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PERSPECTIVE

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Volcanic ash as multi-nutrient mineral fertilizer: Science and early applications

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Abstract

Volcanic ash is a multi-nutrient mineral fertilizer whose catalytic mechanism of action, replenishing trace metals are necessary for soil bacterial enzymes for the efficient biogeochemical cycling of key elements, such as N, C, P, and S, ensures use of relatively small amounts to fertilize large soil surfaces. Chiefly demonstrated in the course of the 2010 s in Russia's Kamchatka and in Indonesia, two world's areas hosting highly active volcanoes, these findings remain poorly known. Fulfilling the principles of the emerging circular economy, the large-scale use of readily available and overabundant tephra as agricultural fertilizer is a significant economic opportunity for both farmers and populations living near active volcanoes, affording also important environmental advantages. Providing a unified picture, this study will hopefully accelerate such progress.

KEYWORDS

circular economy, fertilizer, mineral fertilizer, soil conditioner, tephra, volcanic ash

INTRODUCTION

Volcanic soils are well-known for their exceptional fertility.[1] Typical of regions and countries such as Indonesia, Mexico, the Hawaiian Islands, Kamachatka peninsula, southern Italy, the Philippines and Japan, andisols (or andosols, from Japanese *ando* for "black soil") are highly fertile, volcanic soils derived from tephra/volcanic bedrock.[2] "The intermittent additions of volcanic ash renew the long-term fertility status of terrestrial ecosystems by providing a source of nutrients from the rapid weathering of volcanic deposits" reads one of the most cited book chapters on volcanic soils.[3] Yet, the deliberate use of volcanic ash as fertilizer is still generally limited (see below).

This is somehow surprising, given a number of relatively recent studies published in the 2010s in which its effectiveness as soil fertilizer and soil conditioner has been clearly demonstrated. For example, scholars in the USA showed as early as of 2012 that the addition of volcanic ash (basaltic ash from the 2004 Grimsvötn eruption and trachyandesite ash from the 2010 Eyjafjallajökull eruption) to simulated soil resulted into higher germination rates, higher growth rates, and produced fast growth grain plants that were healthier in appearance than the soil made from peat mixed with quartz sand.[4] Similar results were found 6 years later by scholars in Egypt, this time on a much larger scale, for potato crops grown in soils fertilized with volcanic ash from Indonesia's Papandayan volcano collected in early 2015 which is used as solid fertilizer and conditioner.[5]

In 10 years, the 2012 conference communication[4] mentioned above has been cited only nine times. The study from Egypt,[5] in its turn, to date (early 2022) has not yet been cited, regardless being an open access study which ensures unrestricted access and a significantly higher number of citations when compared to paywalled journals.[6]

Information of practical value is scarce, scattered, and generally not updated. For example, a search on two large research databases with the query "Volcanic ash as soil fertilizer" did not return any result as of late March 2022.[7]

Accordingly, farmers harvesting crops in open field and greenhouses are generally not aware of its fertilization potential. On the other hand, populations living nearby active volcanoes are aware of the fertilization potential of both volcanic ash and crushed lava stones, even though in addition to positive effects temporary negative effects such as hydrophobicity of coated surfaces due to newly deposited ash, as well as dirt accumulation and small damage to the built environment are also observed.

For example, "natural plant granules made of lava and broken swelling clay for cacti and succulent plants" are sold online in Germany at €0.91/L in 7 L batches as alternative to potting soil.[8] In Sicily, on the other hand, the powder residue of Mount Etna's lava stone processing is sold as soil fertilizer and plant reinforcing agent at €30 for a 20 kg bag (namely at €1.5/kg rate).[9]

In general, rather than being collected and supplied to farmers, volcanic ash falling on roads, squares, and buildings is collected and disposed off as waste at high economic cost. For instance, to remove the ash in the built environment of 42 cities hit by Etna's ash emissions on March 2022, Sicily's government estimated an expense of at least €15 million.[10]

Volcanic ash is a multi-nutrient mineral fertilizer whose catalytic mechanism of action, replenishing trace metals necessary for soil bacterial enzymes for the efficient biogeochemical cycling of key elements such as N, C, P, and S, ensures use of relatively small amounts to fertilize large soil surfaces. Chiefly demonstrated in the course of the 2010s in Russia's Kamchatka and in Indonesia, two world's areas hosting highly active volcanoes, these findings are still poorly known not only amid people living near large active volcanoes, but also in the scholarly community.

Fulfilling the key principle of the emerging circular economy to reuse materials previously considered waste, the use of readily available and overabundant volcanic ash as agricultural fertilizer is a significant economic opportunity for both farmers and populations living nearby active volcanoes, affording also important environmental advantages. Providing a unified picture, this study will hopefully accelerate such progress.

