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A review of the sustainable contributions of the use of some mine wastes in soil improvement and as fertilizer in agriculture

Abbreviation list

BW – Boron waste,	Pb – Lead,
CEC – Cation exchange capacity,	PG – Plant growth,
Cu – Copper,	REE – Rare earth element,
Fe – Iron,	S – Sulfur,
IW – Industrial waste,	SRF – Slow-release fertilizer,
K – Potassium,	SDGs – Sustainable Development Goals,
Mg – Magnesium,	SF – Soil fertility,
MW – Mine waste,	TM – Termomagnezyum,
N – Nitrogens,	WP – Waste pyrite,
P – Phosphorus,	WR – Water retention,
P _m – Phosphate,	Zn – Zinc.

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Introduction

Human actions can degrade soils in a very short time (Jie et al. 2002) and increase the scarcity of these resources (Epelde et al. 2019). On the other hand, the global economy is increasingly dependent on finite mineral resources (Maisel et al. 2023; Yıldız 2025a). Advances in science and technology have continuously increased the consumption of mineral resources, which are the basis for economic development, industrial expansion, urbanization, and population growth. These processes are highly dependent on the mining industry (Yıldız 2021). The rapid increase in demand for mineral resources leads to various environmental consequences (Yıldız et al. 2016). At this point, there is a need to reduce MW and use it in sustainable practices to ensure environmentally sensitive and feasible sustainable mining (Yıldız 2020a, 2024a, 2024b). Legislation is being developed for this purpose (Yıldız et al. 2024a; García and Rosique 2025).

Integrating waste management, environmental sustainability, and economic development is an important milestone in the circular economy (Das et al. 2024; Vivoda et al. 2025). Within the scope of the 2030 SDGs, “recycling and waste reduction” is recognized as the sustainable policy with the highest number of applications (Yıldırım and Kantarcı 2022). At this point, countries are expected to align their use of natural resources with SDGs (Allesch and Huber-Humer 2023; Satrovic et al. 2023). The findings indicate that country-specific action plans should be implemented to ensure environmental sustainability in the developing world (Ahmad et al. 2021). E.g., stronger environmental policies supported by R&D significantly improve eco-efficiency. It is particularly recommended to combine environmental policies with technological innovations in applications (Bergougui and Satrovic 2024; Satrovic et al. 2025). Mining companies and countries strive to adopt SDGs (Deveci et al. 2022). On the other hand, adopting the values of sustainable development (Yıldırım et al. 2023) implies an increase in the environmental and social costs of the mining industry (Humphreys 2001; Badakhshan et al. 2023, 2024; Hassan et al. 2023). MW management and rehabilitation costs account for a significant share of operating costs (Yıldız 2020a, 2025c; Das et al. 2023). Despite these costs, well-managed mining and recycling are important for sustainable supply to ensure sustainable development (Yıldız 2020a; Buchholz et al. 2022). Wastes that do not harm the environment or that have this harm removed can serve to maximize the utilization of natural resources and the circular economy (Araujo et al. 2022; Śliwka et al. 2022; Abbadi and Mucsi 2024; Yıldız and Tombal-Kara 2024; Yıldız et al. 2024b). At this point, identifying alternative uses of MWs in different sectors can improve the sustainability of mining and help recover waste costs.

Mining operations can have significant negative impacts on surrounding ecosystems. The operation of mines and quarries can generate large amounts of waste that accumulate in the environment (Przewłocki and Ślizowski 2004; Çetiner et al. 2006; Kuczyńska et al. 2008; Namin et al. 2011). Incorporating these wastes into economic activity is an extremely urgent task. In this way, the economy can be made more sustainable, and the negative effects of waste on ecosystems can be reduced (l), (m) (Malyukova et al. 2023).

