPV of €1,042,551 and an IRR of 15.82%. As the NPV is greater than zero and the IRR is greater than the defined cost of capital, the project is deemed profitable. Analyzing the cumulative cash flow presented in Figure 4, it is possible to conclude that the payback period is 8.5 years.

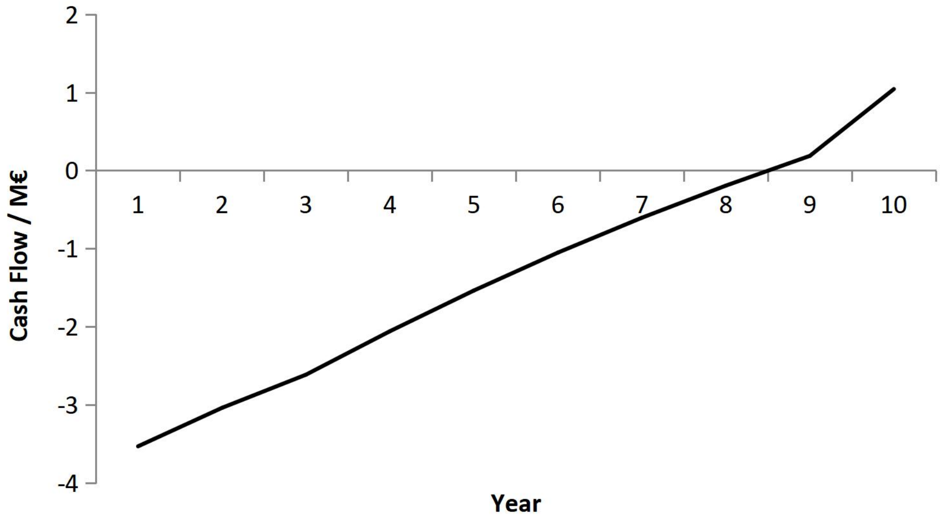


Figure 4: Company´s cash flows during 10 years

It is also of interest to represent the values of accumulated sales and costs over time as to understand the magnitude of the proposed project and as an alternative way of obtaining the payback period. The payback period is also obtained when the accumulated sales equal the accumulated costs. In this case, as represented in Figure 5 and in accordance with the value previously obtained, the payback time is of 8.51 years.