A MULTI-NUTRIENT MINERAL FERTILIZER

During explosive volcanic eruptions, along with pyroclastic rocks (size > 256 mm), lapilli (2–64 mm), fine blocks (angular to subangular clasts, 64–256 mm), and fine bombs (rounded to subrounded clasts, 64–256 mm) alongside volcanic ash (VA) microparticles of different size and shape are released into the atmosphere.[11]

The larger VA particles (d > 63 μm) settle in a few hours as particle aggregates that cumulatively have larger sizes, lower densities, and higher terminal fall velocities than individual constituent particles;[12] whereas the fine ash particles (d < 63 μm) settle in days and months, being transported up to thousands of kilometers away from the eruptive crater.[13]

Depending on individual magma properties (including composition, rheology, and gas content), volcanic ash is generally comprised of about 50% in weight silica (basalt igneous rock type, 48.5%) up to ~80% SiO_2 content for ehyolite rock type.[14] In other words, the geochemistry of the ash can be quite different from rhyolite to basalt depending on the volcano. We briefly remind that volcanic ash is chemically classified based on the total alkali (Na_2O and K_2O) and silica content into the main igneous rock types basalt, basaltic-andesite, andesite, dacite, and rhyolite.[15] Fertilizers based on slag silicate started to be used in Europe in the Middle Age. Silicon (Si) provides substantial beneficial effects on growth and yield, especially in plants under stressful environments, enhancing plant resistance to fungal and bacterial diseases and insect pest damage.[16]

TABLE 1 Elemental compositions of volcanic ash from Indonesia's Papandayan volcano used to fertilize potato tuber growth in Egypt's soil by Mahmoud and co-workers (reproduced from Reference 5, with kind permission)

Element	Soil (%)	Volcanic ash (%)
Si	45.68	48.00
Al	16.67	14.00
K	1.85	2.45
Na	2.79	3.24
Fe	10.65	9.05
P	0.34	0.13
Mg	0.45	1.13
Ca	0.33	1.50
Ti	0.49	0.63

TABLE 2 Nutrient content in potato tubers from Egypt's soil fertilized with volcanic ash from Indonesia's Papandayan volcano, and with potassium sulphate (control). (reproduced from Reference 5, with kind permission)[a]

Control (K_2SO_4)	Volcanic ash
N (1.92%)	N (1.08%)
P (0.19%)	P (0.30%)
Ca (0.04%)	Ca (0.07%)
K (2.46%)	K (3.06%)
Mg (0.05%)	Mg (0.07%)
Na (0.00)	Na (0.03%)
SO_4 (0.46%)	SO_4 (0.65%)
Cu (9.20 mg/g)	Cu (11.00 mg/g)
Fe (53.00 mg/g)	Fe (46.00 mg/g)
Mn (13.00 mg/g)	Mn (41.50 mg/g)
Zn (20.00 mg/g)	Zn (34.60 mg/g)

[a]Tuber samples picked at harvesting time (115 days after plantation).

A quick look at the composition of VA from Indonesia's Papandayan volcano,[5] which includes MgO and CaO amid the alkali components, used to fertilize potato tuber growth by Mahmoud and co-workers in 2018 suggests its immediate relevance to agriculture.

In closer detail, Table 1 shows that beyond Si and Al components of aluminosilicates in silica and alumina, the four common alkali metals and alkaline earth metals K, Na, Ca, and Mg are present in higher concentration in tephra than in soil. In contrast (not shown in Table 3) the concentrations of Cr (0.033 mg/g) and Ni (0.010 mg/g) in VA are lower than those found in soil (0.041–0.019 mg/g respectively).

The fact that the former mineral nutrients in VA are highly bioavailable is shown by the outcome that their content in potato tuber was significantly higher (Table 2), Furthermore, showing evidence of enhanced activity of the soil enzymes making bioavailable the

TABLE 3 Nitrate and starch in potato tubers grown in soil fertilized with different amounts of ocherous (ash_{old}) and fresh (ash_f) volcanic ashes and NPK commercial fertilizer. (adapted from Reference 18, with kind permission)[a]

Experimental options	Nitrate (mg/g)	Starch (%)
No fertilizer (control)	182.0	11.00
$Background_1$ ($N_{120}P_{120}K_{120}$)	213.8	10.20
$Background_1 + ash_{old}$ 2.5 t/ha	347.3	10.70
$Background_1 + ash_{old}$ 5.0 t/ha	281.8	10.70
$Background_1 + ash_f$ 2.5 t/ha	257.8	10.50
$Background_1 + ash_f$ 5.0 t/ha	338.8	11.00
$Background_1 + ash_f$ 7.5 t/ha	446.7	10.20
No fertilizer (control)	133.0	11.20
$Background_2$ ($N_{60}P_{60}K_{60}$)	180.2	11.20
$Background_2 + ash_{old}$ 2.5 t/ha	190.5	11.50
$Background_2 + ash_{old}$ 5.0 t/ha	138.0	11.90
$Background_2 + ash_f$ 2.5 t/ha	168.0	11.50
$Background_2 + ash_f$ 5.0 t/ha	183.4	11.00
$Background_2 + ash_f$ 7.5 t/ha	184.8	10.70