Soil degradation has become a global problem due to the intensive use of chemical fertilizers in the world. This has led to a decrease in organic matter and SF. Meanwhile, the intensification of agriculture along with urbanization and industrialization has significantly accelerated the rate of waste production. At this point, sustainable food production is driving global innovations to better utilize various waste materials to produce value-added products such as soil conditioners. Nowadays, soil conditioners are of great importance to improve PG and soil health and reduce the use of chemical fertilizers (Babla et al. 2022). Making changes to the soil can immobilize metals in the soil. It can also reduce metal exposure risks and associated impacts on flora, fauna, and human health (k), (l), (x), (y) (Munksgaard and Lottermoser 2011). Topsoil in post-mining areas generally has low productivity levels, including the effects of heavy metal pollution (Ersoy and Yünsel 2018; Ersoy 2021). Its availability may not always be in quantities sufficient to meet the minimum needs for mine reclamation, hence the need for replacement materials and amendments to improve its quantity and quality (Sriningsih and Suryaningtyas 2022). At this point, MWs can play an important role as a supplement to meet the nutrient needs of the soil. These uses of MW can support sustainable agriculture (Yıldız 2025b). Especially thanks to its use in organic agriculture, sustainable agriculture is envisaged as a policy approach that maximizes economic benefits while protecting environmental quality (Zilberman et al. 1997; Mupambwa et al. 2020; Karaca and Ince 2023; Satrovic et al. 2022, 2024).

1. Scope and method

Although studies on the use of different MWs in soil improvement and agriculture as fertilizers have increased in the literature in recent years, there was no study in the literature that demonstrated the sustainable contributions of these wastes and that stakeholders (e.g., the state, the people of the mining region, and mining and recycling operators) affected by MWs could benefit from these wastes within the specified scopes. In an attempt to close this gap in the literature, (Yıldız 2025b) reviewed studies on the use of Pm, K, coal wastes, coal combustion, and natural stone wastes in soil improvement and agriculture. E.g., (Babla et al. 2022; Symanowicz and Toczko 2023) evaluated the use of coal waste and (Tozsın et al. 2014a, 2014b, 2015a, 2015b; Demir Şahin et al. 2022; Eker 2023) marble waste in agriculture. (Żelazny and Andrzej 2019) analyzed the use of fly ash from biomass combustion as fertilizer. Many studies like these have been published in the literature (Yıldız 2025b). However, there is a lack of studies in the literature on the sustainable contribution of other mineral wastes in agriculture. In an attempt to fill this gap, in this study, the sustainable contributions of zeolite, sulfur, dunite, serpentinite, nickel, boron, and perlite mineral wastes in soil improvement and their use in agriculture as fertilizer were determined (The use of MWs in agriculture is not limited to the MWs listed in this study. The use of MWs other than those listed in agriculture for soil improvement and as fertilizer can be found in the literature. In this study, it was preferred to examine only

these selected MWs. The wastes examined in this study are not limited to MWs only, and exceptional examples of mixtures of industrial wastes with minerals are also included). The scope of the study is as follows:

- ◆ In Section 2, the uses of selected MWs in soil improvement and agriculture are evaluated, respectively. The selected MWs order is as follows: The wastes of zeolite, sulfur, dunite, serpentinite, nickel, boron, and perlite.
- ◆ In Section 3, the results from the literature were summarized. Then, considering these results, a discussion was held and suggestions were presented. For this purpose, first of all, the codes corresponding to each sustainability contribution criterion of the use of all selected MWs in soil improvement and as fertilizer in agriculture were created in Table 1. For this purpose, firstly, the codes corresponding to each contribution of the sustainability criterion for the use of all examined MWs in agriculture and soil remediation were created in Table 1. The codes given to these contribution types are referred to in the text and analyzed in which types of MWs in which these contributions were demonstrated in the literature. In Section 3, Table 1 was created by determining which sustainable criteria each MW contributes to. In Table 1, “✓” is placed for the identified contributions of each waste to different sustainable criteria, and “N/A” for those whose contribution could not be identified. Thus, it was shown which sustainability criteria the selected MW types contribute to. In addition, considering these codes in reverse, the types of MW that specifically support sustainability contributions were shown in Table 1. The “c” coded “contribution to soil remediation” classification in Table 1 covers many sustainability contributions in Table 1. Many other similar types of contributions in Table 1 may also cover others. However, to easily identify the contribution of each MW, this inclusion was ignored. In addition, they were added to Table 1 as different sustainable criteria so that the reader can more clearly recognize the sustainable contributions of MWs in agriculture.

