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An Economic Analysis of the Use of Local Natural Waste: Volcanic Ash of Mt. Etna Volcano (Italy) for Geopolymer Production

Marina Cavalieri [1], Paolo Lorenzo Ferrara [2,*], Claudio Finocchiaro [3] and Marco Ferdinando Martorana [1]

1 Department of Economics and Business, University of Catania, 95129 Catania, Italy; mcavali@unict.it (M.C.); marco.martorana@unict.it (M.F.M.)
2 Department of Law, University of Catania, 95124 Catania, Italy
3 Department of Biological, Geological and Environmental Sciences, University of Catania, 95129 Catania, Italy; claudio.finocchiaro@unict.it
* Correspondence: paolo.ferrara@unict.it

Abstract: This paper analyses the net social benefits deriving from the medium-scale production of geopolymers based on volcanic ash compared to traditional cementitious materials used in construction and restoration sectors. In contrast to the existing literature grounded on the physical and mechanical characterization of geopolymers, our analysis considers two aspects: public finance savings from avoiding the disposal of volcanic ash in landfills and environmental benefits deriving from reduction in CO_2 releases due to the production process at room temperature. Our case study focuses on the reuse of natural waste, namely the volcanic ash of the Mt. Etna volcano (Italy), whose disposal involves significant costs for society. Its use in the alkaline activation process avoids the exploitation of natural resources. Considering the huge amount of volcanic ash from Mt. Etna that falls on the urban areas of Eastern Sicily, the results show relevant economic benefits, in terms of both avoided costs and tax reductions for the citizens. Alongside these, significant environmental benefits are evidenced thanks to the release of up to 78% lower CO_2 emissions by synthesised materials with volcanic ash than by traditional cementitious ones. Overall, the social cost savings compared to traditional materials is 0.339 EUR/kg for geopolymer.

Keywords: sustainability; construction industry; geopolymers; volcanic ash; regional economy; circular economy; environmental and resource economics; waste management

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1. Introduction

Concerns about sustainability mainly relate to the environmental consequences of anthropogenic activities on future generations [1], among which is the over-exploitation of natural resources [2]. In this perspective, recovering value from waste is acknowledged to minimise the use of non-renewable materials [3,4]. By supporting the conservation of natural resources while reducing disposal problems, waste material recycling is a socially valuable activity that benefits both the environment and the economy [3]. Indeed, recycling is the main component of the circular economy, namely "an economic system based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production, distribution and consumption processes with the aim to accomplish sustainable development" [5]. In addition, the circular economy helps to improve the economic and social conditions of people and territories, creating new job opportunities, decreasing the dependence on external resources and promoting sustainable and inclusive development, especially benefitting lagging countries [6]. Recycling is also one of the pillars of both sustainability economics, which focuses on the efficient use of scarce resources and non-wastefulness [7], and environmental sustainability [8].

In the last few years, sustainability issues have gained momentum in the construction industry [9,10], with particular attention on the materials used [9,11,12]. From the point of view of recycling policies and environmental sustainability initiatives, inorganic polymers can play a relevant role, enabling the reuse of wastes in a wide range of potential applications [11,13–16]. Specifically, the use of these materials in the construction sector is of particular interest as they can be a sustainable alternative for cement and concrete [17–20], whose production requires an intensive consumption of non-renewable raw materials (i.e., limestone, clay or its natural mixture, marl) and constitutes one of the major causes of global CO_2 emissions (e.g., [21–25]). In this sense, in the literature [26], there are several studies on the reuse of industrial and artificial wastes (e.g., [27–32]) or biomass ashes from agricultural farming wastes [33].

Moreover, there is a substantial number of papers on the technical properties of volcanic ash geopolymers [34–41] and an increasing interest in regional sustainability initiatives [42–49]. However, to the best of our knowledge, no other work has so far analysed the recycling of natural wastes in the form of geopolymers from a comprehensive sustainability perspective, complementing the effects in terms of pollution reduction and economic benefits for society.

The present work aims to fill this gap, considering the use of natural waste such as the volcanic ash periodically erupted by the Mt. Etna (Italy) volcano to produce geopolymers. Following [43], which highlights the existence of important synergies between regional solutions and global issues, we focus our attention on the potential economic benefits for local communities and on the environmental benefits for society as a whole (e.g., in terms of avoided costs for waste disposal and lower CO_2 emissions) deriving from the recycling of volcanic ash in the production of geopolymer binders and their use as substitutes for more conventional (i.e., clinker-based) materials in the construction and restoration sectors, considering the relevant impact of the construction industry on the environment [50,51].