[a]$Background_1$ = addition of mineral fertilizers in the dose $N_{120}P_{120}K_{120}$; $Background_2$ = addition of mineral fertilizers in the dose $N_{60}P_{60}K_{60}$.

nutrients contained in soil, all nutrients with exception of nitrogen and iron, were significantly higher in potato tubers from soil fertilized with tephra.

Reporting also the significant increase in the humidity of soil added with volcanic ash, the scholars concluded that tephra can be safely used not only to enhance the soil fertility but also its properties as soil conditioner.[5]

Six years before, noting that few studies had been published examining the effects of the addition of volcanic ash to soils immediately after an eruption, volcanologists Edwards and Seward in the USA conducted a nearly 6-week growth experiment in controlled environment using fast growing grain seeds as a test crop. In detail, peat was mixed in known but systematically differing proportions with commercial quartz sand, basaltic ash from the 2004 Grimsvötn eruption, and trachyandesite ash from the 2010 Eyjafjallajökull eruption.[4] For all experiments, the seeds growing in the simulated soil created with the two different composition volcanic ash had higher germination rates, higher growth rates, and produced plants that were healthier in appearance than the soil made from peat mixed with quartz sand.

Concluding that long-term studies were important to document how changes to ash during pedogenesis might affect long-term soil structure and fertility, the scholars highlighted the benefits of fresh volcanic ash as a fertilizer whose use in soil fertilization could "lower the cost of raising crops in countries disrupted by explosive volcanic eruptions"[4] turning a "short-term negative associated with volcanic eruptions (ash fall) into a societal benefit (local source of inexpensive fertilizer)".[4]

In the subsequent decade, the study (a conference communication) received nine citations.[17] Among the citing studies, however, one in 2016 by Zakharikhina and co-workers in Russia reported the outcomes of the first open field agricultural experiments with potatoes grown in soil fertilized with volcanic ash from Kamchatka in combination with traditional mineral fertilizers in ochreous volcanic soils.[18]

In detail, both freshly fallen VA from the volcano Shiveluch, and VA from ochreous soils were applied in soils at a rate of 2.5–7.5 t/ha (amounts of ash comparable to those deposited on soil during a weak ordinary ash fall), in combination with traditional NPK mineral fertilizer containing the basic nutrient elements nitrogen, phosphorus, and potassium at rates of 120–60 kg/ha.

Table 3 shows that after the first year in which fresh VA was used in combination with different doses of commercial NPK fertilizer an average increase in potato yield of 47% was observed (varying between 31% and 63%). A similar average 52% increase was observed in the case of using tephra from ocherous horizons (varying between 37% and 72% for different experimental options).

The finding was ascribed to the richer chemical composition of ocherous old ashes compared with fresh ashes. Surprisingly, a higher yield increase was achieved when the amount of NPK fertilizer was halved from the 120 kg/ha rate conventionally used in Kamachatka to 60 kg/ha, with the average yield increase going from 37% to 62%.

Taking into account the low amounts of VA added to soil (between 2.5 and 7.5 t/ha, namely between 250 and 750 g/m^2), the scholars concluded that the greater potato yields and increased concentration of starch in potato tubers by 3%–5% was not due to the additional nutrients, but rather to the catalytic activity of the numerous metals present in trace amount in VA which improve microbiological processes in the soil.

According to this hypothesis, the presence of trace elements such as Mn, Zn, Mo, Cu, Fe would accelerate the development and reproduction of bacterial cells in soil microflora, which in its turn releases enzymes into the soil dissolving and making bioavailable mineral salts as valued nutrients assimilated by plants.

The effect of volcanic ash addition on soil enzyme activity has not yet been studied, but it is well-known that soil microorganisms and soil enzymes crucially affect soil fertility due to their key role in the biogeochemical cycling of elemental nutrients such as carbon, nitrogen, sulfur, and phosphorus.[19] Furthermore, the study of the enzyme activity in Chilean andisols has shown very high activity in soils undertaking no tillage.[20]

The aforementioned remarkable findings[18] were published in *The Journal of Volcanology and Seismology*, a paywalled journal owned by a publisher of English translations of scientific and technical journals first published in Russian, Chinese, and Japanese. These journals, unfortunately, have a relatively small readership in other countries.