Some soil-improving properties are as follows:

- 1) Providing better aeration by preventing soil compaction.
- 2) Increasing water permeability & water holding capacity of the soil.
- 3) Protecting soil moisture by reducing water losses against drought.
- 4) Increasing the amount of organic matter in soils.
- 5) Regulating the pH structure of the soil and neutralizing the soil.
- 6) Reducing pollution during PG (İstanbulluoğlu 2012).

As seen from the literature in the study, the number of soil remediation features can be further increased. In addition to the types of soil improvement, parameters such as waste reduction, mixing with other wastes, technosol production, use in other sectors, and reducing environmental impacts, some of which are close to each other, were determined in different codes in Table 1. Thus, criteria for sustainable contribution of MW to agriculture and soil improvement were established. These codes were prepared to improve the sustainable contribution of MW to agriculture and soil remediation. The fact that these codes were not given in the quoted text contents of the references examined in the study does not mean that

the features of those codes were not present in those studies. In other words, several codes were added to the citations in the text in this study, considering that they contain features that were particularly emphasized or important in the cited reference studies, and the mineral wastes that meet these codes are marked with “✓” in Table 1. The codes placed in these citation sentences were evaluated to determine which of the different sustainability criteria in Table 1 different MWs contribute to. This assessment was made in the explanations of Figure 1.

2. MWs used in soil improvement and agriculture as fertilizer

2.1. Zeolite wastes

Zeolites are natural crystalline aluminosilicates. They are among the most common minerals found in sedimentary rocks. Of the 40 natural zeolites analyzed by research groups, the best known are clinoptilolite, erionite, shabazite, hōlandite, mordenite, stilbite, and fillipsite. Pores and voids are the main features of zeolite materials, and these voids are filled by cations and water molecules. The internal surface area of these channels is reported to reach up to several hundred m² per gram of zeolite, making zeolites a highly effective ion exchanger. The Si/Al ratio is an important property of zeolites. The charge imbalance resulting from the presence of Al in the zeolite framework determines the ion exchange property of zeolites and enables them to increase pH in potentially acidic regions. The unique physical and chemical properties of zeolites, combined with their abundance in sedimentary deposits and rocks derived from volcanic parent materials, have made them useful in many agricultural applications. Much of the early research on the use of zeolites in agriculture was conducted in Japan in the 1960s. A brief review of the literature indicates that Japanese farmers have been using zeolite rock for years to control moisture content and increase the pH of acidic volcanic soils (A-e). Zeolites can be used in agriculture due to their ion exchange properties, large porosity, and high CEC (A-k). They can be used both as nutrient carriers and as free nutrients (A-j). Adding zeolite to soil was found to increase crop yields and improve nutrient utilization efficiency (A-f). Other possible uses under investigation include applications as carriers of slow-release fertilizers, insecticides, fungicides, and herbicides, and as inhibitors of heavy metals in soil (A-i), (A-o), (A-y) (Ramesh and Reddy 2011). One of the most important areas of use of natural zeolites, which have become an important industrial raw material in recent years, is agriculture and animal husbandry (A-r), (A-w). Other uses in agriculture and animal husbandry are as follows: (Yasuda et al. 1998; Leggo 2000; Ramesh et al. 2001; Demir and Polat 2003; Ramesh and Reddy 2011; Fertu and Gavrilescu 2012; Sangeetha and Baskar 2016; Eroglu et al. 2017; Yuvaraj et al. 2018; Kalita and Zaman 2021; Aslan and Arslan 2024; Franco et al. 2024):