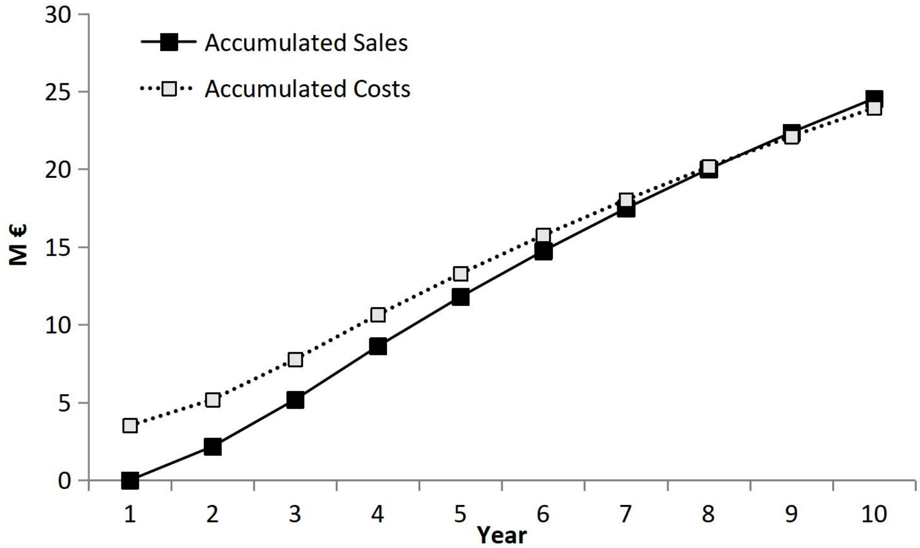


Figure 5: Accumulated sales and costs across 10 years

8. Conclusions

In order to create a sustainable product that responds to market needs and favors a circular economy, several ideas were presented that use waste from the Portuguese wine sector as raw material. Following the steps of Chemical Product Design, the lightweight clay brick was developed. This is a product obtained using grape pomace as a raw material mixed with clay. The purpose of this product is to serve as a construction material for the inner walls of buildings. In comparison to the clay bricks already on the market, the product developed has higher porosity. As a result, it has a lower density and lower thermal conductivity. The use of the organic additive also means that linear shrinkage is lower, resulting in a lower probability of cracks or defects in the production of the brick. However, the use of grape pomace causes a higher mass reduction during the firing of the brick (higher LoI). Even so, the maximum limit (15%) is respected. Good mechanical resistance is also verified. All these characteristics are obtained by incorporating a pomace fraction equal to 5% (in weight). The production process was divided into two parts: extraction of the raw materials and production of the lightweight clay brick.

The economic analysis showed that an initial investment of 3.5 million euros was needed in order to reach a maximum production of 73,500 t of bricks after 4 years. Each tonne of bricks would be sold at €57.96. A ten-year financial assessment was conducted obtaining a NPV greater than zero (€1,042,551) and the IRR (15.82%) greater than the defined average cost of capital (10%). For these reasons, the project is considered profitable. As to the payback period, it is possible to conclude that it is 8.51 years.

Alternatively, it would be possible to use wine lees as a raw material instead of pomace. However, this is a waste that exists in smaller quantities, which would reduce the production of bricks, as well as being an organic additive with greater added value when compared to grape pomace. In order to optimize the production process, further research should be carried out with the aim of reducing CO_2 emissions by using another energy source or integrating into the process a way of capturing and storing it. In terms of financial analysis, a more detailed assessment would be needed to guarantee the reliability of all the values used.

In short, the production of lightweight clay brick is a profitable and viable project that contributes to a circular economy through the valorization of grape pomace.

References

Alves, Tiago Filipe Lourenço Pereira. 2015. “Formulação de Pastas Cerâmicas a Partir de Matérias -Primas Dos Concelhos de Vila Viçosa e Redondo Para a Produção de Olaria Tradicional.” UNIVERSIDADE DE ÉVORA ESCOLA DE CIÊNCIAS E TECNOLOGIA.

APX Construction Group. 2023. “Average Warehouse Construction Cost: What You Need to Know.” Accessed 10 December, 2023. https://apxconstructiongroup.com/warehouse-construction-cost/.

BIA - Brick Industry Association. 2007. “Specifications for and Classification of Brick.” *Technical Notes*, no. 9A.

Contreras, María del Mar, Juan Miguel Romero-García, Juan Carlos López-Linares, Inmaculada Romero, and Eulogio Castro. 2022. “Residues from Grapevine and Wine Production as Feedstock for a Biorefinery.” *Food and Bioproducts Processing* 134: 56–79. https://doi.org/10.1016/j.fbp.2022.05.005.

Crespo-López, Laura, Alberto Martínez-Ramirez, Eduardo Sebastián, and Giuseppe Cultrone. 2023. “Pomace from the Wine Industry as an Additive in the Production of Traditional Sustainable Lightweight Eco-Bricks.” *Applied Clay Science* 243 (June). https://doi.org/10.1016/j.clay.2023.107084.

Dludla, Phiwayinkosi V., Bongani B. Nkambule, Babalwa Jack, Zibusiso Mkandla, Tinashe Mutize, Sonia Silvestri, Patrick Orlando, Luca Tiano, Johan Louw, and Sithandiwe E. Mazibuko-Mbeje. 2018. “Inflammation and Oxidative Stress in an Obese State and the Protective Effects of Gallic Acid.” *Nutrients* 11 (1). https://doi.org/10.3390/NU11010023.

Engineering ToolBox. 2009. “Conveyors - Load & Power Consumption.” Accessed 19 November, 2023. https://www.engineeringtoolbox.com/conveyor-power-load-d_1560.html.

Eurostat. 2023. “Statistics.” Accessed 14 November, 2023. https://ec.europa.eu/eurostat/databrowser/view/tag00121/default/table?lang=en.

Ferrer-Gallego, Raúl, and Paula Silva. 2022. “The Wine Industry By-Products: Applications for Food Industry and Health Benefits.” *Antioxidants 2022, Vol. 11, Page 2025* 11 (10): 2025. https://doi.org/10.3390/ANTIOX11102025.