The team led by Zakharikhina and Litvinenko continued the researches and published two works on volcanism and the geochemistry of the soil and vegetation in Kamchatka,[21,22] followed by a study

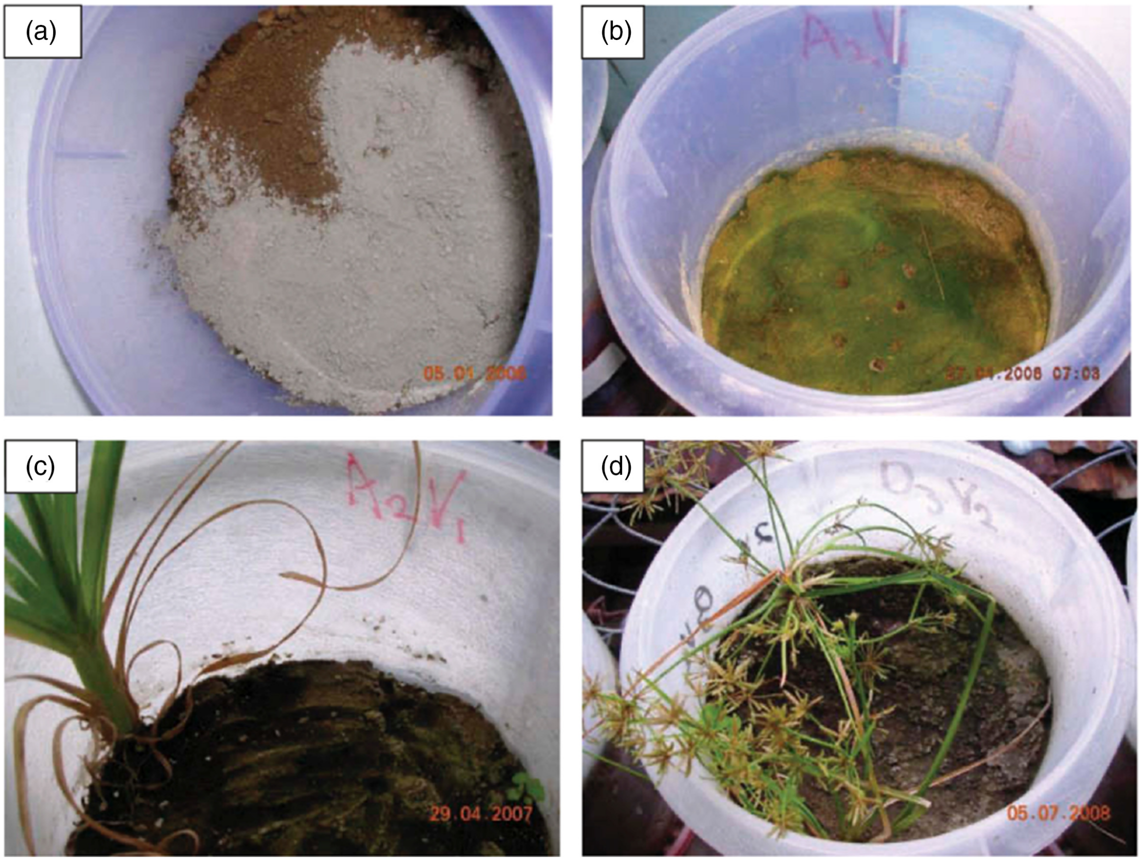

FIGURE 1 (a) Mount Talang's tephra applied on the surface of soil; (b) surface of tephra layer after 4 months; (c) surface of the 2.5 cm tephra layer after 16 months; (d) surface of the 5.0 cm tephra layer after 18 months. (reproduced from Reference 25, with kind permission).

(in Russian) identifying volcanic ash as a broad-scope fertilizer capable to enhance the bioproductivity of soils.[23] Therein, the team reported the outcomes in growing the yield of annual forage grasses in soils fertilized with tephra. Alongside an increase in yield by 32%, a rise in the content of raw protein was observed thereby confirming the catalytic mechanism of action mentioned above. In addition to increasing the yield of agricultural crops in forage grasses, indeed, after harvesting the soil showed an increase in the content of mobile phosphorus by 7%–21%, of potassium by 16%–77%, and an increase in the degree of soil saturation with bases by 9.27%. Relative to the background, an increase in the content of mobile Co (by 32%), Mn (by 29%), S (by 20%), Zn (by 23%), and Cu (by 8%) was also found.[23]

Finally, in 2021 the Russian scholars introduced a potential fertility index (PFI) defined as the ratio of the cumulative concentrations of chemical elements in the ash relative to their overall concentrations in the soil ($PFI = \sum Ci_{va}/Ci_{soil}$).[24] Confirming empirical findings for which more basic ashes lead to better fertilization, the team revealed a reverse relationship between PFI and the concentration of SiO_2 in the ash. The higher the basicity of an ash (lower silica content), the higher its potential fertility index.