- 1) Fertilization and soil preparation: due to their high ion exchange and WR properties, natural zeolites are widely used in soil preparation for agriculture, mostly in clay-poor

- soils (A-c). In addition, due to its high ammonium selectivity, the use of clinoptilolite as a carrier in fertilizer preparation provides more efficient use of ammonium by plants and fertilizer savings (A-p). Since clinoptilolite adsorbs excess moisture, cooking and hardening of fertilizers during storage are also prevented (A-v).
- 2) Control of soil pollution: the cation-selective and exchange properties of natural zeolites can be utilized not only for the transfer of nutrient ions to plants (A-j) but also for the retention of some undesirable heavy metal cations such as Pb, Cd, Zn, and Cu in the food chain. The addition of clinoptilolite used in this field to radioactively contaminated soils has also been found to greatly reduce the amount of S90 taken up by the plant (A-l), (A-y).
 - 3) Livestock: it was determined that the weight of chickens, pigs, and ruminants fed with zeolite added to their feed increased without deteriorating their health compared to those fed with normal feed (A-o), (A-w). The main zeolites used in this field are clinoptilolite and modernite.
 - 4) Use of organic waste: natural zeolites used in this area remove the foul odor of feces, control their moisture content, and separate the methane gas produced by the decomposition of feces in an oxygen-free environment from other gases. Deodorization and control of moisture content create healthier conditions in animal shelters (A-l), (A-w).
 - 5) Aquaculture: natural zeolites, especially clinoptilolite, are used effectively in cleaning the pollution caused by biological residues in lakes and ponds. In addition, natural zeolites are also utilized to provide oxygen-rich airflow needed in live fish transportation and aquaculture environments (A-l), (A-w).

Many studies have been conducted on the use of zeolite alone or in combination with other fertilizer materials for soil improvement. E.g., (Tsintskaladze et al. 2017) applied a nanotechnological method involving the addition of N-containing material to the structure of natural zeolite to reduce the negative effects and losses of N fertilizers (A-u). The resulting nanomaterials can be used as N fertilizers that allow the gradual transfer of nitrates to the soil and minimize fertilization losses (A-p). They also significantly reduce groundwater pollution, evaporation, and drainage losses of N (A-l). The proposed zeolite nanomaterial represents a powerful reserve of N compounds necessary to feed plants (A-h). Thus, it is indicated that the zeolite nanomaterial obtained by the proposed method can be successfully used as a long-acting N fertilizer to supply N to the plant throughout the entire vegetative period (A-r). The application of this fertilizer to the soil is done only once. This reduces logistical costs (A-v). It is environmentally safe (A-v) (reduces nitrate runoff into groundwater), and has a long-lasting effect (A-i). It also regulates the absorption of water and N by the plant (A-f). The fertilizer mentioned above can be used in the open field as well as in greenhouses, nurseries, and decorative house plants.

South of Lille, a land contaminated with heavy metals from local metal refineries has become the subject of intensive research (A-x). (Leggo and Ledésert 2001) analyzed the growth behavior of spring wheat by replacing the topsoil in this area with organo-zeolitic

fertilizer. Investigations showed that soil substrates amended with ammoniated zeolitic tuff supported large populations of nitrifying bacteria that produced usable N along with H⁺ ions as a result of subsequent enzyme reactions. Proton activity was found to promote cation mobilization, allowing plant uptake to levels that largely meet the nutrient requirements of the plant. When the plants were grown on the modified substrates, very large differences in plant morphology emerged. The consequent development of dense root systems capable of binding soil particles is particularly important for their ability to reduce surface erosion and pollution from runoff (A-f), (A-g), (A-l). (Leggo et al. 2010) conducted fertilizing zeolitic tuff containing significant amounts of clinoptilolite along with animal waste to produce a dry, friable, odorless material that can be easily mixed with soil to form an amended soil substrate (A-n), (A-o), (A-r), (A-u). As a result, nitrification was enhanced by the stimulation of ammonium-oxidizing microorganisms, and the ionic mobility of the substrate pore water was increased. These functions allow the stabilization of PG on acid MWs in a way that promotes luxuriant growth in such areas normally devoid of vegetation (A-e).