The rest of the paper is organised as follows: In Section 2, we provide background information on the environmental benefits of geopolymers as they emerge from the literature. In Section 3, we describe the material and methods used in the analysis and discuss our data sources, while in Section 4, we estimate the economic and environmental benefits deriving from the use of geopolymers based on volcanic ash. Finally, Section 5 concludes by providing some directions for future research.

2. Background on Geopolymers and Their Environmental Benefits

The global concerns about environmental sustainability have roused interest in innovative green technologies, including those related to geopolymer production [10,52]. Geopolymer technology traces back to the pioneering research in 1957 by Victor Glukhovsky, who investigated the possibility of preparing low-calcium or even calcium-free cementitious materials (initially called “soil cements”), using clays and alkaline metal solutions [53]. However, the term geopolymer was first used by Davidovits to describe synthetic alkali aluminosilicate materials, hitherto broadly termed “inorganic polymers” [54]. Geopolymers are, indeed, aluminosilicate synthetic materials obtained from a reactive powder of silicon and aluminium (i.e., precursor) mixed with an activating alkaline solution (i.e., activator), whose process is commonly named the alkali activation process [55]. Moreover, their structure makes them very versatile thanks to some features, namely chemical attacks and fire resistance, thus suitable in different sectors, particularly in the building and restoration ones [56,57].

Apart from their physical/mechanical properties, whose discussion is out of the scope of this research, the growing interest in geopolymers is due to their production process, which is less polluting than that of traditional alternatives. Indeed, the production of clinker needed for the Ordinary Portland Cement production (OPC) requires thermal treatments at high temperatures of around 1400 °C [58], thereby consuming large amounts of natural raw materials and energy, and releasing a massive amount of CO_2 into the atmosphere [59]. Moreover, the activation of clinker-based materials and thus their application need a substantial amount of water that directly causes an additional burden on the already scarce natural resource. Therefore, it is not surprising that the cement industry is among the top CO_2 emitters in the world, responsible for about 5–8% of global anthropogenic CO_2 emissions [60]. In this scenario, Miller et al. [61] show that in 2012 concrete production was responsible for 9% of global industrial water withdrawals (approximately 1.7% of total global water withdrawal). Furthermore, the global demand for OPC is set to increase further by 2050, especially in developing countries [62], where water stress is expected to be a more serious problem [45].

In contrast, geopolymer production requires a lower temperature, or generally, the process is at room temperature [63], implying less energy and water consumption, reducing CO_2 emissions and turning waste streams into "green" cement [4,23,64–66]. In reference to the production process, empirical studies have shown that geopolymer concrete mixes indicate a potential for up to a 40% reduction in overall energy consumption [67] and up to 80% reduction in CO_2 emissions [68] compared to OPC. Additionally, if the raw materials are available locally, the production of geopolymers can take place in situ, also reducing the emissions (and the related social costs) from transport [69].

Further environmental benefits concern the production of waste-based geopolymers, to the extent that both the extraction of non-renewable raw materials from (existing or new) quarries and the disposal of waste itself (with the related costs and landfill space saved) are avoided [28]. Indeed, the use of waste materials as precursor is a good example of waste management as it gives them a new life and prevents the possible contamination of the environment that might have resulted from their improper disposal.

What has been said so far also concerns the geopolymer considered in the present analysis, i.e., the one based on the use of volcanic ash whose disposal in Italy is strongly regulated. In fact, volcanic ash is classified by law as a special municipal waste, to be disposed of in highly specialised landfill implants, with significant costs for the local community that are damped on to citizens in the form of higher local taxes. Recently, to lighten the heavy financial burden on the eastern Sicilian municipalities involved in a prolonged eruptive activity of Mt. Etna, the central government has allowed the reuse of volcanic ash "to replace raw materials within production cycles, using processes or methods that do not harm the environment or endanger human health" (Law no. 108 on 29 July 2021). Furthermore, the use of volcanic ash, readily and freely available in areas surrounding eruptive volcanos such as Mt. Etna, can help alleviate the problem of the lack of enough natural materials that is expected to affect the market of cement worldwide. In fact, while it is expected that the global consumption of concretes will grow considerably in the future, the production of industrial wastes (e.g., fly ash and slag) to be used as precursor materials is likely to decrease, due to the worldwide adoption of stricter environmental regulations of polluting industrial activities.