Around the same years, a number of key findings concerning the use of tephra as fertilizer were independently reported by an international team led by Faintis in Indonesia. Using fresh tephra collected immediately after eruption of Mount Talang on 12 April 2005 in West Sumatra the team discovered that tephra plays indeed a crucial role in capturing carbon from the atmosphere via primary plant succession and new soil formation commencing after tephra deposition.[25] In other words, the weathering of the ash (minerals) not only releases nutrients, but also involve decarbonization process, Ca^{2+} will take CO_2 molecules in the air which is being deposited in the soil or transported in the river system.

In detail, tephra was applied in 0, 2.5, and 5 cm thick layers to simulate natural tephra deposition, watering every day with 250 ml of water allowed it to percolate over a period of 4 years. After 2 months, blue-green algae (cyanobacteria) started to colonize the bare surface tephra layer to form an algae mat. After 4 months, the surface was transformed into a green biofilm of lichen (Figure 1).

Finally, after 24 months, vascular plants (grasses and shrubs) started to grow. The matrix of tephra color changed gradually with time from light gray to very pale brown and then to pale brown, approaching the color of soil, due to liberation of Fe and accumulation of organic carbon.

The highest organic carbon content, 1.22%, was found in the 2.5 cm tephra layer with the soil underneath after 46 months of incubation.[25] This seminal work demonstrated that newly deposited tephra could accumulate soil organic carbon capturing CO_2 from the atmosphere through pioneer vegetation at very high rate of 1.8–2.5 t

CO_2 per ha per year through the establishment of lichens and vascular plants.

Fiantis' team continued its pioneering researches and eventually published a paper on applying volcanic ash to croplands seen as "the untapped natural solution",[26] calling countries with active volcanoes to use tephra to supply nutrients and reduce CO_2 from the atmosphere as "volcanic ash with 0% carbon can turn into soils with around 10% organic carbon".[26]

OUTLOOK AND PERSPECTIVES

Volcanic ash is a versatile and effective multi-nutrient mineral fertilizer whose catalytic mechanism of action is based on the supply of trace metals to the soil microflora involved in the biogeochemical cycling of elemental nutrients, such as carbon, nitrogen, sulfur, and phosphorus.[18] First proposed by Zakharikhina and Litvinenko, this mechanism allows to use small amounts (between 2.5 and 7.5 t/ha, namely between 250 and 750 g/m^2)[18] to fertilize huge soil surfaces.

Thoroughly demonstrated in the course of the 2010s chiefly with experiments carried out in Russia's Kamchatka[18,21] and in Indonesia,[25,26] two world's areas hosting highly active volcanoes, these findings are still poorly known by populations living near large active volcanoes, and also in the scholarly community.

De Beaumont in 1855 and Ricciardi in 1881 ascribed the fertility of Mount Vesuvius and Mount Etna soils to the abundance of alkali metals and phosphoric anyhydride.[27] One century later, d'Hotman de Villiers in 1961 suggested the use of volcanic basalt dust as a soil amendment for soil rejuvenation using sugarcane as the test crop after a series of long-term field trials in Mauritius, though at high applied rates varying from 200 to 400 t/ha.[28]

The study of volcanic ash as a mineral fertilizer thus offers another example of scientific findings of large (and global) societal and environmental relevance that remained of limited interest for decades until rediscovery. To remain in the chemistry and life science fields, examples span from the antimicrobial activity of pectins[29] through the rediscovery of cyanobacteria as sources of valuable bioactive compounds.[30]

On small scale, the practical use of VA as multi-nutrient mineral fertilizer is increasing. In the digital era in which more than 4 billion people regularly use the internet to share information, residents living around active volcanoes started to share videos on its practical utilization. Examples include farmers living near Mount Etna,[31,32] in Sicily, or near the Taal volcano in the Philippines.[33] Similarly, in 2016 Costa Rica's tv broadcasted the news that the ashfall of Turrialba's eruption was being sold as fertilizer.[34]

Several small companies in Europe, North and South America, already commercialized powdered "lava stone",[9] "granules made of lava and broken swelling clay",[8] "volcanic rock dust" sold at \$20 per 20 kg bag,[35] or directly the ash freshly collected during or right after the eruption.[34] Using volcanic ash, there is no need to use lava fine particles obtained by lava stone so that 95% or more of the lava stone has a particle size of 10–500 μm.[36]

During large eruptions, crop plants cultivated in of areas reached by large ashfall including bombs and lapilli are readily lost. This is not the case for more distant plants that are reached by volcanic ash in relatively low amount (Herculaneum was completely buried under several m of tephra and pumice during the famous eruption of Mount Vesuvius in 79 AD).