Research has demonstrated the effectiveness of organo-zeolitic soil improvement (A-c). Although there is no geological evidence on which to base an estimate of world resources, the resources available in Eastern Europe, Turkey, Iran, the USA, Russia, Southeast Asia, Japan, and China are vast and will not be exhausted shortly (A-b). Currently, in regions without economic resources, such as Western Europe and Scandinavia, the cost of imports limits the use of zeolite for the remediation of contaminated land and horticulture (Leggo and Ledesert 2009). Natural zeolites have relatively strong, hard structures that are stable in normal soils. Clinoptilolite, e.g., is stable against temperature increases of 4500 C⁰ and can withstand acid conditions up to pH 2 (A-e). Therefore, an organo-zeolitic amendment can be considered rechargeable when the organic component loses its ability to supply ammonium ions (A-u). (Leggo and Ledesert 2009) found that the interaction of zeolite mineral surfaces with the microbial activity of waste organic material provides a soil amendment that delivers both available carbon and N to biodiversity-deprived, damaged, and degraded soils (A-x). During the decomposition of the organic phase, ammonia is released and rapidly adsorbed by the zeolite mineral. This reaction promotes the formation of a large population of nitrifying bacteria that oxidize the ammonium ions on the surface of the zeolite crystals, producing first nitrite and finally nitrate ions that enter the pore water of the soil. This process is continuous as adsorbed ammonium ions are oxidized and replaced by other ammonium ions until their supply is exhausted. Non-metal elements such as P and S, as well as trace metal elements essential for plants, are present in sufficient concentrations in decomposing organic waste and in reactions with inorganic soil substances (A-j). PG experiments have demonstrated the effectiveness of the organo-zeolitic soil system in both clean and contaminated situations. This practice can overcome the problem of intensive use of inorganic fertilizers (A-q). This is because the loss of carbon in the soil is limited by the addition of organic material (A-d). Therefore, the loss of soil biodiversity and the consequent degradation of soil structure caused by the overuse of synthetic chemical fertilizers seems to be reversible to a greater or lesser extent by this geomicrobial approach to SF, depending on climatic conditions and access to suitable materials (A-c), (A-l).

Restoration of mining soils is important for vegetation and the environment. (Li et al. 2023) investigated changes in soil nutrient content, microbial abundance, and biomass under different degrees of substrate alteration in mining soils to select effective measures. Soil samples were collected from the Bayan Obo mining district in the Inner Mongolia Autonomous Region, China. Application of artificial zeolite increased soil organic matter content, available N, and available P by 20.3%, 23.6%, and 40.4%, respectively (A-d). Artificial zeolite increased the abundance of bacteria, fungi, and actinomycetes by 0.6, 3.1, and 1.9 times, respectively. Soil properties were generally improved by the amendment strategies used in this study (A-c), (A-x). However, the type of amendment affected soil quality in different ways. Artificial zeolite improved soil quality by increasing porosity and WR, while microbial fertilizer improved soil quality by providing soil nutrition and enriching the microbial community (A-u). Pot experiments conducted in this study showed that the application of artificial zeolite and applied fertilizer increased soil nutrition and vegetation biomass from 3.1% to 91.2% in arid mining soils (A-h). In addition, in abandoned coal mining soils, amendments affected soil nutrient content and PG (A-f). In this study, the application of artificial zeolite at a concentration of 10 g/kg in mining soils planted with clover was the most appropriate treatment strategy for nutrient improvement (A-g), (A-h).