Nevertheless, the production of geopolymers also has environmental weaknesses. The research focus is currently on minimizing the use of alkali activators (e.g., sodium silicate and sodium hydroxide), which are the least ecological part of the entire production process, being highly corrosive and the highest contributors of embodied energy and carbon emissions [70].

Because of the above environmental benefits, the use of recycling-based geopolymers in the construction sector is set as a priority in the recent European political agenda. The worsening of the global environmental crisis has prompted the European Commission to develop a long-term strategy to promote sustainability. Accordingly, the European Green Deal includes a roadmap to mitigate the negative environmental impact of the construction sector, with the aim of reducing greenhouse gas emissions by up to 60% by 2050 and conserving natural resources. Among the key actions are investments in "greener" cementitious binders and the promotion of the use of recycled materials and industrial by-products as secondary raw materials.

3. Material and Methods

3.1. Material

This paper benefits from the research work conducted within the "Advanced Green Materials for Cultural Heritage" Italian project (https://www.unict.it/en/research/projects/agm-cuhe), aimed at creating innovative and eco-friendly materials for the conservation and restoration of local cultural heritage.

For this purpose, alkali-activated formulations based on volcanic ash of Mt. Etna volcano (Figure 1) have been experimentally analysed from different points of view. Once pyroclastic materials on the southern-eastern flank of Mt. Etna volcano are sample, dry milling and sieving are performed to obtain a powder with grain size < 75 μm. The suitability of use of the volcanic powder in alkaline environment has been demonstrated thanks to its high aluminosilicate composition (i.e., SiO_2/Al_2O_3 molar ratio = 5.1) and modest amorphous amount (i.e., also up to 70% in weight). These latter are considered important points, together with the grain size of the powder, to guarantee the reactivity in the alkaline system [71]. Moreover, insights on molecular vibrations with Raman and FTIR spectroscopies have been carried out on the volcanic raw material, which has confirmed an aluminosilicate and glassy composition [72]. In the alkaline synthesis, small amounts (10–25 wt.% of the total amount of volcanic ash) of commercial ARGICAL™ M1000 metakaolin (IMERYS, France, reported chemical composition from producer: SiO_2 = 55%; Al_2O_3 = 40%, Fe_2O_3 = 1.4%; TiO_2 = 1.5%; $Na_2O + K_2O$ = 0.8%; $CaO + MgO$ = 0.3%; LOI = 1%) have been added to the solid mixtures to allow the setting time at room temperature of the pastes. Moreover, different mix designs have been tested to evaluate the effects of the reactants involved in process (e.g., activators type and amount) on the final performance (e.g., chemical stability and mechanical performance) with multiple linear regressions and artificial neural networks, whose results evidenced a positive influence of metakaolin amount and higher SiO_2/Na_2O molar ratio [73]. According to mechanical performance, satisfying uniaxial compressive strengths have been recorded on samples with 10 and 20 wt.% of metakaolin addition, namely 18 and 50 MPa, respectively, after 21 days of curing [74]. Moreover, it has been observed in previous studies that there were minimal observable alterations to surface conditions following six months of exposure to atmospheric conditions [75]. Furthermore, the material demonstrated exceptional durability, exhibiting resistance to salt mist corrosion without any structural defects during an aging test designed to simulate the corrosive effects of sea spray in local coastal environments [76]. Moreover, this material has proven effective in real-world restoration efforts, as exemplified by its successful application in the replication of AA-mortar for the restoration of a mosaic section within the Monreale Cathedral, a UNESCO Heritage site situated in Sicily, Italy [77]. Finally, these binders evidenced a wide versatility, considering the tests with foaming agents for the production of foamy paste [78] or the high fire resistance observed up to 1000 °C [79].