Besides the aforementioned direct physical damage to crops, volcanic eruptions are not harmful to agricultural activity. This has been clearly shown, for instance, by the recent 2021 volcanic eruption on the island of La Palma, in the Canary Islands, where thousands of hectares host banana plantations. No heavy metal or rare earth element contamination was observed.[37] For example, even in the worst-case scenario (higher consumption of the fruit), Mo concentrations in banana flesh translate into a higher nutritional intake of this trace element up to 35% of the daily nutritional intake requirement, and not exceeding 5% of the tolerable daily intake for toxic and potentially toxic metals would be observed (most metals indeed remain entrapped in the banana skin rich in pectin, which binds and sequesters most metal ions).[37]

Besides the top five countries with most active volcanoes (USA, Indonesia, Russia, Japan, and Chile), many countries host active volcanoes.[38] It will be enough to collect the tephra abundant along the slopes of active volcanoes or accumulated in the built environment during large eruptions and use it to confer the huge benefits of VA fertilization to distant soils. Noticeably, the idea in case of large eruptions to transport VA to areas of weathered soils for soil rejuvenation was first proposed by Indonesian scholars as early as of 2016.[39]

Yet, 5 years later Fiantis was continuing to observe that "tephra is not widely used and has not been adequately investigated".[26] To answer the question why large-scale use of VA as soil mineral fertilizer is not yet a reality, the role of poor and misleading information amid companies and entrepreneurs should not be undervalued.

For instance, in 2019 reports in reputed scientific journals cited data going back to 2010 for which lithium-ion batteries were recycled at a meager rate, while globally 58% of the world's spent lithium batteries were already recycled.[40] It is said that misleading information on lithium battery recycling, still frequently found in the general press today, has delayed the development of the recycling industry beyond China.

Most fertilizer company managers and agronomists will be surprised to learn that a company in North America successfully commercializes an agricultural fertilizer and soil amendment product mined from an ancient volcanic ash deposit in Utah in the form of highly mineralized complex silica ore sold for more than 70 years to support plant growth and vitality.[35]

From greenhouse tomato (79% increased yield and far higher nutritional compounds in the tomato) and potato (10% increased yield in salable potatoes) through wine grape (3.5% increased yield and 20.6% increased Brix) and wheat (7.2% increased yield), the company's website hosts numerous studies reporting the effects of its use on the growth of different crops.[41]

Besides high cost, it is now clear that synthetic mineral fertilizers cause several problems to soils and water bodies,[42] including reduction of the humus content and biodiversity in the soil, heavy metal accumulation, soil acidification, and eutrophication of the water bodies.

Fulfilling the key principle of the emerging circular economy calling for the valorization in the production of goods of inorganic and organic materials previously dealt with as waste,[43] the use of readily available and overabundant volcanic ash as multi-nutrient fertilizer to be used in moderate amount is a significant economic opportunity for both farmers and populations living near active volcanoes.

As clearly noted by the pioneering researchers in the field,[4,5,18,24,26] its large-scale use will bring about also significant environmental advantages especially in combination with new generation organic fertilizers such as those obtained from biowaste.[44] Providing a unified picture from scattered and poorly known research findings, this study will hopefully accelerate such progress.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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REFERENCES