García-Lomillo, Javier, and María Luisa González-SanJosé. 2017. “Applications of Wine Pomace in the Food Industry: Approaches and Functions.” *Comprehensive Reviews in Food Science and Food Safety* 16 (1): 3–22. https://doi.org/10.1111/1541-4337.12238.

IEA - International Energy Agency. 2023. “Prices – Coal Market Update – July 2023 – Analysis.” Accessed 21 November, 2023. https://www.iea.org/reports/coal-market-update-july-2023/prices.

IVV - Instituto do Vinho e da Vinha. 2023. “IVV // Produção.” Accessed 6 December, 2023. https://www.ivv.gov.pt/np4/163.html.

Kalli, Efstathia, Iliada Lappa, Pavlos Bouchagier, Petros A. Tarantilis, and Efstathia Skotti. 2018. “Novel Application and Industrial Exploitation of Winery By-Products.” *Bioresources and Bioprocessing 2018 5:1* 5 (1): 1–21. https://doi.org/10.1186/S40643-018-0232-6.

Maithel, Sameer, Dheeraj Lalchandani, Gaurav Malhotra, Prashant Bhanware, R. Uma, Santhosh Ragavan, Vasudev Athalye, et al. 2012. “Brick Kilns Performance Assessment A Roadmap for Cleaner Brick Production in India.”

Moggridge, G. D., and E. L. Cussler. 2003. “Teaching Chemical Product Design.” *Computer Aided Chemical Engineering* 15 (C): 1460–65. https://doi.org/10.1016/S1570-7946(03)80516-3.

Muñoz, P., M. P. Morales, M. A. Mendívil, M. C. Juárez, and L. Muñoz. 2014. “Using of Waste Pomace from Winery Industry to Improve Thermal Insulation of Fired Clay Bricks. Eco-Friendly Way of Building Construction.” *Construction and Building Materials* 71: 181–87. https://doi.org/10.1016/j.conbuildmat.2014.08.027.

Niculescu, Violeta Carolina, and Roxana Elena Ionete. 2023. “An Overview on Management and Valorisation of Winery Wastes.” *Applied Sciences (Switzerland)* 13 (8). https://doi.org/10.3390/app13085063.

Oprea, Oana Bianca, Mona Elena Popa, Livia Apostol, and Liviu Gaceu. 2022. “Research on the Potential Use of Grape Seed Flour in the Bakery Industry.” *Foods 2022, Vol. 11, Page 1589* 11 (11): 1589. https://doi.org/10.3390/FOODS11111589.

Phan, Kim, Katleen Raes, Veronique Van Speybroeck, Martijn Roosen, Karen De Clerck, and Steven De Meester. 2021. “Non-Food Applications of Natural Dyes Extracted from Agro-Food Residues: A Critical Review.” *Journal of Cleaner Production* 301 (June): 126920. https://doi.org/10.1016/J.JCLEPRO.2021.126920.

Preceram - Indústrias de Construção, SA. 2023. “Preceram - Preços.” Accessed 20 November, 2023. https://preceram.pt/precos/.

Rivas, S., L. López, C. Vila, and J. C. Parajó. 2021. “Organosolv Processing of Vine Shoots: Fractionation and Conversion of Hemicellulosic Sugars into Platform Chemicals by Microwave Irradiation.” *Bioresource Technology* 342 (December): 125967. https://doi.org/10.1016/J.BIORTECH.2021.125967

Roca, Pau. 2023. “STATE OF THE WORLD VINE AND WINE SECTOR INTERNATIONAL ORGANISATION OF VINE AND WINE.”

Rodrigues, Rafaela P., Licínio M. Gando-Ferreira, and Margarida J. Quina. 2022. "Increasing Value of Winery Residues through Integrated Biorefinery Processes: A Review." *Molecules 2022, Vol. 27, Page 4709* 27 (15): 4709. https://doi.org/10.3390/MOLECULES27154709.

Rubia-García, M. Dolores La, África Yebra-Rodríguez, Dolores Eliche-Quesada, Francisco A. Corpas-Iglesias, and Alberto López-Galindo. 2012. "Assessment of Olive Mill Solid Residue (Pomace) as an Additive in Lightweight Brick Production." *Construction and Building Materials* 36 (November): 495–500. https://doi.org/10.1016/J.CONBUILDMAT.2012.06.009.