The use of zeolites in compost materials is also becoming widespread. Composting is an effective waste management technique that not only reduces potentially harmful waste but also produces valuable products for agricultural applications. (Idim et al. 2024) investigated the effect of natural and Mg-modified zeolite additives on the composting of chicken manure and sawdust, and the effect of the produced compost on barley growth and yield. Thus, it was aimed to produce useful agricultural materials from these wastes. Three different levels of natural zeolite and Mg-modified zeolite (0%, 10%, and 15%) were co-composted with chicken manure, sawdust, and dried leaves mixture to produce five different composts (A-n), (A-u). These composts containing 100% compost as control were then added to sandy soil at a ratio of 1:3 (compost/soil). The results revealed that the addition of zeolites improved the composting process, especially the 15% Mg modified zeolite composts, which showed lower electrical conductivity and more NH_4^+ and P retention compared to other modified and unmodified composts (A-c). When the Mg content was increased from 10% to 15% in the modified zeolite, the NH_4^+ and P retention increased by over 30% and 52%, respectively. Moreover, the use of some composite types in soil amendment and pot experiments under greenhouse conditions resulted in higher shoot biomass of barley plants. This research showed that co-composting of chicken manure and sawdust with zeolite, especially Mg-modified zeolite, increased the compost quality and hence the agricultural product yield (A-o), (A-h). (Zubkova et al. 2021) investigated the chemical and analytical properties of zeolite-containing rock, poultry farm waste, and composite mixtures with poultry farm waste (A-s), (A-u). The use of composite mixtures contributed to the formation of fertilizers in terms of mineral composition. The suitability of composite mixtures of zeolite-containing rocks with poultry farm wastes as organomineral fertilizers in agricultural and

plant production technologies was confirmed (A-d), (A-n), (A-j), (A-o). (Latifah et al. 2015) conducted the co-composting of rice husk and chicken slurry with clinoptilolite zeolite and urea as an additive in field experiments in Malaysia (A-n), (A-u). Clinoptilolite zeolite was used to increase ammonium and nitrate retention in compost. It was found that clinoptilolite zeolite used in co-composting reduced the accumulation of heavy metals that may have damaging effects on test plants (A-y). Thus, it was concluded that mature compost with good agronomic properties could be produced by co-composting chicken manure and rice husk using clinoptilolite zeolite and urea as additives (A-c), (A-f), (A-o). (Šubová et al. 2021) conducted the effects of two different composts, manure mixed with zeolite and manure mixed with zeolite and lime, on the improvement of cow manure (A-o), (A-s), (A-u). The aim of the study was to investigate the effect of amending cow dung with natural zeolite-clinoptilolite and hydrated lime on decomposition processes over a period of 90 days. It was found that amending composted manure with inorganic substances such as zeolite and hydrated lime has a great potential in reducing N losses and contributing to better stabilization of substrates during composting (A-c), (A-j). (Hayawin et al. 2014) mixed natural zeolites such as clinoptilolite and charcoal with vermicompost in different proportions before pelletizing. This research is related to the production of vermicompost from empty fruit bunch mixed with cow dung using an epigeic earthworm (A-u). Vermicompost mixture was conducted in a humid environment with moisture content between 70–80% and pH value between 6–8. The highest CEC was observed in 10% zeolite and 20% coal mixtures (A-c). The reduction of total N, total P, total K, and C/N ratio, i.e., the greatest reduction efficiency of metals was determined in 10% natural zeolite and 15% coal amounts, respectively (A-s). Natural zeolite and coal took up significant amounts of heavy metals. All proportions of zeolite and coal removed Cu, Fe, and significant amounts of Zn and Mn (A-k), (A-y).

Soil application of moisture-absorbing materials such as farmyard manure and natural zeolite is considered a simple and inexpensive way to maintain soil moisture in arid areas and light soils. (Zokaee Khosroshahi et al. 2023) conducted an experiment in Hamadan, Iran, during the 2022 and 2023 growing seasons to study the effect of two soil conditioners on the physiological traits of grapevines under drought stress. The treatments included two levels of irrigation cycles (7 and 21 day intervals) and four levels of soil amendment (control, 12 kg zeolite vine-1, 15 kg sheep manure vine-1, 12 kg zeolite + 15 kg sheep manure vine-1 combination) (A-s). The results showed that drought stress caused a decrease in chlorophyll content, leaf relative water content, and leaf water potential. Drought stress also caused an increase in electrolyte leakage and antioxidant enzyme activity. On the other hand, the application of farmyard manure and zeolite improved all investigated indicators due to their ability to absorb and retain water in the soil. The results of the study proved that it is possible to reduce the negative effects of drought stress on grapevines by preserving the moisture of light soils by applying natural zeolite alone or together with farmyard manure (A-c) (A-g).