1. Dahlgren RA, Saigusa M, Ugolini FC. The nature, properties and management of volcanic soils. Advances in agronomy. Volume 82. Cambridge, MA: Academic Press; 2004. p. 113–82. https://doi.org/10.1016/S0065-2113(03)82003-5
2. Wada K. The distinctive properties of andosols. In: Stewart BA, editor. Advances in soil science. Advances in soil science. Volume 2. New York: Springer; 1985. https://doi.org/10.1007/978-1-4612-5088-3_4
3. Ref.1, p.116.
4. Seward W, Edwards B. Testing hypotheses for the use of Icelandic volcanic ashes as low cost, natural fertilizers. Geophys Res Abstr. 2012;14:11493. European Geosciences Union General Assembly 2012, Vienna, 22–27 April 2012.
5. El-Desoky AI, Hassan AZA, Mahmoud AM. Volcanic ash as a material for soil conditioner and fertility. J Soil Sci Agric Eng. 2018;9:491–5. https://doi.org/10.21608/jssae.2018.36445
6. Razumova IK, Kuznetsov A. Impact of open access models on citation metrics. J Inf Sci Theory Pract. 2019;7:23–31. https://doi.org/10.1633/jjstap.2019.7.2.2
7. Search carried out on Dimensions (https://app.dimensions.ai/) and on Google Scholar (scholar.google.com) on March 17, 2022, including citations and patents amid the searched online items.
8. Seramis, Spezial Substrat für Kakteen und Sukkulenten, Mogendorf, Germany: 2022. The product is sold online via several e-shop partners. For example, via amazon.de: https://amzn.to/3if7FZV. Accessed 17 March 2022.
9. d'Arte T. Terra Silt – Farina di roccia lavica utile nel compostaggio – fertilizzante. Italy: Misterbianco; 2022. https://eshop.terradarte.it/prodotto/terra-silt-farina-di-roccia-lavica-utili-nel-compostaggio-fertilizzante/. Accessed 17 March 2022.
10. Pioggia di cenere vulcanica: la Regione delibera lo stato di crisi per 43 Comuni. Himera live, 12 March 2021. https://www.himeralive.it/2021/03/12/la-regione-delibera-lo-stato-di-crisi-per-43-comuni-foto/. Accessed 17 March 2022.
11. Mackie S, Cashman K, Ricketts H, Rust A, Watson M, editors. Volcanic ash. Amsterdam: Elsevier; 2016.
12. AJ Durant, R Brown, C Bonadonna. Volcanic ash aggregation: a new classification scheme, American Geophysical Union, Fall Meeting 2012. https://ui.adsabs.harvard.edu/abs/2012AGUFM.V53H.05D
13. Bonadonna C, Ernst GGJ, Sparks RSJ. Thickness variations and volume estimates of tephra fall deposits: the importance of particle Reynolds number. J Volcanol Geotherm Res. 1998;81:173–87. https://doi.org/10.1016/S0377-0273(98)00007-9
14. Vogel A, Diplas S, Durant AJ, Azar AS, Sunding MF, Rose WI, et al. Reference data set of volcanic ash physicochemical and optical properties. J Geophys Res Atmos. 2017;122:9485–514. https://doi.org/10.1002/2016JD026328
15. Le Bas MJ, Streckeisen AL. The IUGS systematics of igneous rocks. J Geol Soc Lond. 1991;148:825–33. https://doi.org/10.1144/gsjgs.148.5.0825
16. Liang Y, Nikolic M, Bélanger R, Gong H, Song A. History and introduction of silicon research In silicon in agriculture. Dordrecht: Springer; 2015. p. 1–18. https://doi.org/10.1007/978-94-017-9978-2_1
17. Search carried out on Google Scholar (scholar.google.com) on March 21, 2022, including citations and patents amid the searched online items.
18. Zakharikhina LV, Litvinenko YS, Ryakhovskaya NI, Gainatulina VV, Arguneeva NY, Makarova MA. The geochemical transformation of natural soils and enhancement of agricenosis productivity due to volcanic ejecta entering the soil. J Volcanol Seismol. 2016;10:203–17. https://doi.org/10.1134/S0742046316030064
19. Yang L, Zhang Y, Li F. Soil enzyme activities and soil fertility dynamics. In: Srivastava A, editor. Advances in citrus nutrition. Dordrecht (the Netherlands): Springer; 2012. https://doi.org/10.1007/978-94-007-4171-3_11
20. Rosas A, López A, López R. Behavior of enzymatic activity in Chilean volcanic soil and their interactions with clay fraction. In: Shukla G, Varma A, editors. Soil Enzymology. Soil Biology. Volume 22. Berlin: Springer; 2010. https://doi.org/10.1007/978-3-642-14225-3_17
21. Zakharikhina LV, Litvinenko YS. Volcanism and the geochemistry of soil and vegetation in Kamchatka. Part 1. Some geochemical features of near-surface volcanic ashes. J Volcanol Seismol. 2019;13:96–106. https://doi.org/10.31857/S0203-03062019234-44
22. Zakharikhina LV, Litvinenko YS. The volcanism and the geochemistry of the soil and vegetation in Kamchatka. Part 3. The elemental composition of vegetation in volcanic ecosystems. J Volcanol Seismol. 2019;13:235–45. https://doi.org/10.31857/S0203-03062019440-51
23. Zakharikhina LV, Litvinenko YS, Gainatulina VV, Arguneeva NY, Makarova MA, Bredu OV. Volcanic ashes of Kamchatka as a potential source to enhance the bioproductivity of soils. Agrokhimiya. 2020;4:66–75. https://doi.org/10.31857/S0002188120040134
24. Zakharikhina LV, Rashidov VA, Anikin LP. The geochemistry and potential fertility of volcanic ash discharged by Alaid and Ebeko volcanoes. Kuril Islands J Volcanolog Seismol. 2021;15:333–48. https://doi.org/10.1134/S0742046321050079
25. Fiantis D, Nelson M, Shamshuddin J, Boon Goh T, Van Ranst E. Initial carbon storage in new tephra layers of Mt. Talang in Sumatra as affected by pioneer plants. Commun Soil Sci Plant Anal. 2016;47:1792–812. https://doi.org/10.1080/00103624.2016.1208755