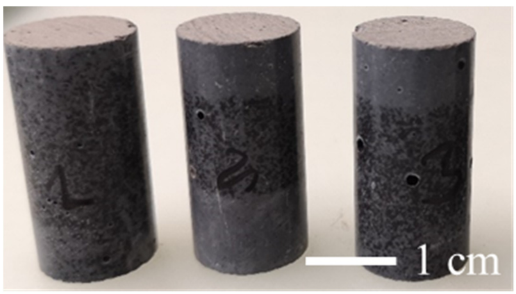

Figure 1. Example of cylindrical-shaped grey geopolymer samples based on volcanic ash of Mt. Etna volcano [74].

3.2. Methods

Currently, different factors hinder large-scale use of geopolymer concrete in the construction and restoration sectors (see [80] for a review of the relevant literature). Among them, there is its economic feasibility. Many papers have investigated the cost competitiveness of geopolymer concrete compared to traditional materials, showing that the former is usually more expensive, although the cost advantage/disadvantage depends on the mix design adopted (among others, [21,27,36,69,81]).

Indeed, estimating cost differential between geopolymer and OPC concrete is not straightforward, depending on the specific geopolymer formulation (e.g., type of precursors, activators and/or aggregates) and the characteristics of the production process (e.g., scale of production) [46,82,83]. However, restricting the benefits of replacing traditional clinker-based materials with geopolymer formulations only to the financial savings resulting from their production process seems a rather simplistic approach, which could lead to inappropriate policy choices. Indeed, the financial analysis does not consider all the benefits to society of such a replacement but restricts them only to those for the profit-maximizing producer. Specifically, the production and use of geopolymer concretes involve (environmental and not) social benefits (among others, the so-called externalities), that cannot be immediately translated into monetary units as they are not traded on the market (and thus do not have a market price). These intangible (non-market) benefits are neglected by financial analysis, despite the fact that they contribute to increasing the welfare of the society.

Therefore, to overcome these limitations, we have applied a broader economic and environmental perspective, which also includes (but is not limited to) financial aspects. In particular, we analyse the potential advantages for society, considering two categories of social benefits: (1) public finance savings from avoiding disposal of volcanic ash in landfills, assuming that the ash employed in the polymerization process is taken in situ immediately after an eruption (i.e., not excavated in quarries) and thus its supply cost is equal to zero; and (2) environmental and social benefits deriving from reduction in CO_2 releases due to the production process at room temperature of geopolymer materials. In doing this, we are largely aware of neglecting other (relevant) social benefits related to the use of an input of waste material such as volcanic ash. Among these, the advantages include a lower exhaustion of non-renewable natural raw materials (e.g., clay and limestone), lower congestion of existing landfills as well as the consequent lower need to foresee new ones and other indirect benefits on human health, which would be particularly demanding but out of the scope of this research.

The analysis of the overall social cost savings consists of two steps. The first step involves a financial analysis, which is the computation of the production costs of geopolymer pastes, and the estimate of the cost savings (in terms of avoided costs) for local governments resulting from the use (recycling) of volcanic ash as precursor. Via subtracting these cost savings from the production cost, we obtain the geopolymer's net social cost. As a second step, we compare CO_2 emissions from the production of volcanic ash geopolymers with those from the production of traditional clinker-based material, in order to quantify the environmental benefits for society in monetary terms. Figure 2 summarises the above steps of the analysis.

3.3. Data

The data used in this article are retrieved from different sources. Data on the costs of geopolymer production are first-hand data, collected as part of the AGM for CuHe project. In particular, data on production costs derive from the actual production of volcanic ash geopolymers (on a medium-scale) by the firms involved as partners in the project, while data on the cost of clinker-based cement correspond to the average market price. Data on the various cost items (i.e., sweeping, transport and landfill) associated with the disposal of volcanic ash and employed in this analysis refer to the year 2019 and are taken from the budgets and other public reports of two municipalities in the province of Catania, namely Mascalucia and Belpasso (Italy). These are among the few large municipalities in the foothills of Etna and among the most frequently involved in the fallout of eruptive material. Data on the quantity of volcanic ash fallen in the geographic area of the Metropolitan

City of Catania were drawn directly from the waste collection company "SRR Catania Metropolitana", which serves the 28 (out of 58) municipalities that constitute the zone most affected by the episodic fall of volcanic ash. Finally, data on CO_2 emissions from the production of volcanic ash geopolymers are taken from the AGM project, while data on cement production quantities and CO_2 emissions of cement firms in Eastern Sicily are directly drawn from the firms' websites and the European Pollutant Release and Transfer Register, respectively.