Santos, M., F. Diánez, M. de Cara, and J. C. Tello. 2008. "Possibilities of the Use of Vinasses in the Control of Fungi Phytopathogens." *Bioresource Technology* 99 (18): 9040–43. https://doi.org/10.1016/J.BIORTECH.2008.04.032.

Silva, Adriana, Vanessa Silva, Gilberto Igrejas, Isabel Gaivão, Alfredo Aires, Naouel Klibi, Maria de Lurdes Enes Dapkevicius, Patrícia Valentão, Virgílio Falco, and Patrícia Poeta. 2021. "Valorization of Winemaking By-Products as a Novel Source of Antibacterial Properties: New Strategies to Fight Antibiotic Resistance." *Molecules* 26 (8). https://doi.org/10.3390/MOLECULES26082331.

Sousa, Diana Rita, Travassos Produção, D E Sistemas, Transdérmicos De Base, and Ácido Lático. 2019. "Produção de Sistemas Transdérmicos de Base Ácido Láctico." *Produção de Sistemas Transdérmicos de Base Ácido Láctico*, January.

Taurino, Rosa, Daniele Ferretti, Luca Cattani, F. Bozzoli, and Federica Bondioli. 2019. "Lightweight Clay Bricks Manufactured by Using Locally Available Wine Industry Waste." *Journal of Building Engineering* 26 (July): 100892. https://doi.org/10.1016/j.jobe.2019.100892.

The Times. 2004. "A Pill for Hangovers?" Accessed 15 November, 2023. https://www.thetimes.co.uk/article/a-pill-for-hangovers-s5dhsbpf77h.

ViniPortugal. 2022. "Estatísticas." Accessed 14 November, 2023. https://www.viniportugal.pt/pt/o-sector/estatisticas/.

Weather and Climate. 2023a. "Leiria, PT Climate Zone, Monthly Weather Averages and Historical Data." Accessed 26 November, 2023. https://weatherandclimate.com/portugal/leiria.

Weather and Climate. 2023b. "Portugal Climate Zone, Weather By Month and Historical Data." Accessed 26 November, 2023. https://weatherandclimate.com/portugal.

Youssef, Nicolas, Zoubeir Lafhaj, and Christophe Chapiseau. 2020. "Economic Analysis of Geopolymer Brick Manufacturing: A French Case Study." *Sustainability (Switzerland)* 12 (18). https://doi.org/10.3390/SU12187403.

Acknowledgments

This work was developed within a framework of awareness for the valorization of natural residues for the manufacture of added-value products under the scope of the Chemical Product Engineering course of the Master in Chemical Engineering at the Faculty of Engineering of the University of Porto. Professor Cláudia Gomes and Doctors Ricardo Santos and Yaidelin Manrique, supervisors of this work, are members of LSRE-LCM – Laboratory of Separation and Reaction Engineering - Laboratory of Catalysis and Materials, supported by national funds through FCT/MCTES (PIDDAC): LSRE-LCM, UIDB/50020/2020 (DOI: 10.54499/UIDB/50020/2020) and UIDP/50020/2020 (DOI: 10.54499/UIDP/50020/2020); and ALiCE, LA/P/0045/2020 (DOI: 10.54499/LA/P/0045/2020).

9. Supplementary Information

9.1. Drying process: mass and energy balance

For the modelling of the drying step, it is essential to know the average temperature and humidity in Portugal. According to Weather and Climate (2023b), the average relative humidity in Portugal is 71.93%. The average temperature in Leiria is 16.79 °C as reported by Weather and Climate (2023a).