26. Minasny B, Fiantis D, Hairiah K, Van Noordwijk M. Applying volcanic ash to croplands - the untapped natural solution. Soil Secur. 2021;3: 100006. https://doi.org/10.1016/j.soisec.2021.100006
27. É de Beaumont (1855), S. Ricciardi (1881) cit. In: O. Comes, Le lave, il terreno vesuviano e la loro vegetazione. Stabilimento Tipografico Vesuviano, Portici: 1888.
28. (a) d'Hotman de Villiers O. Soil rejuvenation with crushed basalt in Mauritius. Part I - the fertility of basalt and its nutritional effects. Int Sugar J. 1961;63:363–4. (b) d'Hotman de Villiers O. Soil rejuvenation with crushed basalt in Mauritius. Part II: fertility of basalt and nutritional effects. Int Sugar J. 1962;64:3–5.
29. Ciriminna R, Fidalgo A, Meneguzzo F, Presentato A, Scurria A, Nuzzo D, et al. Pectin: a long-neglected broad-spectrum antibacterial. ChemMedChem. 2020;15:2228–35. https://doi.org/10.1002/cmdc.202000518
30. Prasanna R, Sood A, Jaiswal P. Rediscovering cyanobacteria as valuable sources of bioactive compounds (review). Appl Biochem Microbiol. 2010;46:119–34. https://doi.org/10.1134/S0003683810020018
31. S Filoramo. Utilizzare la cenere vulcanica come fertilizzante. 22 December 2015. See at the URL: https://www.youtube.com/watch?v=aPa24V7FoCk. Accessed 21 March 2022.
32. G Torresino. Etna mi ha regalato tanta cenere per concimare l'orto. 14 December 2020. See at the URL: https://www.youtube.com/watch?v=bNSf7uIgyps. Accessed 21 March 2022.
33. T Potter. Taal volcanic ashfall as good fertilizer for plants. 19 January 2020. See at the URL: https://www.youtube.com/watch?v=srv3mSX3zl8. Accessed 21 March 2022.
34. Noticias Repretel. La ceniza del Turrialba se está comercializando. 26 May 2016. See at the URL: https://www.youtube.com/watch?v=ktxONyjHyD4. Accessed 21 March 2022.
35. Azomite (micronized). BuildaSoil.com (2022). https://buildasoil.com/products/azomite?rfsn=1326067.ced3b2&variant=1838027472914. Accessed 25 March 2022.
36. F Takei. Fertilizer including lava powder and soil conditioner JP2014111518A, (2014).
37. Rodríguez-Hernández Á, Díaz-Díaz R, Zumbado M, del Mar Bernal-Suárez M, Acosta-Dacal A, Macías-Montes A, et al. Impact of chemical elements released by the volcanic eruption of La Palma (Canary Islands, Spain) on banana agriculture and European consumers. Chemosphere. 2022;293:133508. https://doi.org/10.1016/j.chemosphere.2021.133508
38. Smithsonian Institution. Global Volcanism Program. https://volcano.si.edu/faq/index.cfm?question=countries. Accessed 30 September 2022.
39. Anda M, Suparto SR. Characteristics of pristine volcanic materials: beneficial and harmful effects and their management for restoration of agroecosystem. Sci Total Environ. 2016;543:480–92. https://doi.org/10.1016/j.scitotenv.2015.10.157
40. Pagliaro M, Meneguzzo F. Lithium battery reusing and recycling: a circular economy insight. Heliyon. 2019;5:e01866. https://doi.org/10.1016/j.heliyon.2019.e01866
41. Azomite. https://azomite.com. Accessed 30 September 2022.
42. Ashitha A, Rakhimol KR, Mathew J. Fate of the conventional fertilizers in environment. In: Lewu FB, Volova T, Thomas S, Rakhimol KR, editors. Controlled Release Fertilizers for Sustainable Agriculture. Cambridge (MA): Academic Press; 2021. p. 25–39. https://doi.org/10.1016/B978-0-12-819555-0.00002-9
43. Velenturf APM, Purnell P. Principles for a sustainable circular economy. Sustain Prod Consum. 2021;27:1437–57. https://doi.org/10.1016/j.spc.2021.02.018
44. Muscolo A, Mauriello F, Marra F, Calabrò PS, Russo M, Ciriminna R, et al. AnchoisFert: a new organic fertilizer from fish processing waste for sustainable agriculture. Global Chall. 2022;6:2100141. https://doi.org/10.1002/gch2.202100141

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