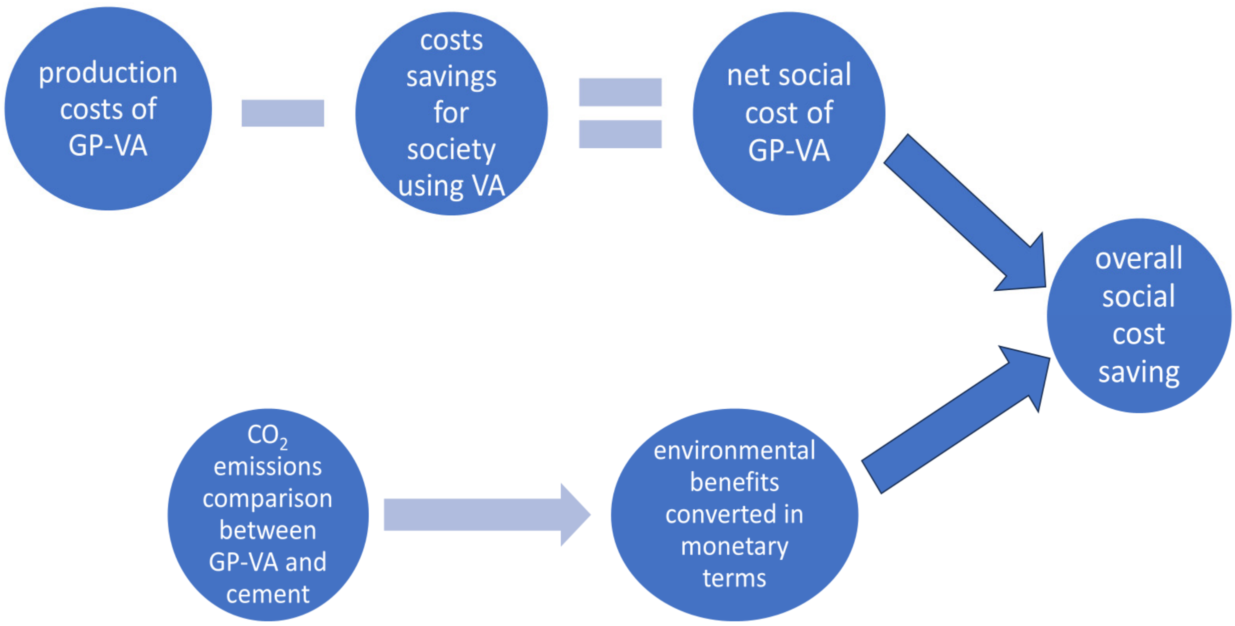

Figure 2. Steps of the analysis. Note: GP-VA = volcanic ash geopolymer.

4. Results and Discussion

4.1. Production Costs and Public Finance Savings

To properly appreciate the social relevance of the costs avoided thanks to the use of a waste material such as volcanic ash, we first consider the production costs of our geopolymer formulation, as they emerge from the financial analysis. Table 1 summarises the results and the underlying assumptions. Among the latter, a medium-scale production process that allows the production of 25 kg of geopolymer output in half an hour is considered. With reference to the inputs, as already mentioned, the supplying cost (net of transport) of the volcanic ash is set to zero, thus assuming that the volcanic ash is collected free of charge, directly from the sites where it falls following an eruption [84]. Based on the technical specification of producing the geopolymer in the AGM project (i.e., mix design proportions: volcanic ash, metakaolin, sodium hydroxide, sodium silicate and water), in computing the cost of labour we consider two workers, one skilled and one unskilled, employed for the entire duration of the production process (i.e., half an hour). Despite their different qualifications, we assume that the two workers receive the same salary of 27 EUR per hour (as specifically established by the financial agreement of the AGM for CuHe project to which this paper refers). After summing up all the direct cost items, adding a flat rate estimate of the overhead costs (15% of the direct costs) and considering a mark-up (+10% of total direct costs and overhead costs), we obtain a total cost of production that is slightly over 2 EUR/kg of geopolymer (Table 1). In addition, the latter can be lower if a higher amount of volcanic ash is used in substitution for metakaolin.

Table 1. Production costs of geopolymer pastes based on volcanic ash of Mt. Etna—medium scale (i.e., an output of 25 kg per cycle of production).