The relative humidity of air (H_r) is related to the water vapor pressure (P_{H_2O}) by the following formula:

$$H_r = \frac{P_{H_2O}}{P_{H_2O}^{sat}} \times 100 \tag{1}$$

$P_{H_2O}^{sat}$ is the water's saturation pressure at the temperature of the air (T) and it is given by Equation 2.

$$P_{H_2O}^{sat}(\text{kPa}) = exp\left(16.5699 - \frac{3984.923}{T(\text{K}) - 39.724}\right) \tag{2}$$

The humidity of the mixture water/air (H) is calculated dividing the mass of water by the mass of dry air. At atmospheric pressure, the relationship between humidity and vapor water pressure is expressed by the following equation:

$$H = 0.622 \times \frac{P_{H_2O}(\text{kPa})}{101.325 - P_{H_2O}(\text{kPa})} \times 100 \tag{3}$$

To calculate the amount of heat needed to completely dry the green bricks (Q), it is necessary to solve the water's mass balance and an energy balance. The water's mass balance is given by:

$$V_g H_{in} + L_s X_{in} = V_g H_{out} + L_s X_{out} \tag{4}$$

V_g is the mass of dry air, X is the water content per mass of dry solid and L_s is the mass of dry solid.

It is expected that the temperature of the air and the solid that leaves the dryer is 95 °C and the relative humidity of air is 15% as reported by Muñoz et al. (2014).

Solving the mass balance, it is possible to obtain V_g.

The energy balance is given by Equation 5.

$$Q = V_g\left(h_{g,out} - h_{g,in}\right) + L_s\left(h_{s,out} - h_{s,in}\right) \tag{5}$$

Where h_g denotes the enthalpy of air per mass of dry air and h_s denotes the enthalpy of solid per mass of dry solid.

Equation 6 and Equation 7 can be used to determine h_g and h_s.

$$h_g\ (\text{kJ/(kg of dry air)}) = (1.006 + 1.86H) \times T_g + 2501H \tag{6}$$

$$h_s\ (\text{kJ/(kg of dry solid)}) = C_p \times T_s + 4.18X \times T_s \tag{7}$$

C_p is the specific heat of the solid phase that was estimated using Aspen plus considering that this solid phase was a mixture of 95% clay and 5% cellulose (to model the wine pomace). The clay compositions used were the ones present in Table 3.

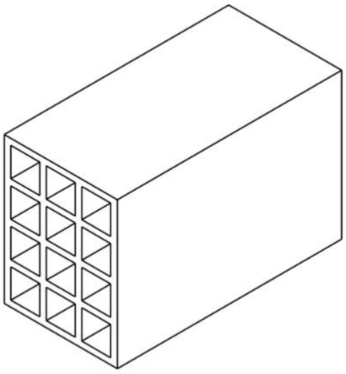
The results obtained using the above-mentioned equations are presented in Table A1.

Variable	Unit	Value
$T_{g,in}$	°C	16.79
$H_{r,in}$	%	71.93
H_{in}	kg of water/kg of dry air	0.0085
$T_{g,out}$	°C	95
$H_{r,out}$	%	15
H_{out}	kg of water/kg of dry air	0.089
$T_{s,in}$	°C	20
X_{in}	kg of water/kg of dry solid	0.20
$T_{s,out}$	°C	95
X_{out}	kg of water/kg of dry solid	0
L_s	kg of dry solid	100
V_g	kg of dry air	248.80
C_p	kJ/(K kg of dry solid)	0.80
$h_{g,in}$	kJ/(kg of dry air)	38.47
$h_{g,out}$	kJ/(kg of dry air)	333.64
$h_{s,in}$	kJ/(kg of dry solid)	32.76
$h_{s,out}$	kJ/(kg of dry solid)	76.18
Q	kJ	77780.41

Table A1: Calculations made for the modelling of the drying process

Assuming an LoI of 14.8%, per 100 kg of green bricks it is produced 85.2 kg of fired bricks. Therefore, the energy consumption of this drying process is 0.91 MJ/ (kg of fired brick).

9.2. Datasheet

Configuration		
Dimension	Length (mm)	290.00 ± 6.81
	Height (mm)	189.00 ± 5.50
	Width (mm)	146.00 ± 4.83
Density ($kg \cdot m^{-3}$)		1560
Mechanical Strength (MPa)		12.50
Unit Weight (kg)		4.9
Fire Hazards		A1 – non-combustible
Water Absorption		Not applicable
Thermal Insulance ($K \cdot m^2 \cdot W^{-1}$)		0.47
Brick Material		Clay
Type of Brick		C62 – Building Brick
Bricks per pallet		198
Weight of a loaded pallet (kg)		970