	Proportions (%)	**Cost per Kilo of Geopolymer**
Input (material) costs		
Volcanic ash	60.61	-
Metakaolin	15.15	EUR 0.2424
Sodium hydroxide	4.55	EUR 0.1365
Sodium silicate	14.39	EUR 0.0331
Water	5.3	-
Labour costs		
Skilled worker		EUR 0.54
Unskilled worker		EUR 0.54
Transportation costs		
Volcanic ash		EUR 0.04
Metakaolin		EUR 0.05
Sodium hydroxide		EUR 0.02
Sodium silicate		EUR 0.02
Energy and equipment (e.g., mixer, mill, tub) *costs*		EUR 0.04
Safety costs (+3% on the total production invoice costs)		EUR 0.05
Direct costs		EUR 1.71
Overhead costs (+15% of total direct costs)		EUR 0.26
Mark-up (+10% of total direct costs and overhead costs)		EUR 0.20
Total Cost of Production		EUR 2.17

Note: The cost of water has not been considered because it is negligible from a financial point of view.

The pie chart in Figure 3 depicts the percentages related to the different items that make up the overall production cost. The high incidence of labour costs (approximately 50%) is due to the medium-scale of the production process (25 kg of geopolymer output in half an hour) and would be substantially reduced in the case of industrial-scale production.

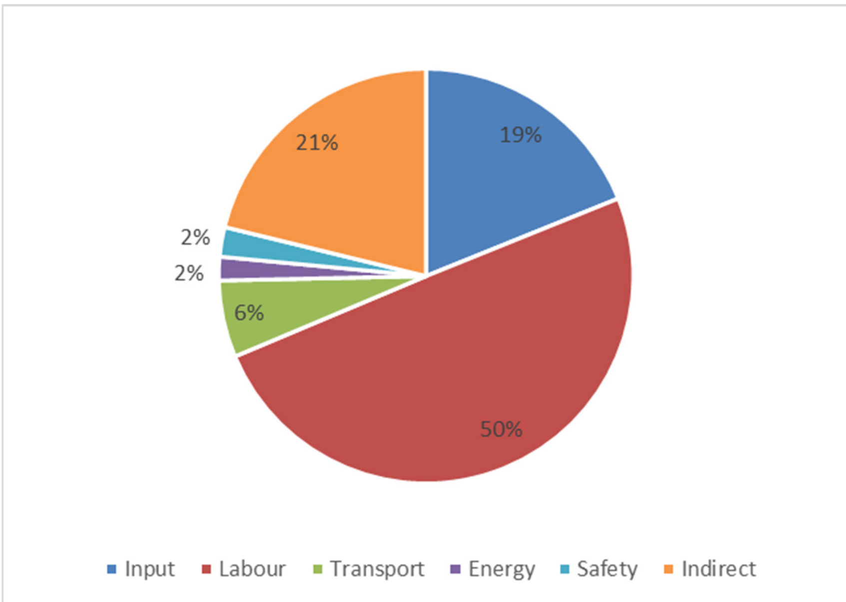

Figure 3. Different items (in percentage) of the overall production cost.

Secondly, we estimate the avoided costs associated with the use of the volcanic ash, which otherwise would have had to be collected and properly disposed of. These savings include the costs of sweeping, transport and landfilling of waste and represent a benefit for society to the extent that they are transformed into tax reductions or, for the same tax revenue, they free financial resources to be allocated to other public priorities.

As shown in Table 2, in the village of Mascalucia, the cost of sweeping the streets to free them from volcanic ash is equal to about 0.53 EUR/kg, while those for transport and disposal in landfills amount to a total of about 0.26 EUR/kg. Similarly, in Belpasso, the cost of sweeping is about 0.15 EUR/kg and those for transport and disposal in landfills are overall about 0.12 EUR/kg. As can be seen, there is some variability in costs, due to the different economic conditions obtained by the winning companies in tenders and, generally, only partly attributable to quality differences in the service management. To account for this variability, we decide to also consider the average costs of the two municipalities, thus obtaining an average total volcanic ash recovery cost of 0.53 EUR/kg.

Table 2. Municipality costs (EUR/kg) for the removal and disposal operations of Mt. Etna volcanic ash.

Municipality	Removal Cost (EUR/kg)	Transport and Disposal Cost (EUR/kg)	Total (EUR/kg)
Mascalucia	0.53	0.26	0.79
Belpasso	0.15	0.12	0.27
Average	0.34	0.19	0.53

Therefore, given that our reference geopolymer formulation includes around 61% volcanic ash (Table 1), the estimated social cost savings due to the re-utilization of volcanic ash in the production of geopolymer mortar varies from a minimum of about 0.16 EUR/kg of geopolymer (municipality of Belpasso) to a maximum of about 0.48 EUR/kg of geopolymer (municipality of Mascalucia), with an average of about 0.32 EUR/kg of geopolymer.

As a mere example, in the period between 16 February and 9 March 2021, over 267 tons of volcanic ash were removed in the Municipality of Catania. In the event that the above quantity had been all used in the production of geopolymers, the average overall cost saving for the public administration from avoiding ash sweeping, transport and disposal would have been equal to a total of 141,510 EUR or 0.48 EUR per resident inhabitant (population data refers to the 1 January 2021 and is taken from the Italian National Institute of Statistics—ISTAT). In return, about 438 tons of geopolymers based on volcanic ash would have been produced with the related environmental benefits. If we enlarge our analysis to the area of the Metropolitan City of Catania, 4031 tons of Etna ash were removed during the year 2021. In this wider scenario, the overall cost savings for the public administration from avoiding ash sweeping, transport and disposal would have been equal to a total of 2,136,430 EUR or 2.96 EUR per resident inhabitant. In return, about 6608 tons of geopolymers based on volcanic ash would have been produced with the related environmental benefits.

Lastly, considering the opportunity cost of the alternative use of inputs, we subtract from the total cost of production the estimated social cost savings thanks to the use of waste material as precursor. Therefore, we obtain the net social cost to produce our geopolymer paste, which ranges from a minimum of 1.69 EUR/kg (under the Mascalucia scenario) to a maximum of 2.01 EUR/kg (under the Belpasso scenario), with an average value of 1.85 EUR/kg (Table 3).

Table 3. Net social cost of geopolymer based on volcanic ash of Mt. Etna.

Scenario	Production Costs in Semi-Industrial Scale (per kg of Geopolymer)	Social Cost Savings (per kg of Geopolymer)	Net Social Cost (per kg of Geopolymer)
Mascalucia scenario	EUR 2.17	EUR 0.48	EUR 1.69
Belpasso scenario	EUR 2.17	EUR 0.16	EUR 2.01
Average cost scenario	EUR 2.17	EUR 0.32	EUR 1.85

4.2. Environmental and Social Benefits

As a second step of our analysis, we consider the use of our geopolymer formulation in the construction sector, to replace traditional cementitious (clinker-based) materials whose production is less environmentally friendly in relation to carbon emissions. We first estimate the environmental benefits of such a choice in terms of reducing the CO_2 footprint. As reported in the literature, the production process of 1 kg of clinker emits about 0.5 kg of CO_2, on average [4,58,69]. However, as far as our polymerization process is concerned, we limit the present analysis of CO_2 emissions only to activators (i.e., sodium silicate and sodium hydroxide), which, as previously explained, represent the most polluting components in the production of geopolymers [11,21,68,70]. As reported in Table 4, the overall CO_2 emissions of our geopolymer due to activators account for 111.06 g of CO_2 per kg of geopolymer produced. The comparison between the two production processes evidences a reduction of around 78% (i.e., 77.79%) of CO_2 emission compared to traditional cement materials, due to the lower CO_2 emissions of volcanic ash geopolymer, equal to 22.21% (Table 4).

Considering the latter environmental benefit and assuming a social cost for carbon dioxide of USD 51 (about EUR 48.4, at the exchange rate of 10 October 2023) per ton, the net social cost per kg of geopolymer (Table 3) would fall by about 0.019 EUR/kg.

In detail, starting from a total cost of production of 2.17 EUR/kg for our specific geopolymer formulation (see Table 3) and estimating an average overall social cost saving (including social savings from transport and disposal cost in the wt.% of the formulation and CO_2 reduction, i.e., 0.32 + 0.019) of 0.339 EUR/kg of geopolymer, we obtain an average net social cost of 1.831 EUR/kg of geopolymer.

It is worth highlighting that the above social cost of USD 51 for a ton of carbon dioxide was set by the Biden administration in the USA in February 2021, based on a previous estimate by the Obama administration (43 USD per ton), revalued at an inflation rate of 3% and is currently used in US policymaking. However, a revision of it is under study.

Table 4. Comparison between CO_2 emissions resulting from volcanic ash geopolymer production with those of traditional cement materials.

	Geopolymer Production			Cement Production
Type of Activator	CO_2 Emissions per kg of Activator	% of Activator	CO_2 Emissions per kg of Geopolymer	CO_2 Emissions per kg of Clinker
Sodium hydroxide	1100 g	4.55	50.05 g	-
Sodium silicate	424 g	14.39	61.01 g	-
Total	1424 g	18.94	111.06 g	500 g

Again, as a mere example, we can think of applying the last environmental benefit for society to the CO_2 releases in the air deriving from the production of cement in the eastern part of Sicily, the geographical area to which the previous data on the volcanic ash of Mt. Etna emissions refers. In the eastern part of Sicily, there are two cement companies: the Buzzi Unicem of Augusta and the Sicical of Melilli. According to the information published on their respective websites, the production capacity of the first cement plant is about

1,200,000 tons of cement per year, while that of the second, which is slightly smaller, is about 912,500 tons per year. Data on pollutant emissions from major industrial plants in Europe are routinely collected by the European Environmental Agency (EEA) under the Industrial Emissions Directive 2010/75/EU and the European Pollutant Release and Transfer Register Regulation (EC) No 166/2006. The cement plant of Augusta is among the 52,000 industrial installations yearly monitored for pollutant emissions and reported under the European Pollutant Release and Transfer Register (E-PRTR). For the year 2021, the CO_2 release for the cement production amounted to 510,117 tons. Under the hypothesis that the annual production of traditional cement materials had been replaced by our geopolymer concrete formulation, the CO_2 emissions would have been reduced by 396,806 tons, corresponding to a social benefit of around 19.20 million EUR/year. Unfortunately, data on CO_2 emissions are not available for the Melilli plant, but assuming that the two plants do not differ a lot in the amount of CO_2 released per kilogram of production, the expected CO_2 emissions would be 387,901 tons and the social benefit deriving from the reduction in CO_2 levels (301,738 tons less) as a result of the replacement of traditional cement with the volcanic ash-based geopolymer of the Mt. Etna volcano would reach approximately 14.60 million EUR/year.

5. Conclusions

This paper aims to enrich the existing literature focused on the physical and mechanical characterization of geopolymers based on the volcanic ash erupted by the Mt. Etna volcano (Italy). In detail, we quantify the social benefits in terms of avoided costs and the reduction in polluting CO_2 emissions resulting from the use of waste natural resources in the production of our geopolymers to replace less eco-friendly traditional materials. The main results of the work are the following:

- An average net social cost of 1.831 EUR/kg of geopolymer based on our case study formulation and produced on a medium (semi-industrial) scale. This cost would be lower if production took place on a full industrial scale, not differing much from that of traditional cement (approximately 1EUR per kg).
- A decrease in CO_2 emissions of approximately 78% with volcanic ash geopolymer production compared to that of the cement industry. The simulation carried out on two cement plants in Eastern Sicily, namely those of Augusta and Melilli, assuming the replacement of cement production with that of our geopolymer, showed significant social benefits in terms of reducing CO_2 emissions, quantified to be, respectively, 19.20 million EUR/year and 14.60 million EUR/year.

From a policy perspective, the results of our analysis can support policy makers to make informed decisions on the feasible production of geopolymers, based on economic and environmental sustainability issues.

However, our analysis is not without limitations. Indeed, the lack of some data has forced us to limit the environmentally relevant (social) benefits of this material class to those deriving from the reduction in CO_2 emissions and not, also, to those stemming from energy and water savings.

Regarding the avenues for further research, it would be interesting to: (i) replicate a similar circular economy approach to geopolymers based on other waste materials and from other geographical areas; (ii) estimate taxpayers' willingness to pay for geopolymer materials (e.g., using stated preference methods such as the contingent valuation approach), so as to guide policy makers (but also scientists) towards the adoption of socially and economically feasible solutions; and (iii) study the most appropriate (fiscal and non-fiscal) policies and schemes to incentivise the adoption of green technologies and materials, going beyond their mere financial cost but rather looking at the broader benefits for society.

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