Combined application of clinoptilolite zeolite with organic and inorganic fertilizers (A-u) has been found to lead to saving of inorganic fertilizers (A-q), (A-p), improve growth (A-f), increase dry matter production, yield, and N, P, and K uptake in maize plant (A-c), (A-d),

and also protect the agro-ecosystem for sustainable crop production (A-g), (A-j) (Ahmed 2010). The effect of the combination of zeolite with chemical fertilizer and organic fertilizers (Sugarcane filter cake) increased sugarcane yield compared to no fertilization (A-f) (A-g) (Cairo et al. 2017). By amending urea with rice straw compost and clinoptilolite zeolite (A-u), N use efficiency and maize yield were increased due to the temporary adsorption and desorption of ammonium in the amendment zones of compost and clinoptilolite zeolite (A-f), (A-g) (Latifah et al. 2018). The combined use of 80 kg/ha N urea + 50 kg/ha composted manure + 21% zeolite increased the highest leaf N concentration (%), and quantity & quality sunflower dry matter yield (kg/ha) (A-f), (A-g), (A-u). However, the effect of their application was greater in the second year than in the first year (Gholamhoseini et al. 2013). Integration of 10 t/ha zeolite with alternating wetting and drying or complete flooding management reduced NH₃ volatilization without increasing N leaching and increased rice grain yield and water productivity with incremental economic benefits of 126–195 USD/ha compared to complete flooding without zeolite (A-c), (A-f), (A-g), (A-v) (Sun et al. 2019). The following topics have been identified for further research direction (Ramesh et al. 2001; Kalita et al. 2020): To investigate whether zeolite addition would reduce the potential for nitrate leaching in agriculture. To characterize the existing zeolite deposits in each country. To develop methodologies for organo-zeolite fertilizers. To characterize the nutrient release pattern from organo-zeolites. To investigate the physical stability of zeolites in various soil environments. To investigate the long-term effect of zeolites on soil flora and fauna. To develop zeolitic herbicides to minimize herbicide residues. To conduct field tests of zeolites in soil and plant systems.

Based on the literature review, there are several advantages of using zeolites as an effective bulking agent that can optimize and stabilize the organic waste composting process. The increase in the percentage of zeolites added results in an increase in the temperature and pH recorded from the composted product (A-s), (A-d). Furthermore, researchers found that the addition of zeolites has significant effects on ammonia emission and maturity index. The more zeolites added, the lower the ammonia emission. The addition of zeolites was able to accelerate the degradation rate and achieve a higher germination index in the shorter maturity period of the compost product, producing a higher quality compost product (A-c), (A-f). As a result, zeolite is a very good regulator that can optimize various parameters, e.g., temperature, pH, electrical conductivity, ammonia losses, and GHG emissions during the composting process and increase the fertility of the soil (A-l). However, (Hamid et al. 2020) suggested that future studies should focus on cost-effective additives and microbial mechanisms in the ideal optimization of the composting process.

Excess N caused by straw returning to rice fields through irrigation deteriorates water quality. (Hu et al. 2023) used both simulated field and pot experiments to explore a new approach using zeolite to recycle this excess N. The results from simulated field experiments in stagnant water showed N adsorption (A-s) with different zeolite treatments (25, 50, 75, 100, 125, and 150 g/L). Pot experiments have shown how straw and reused zeolite applications affect ammonia N, nitrate N, total N, and total P concentrations in surface water and soil

layers of rice fields. Straw recycling releases more N and P than it returns to the field. Zeolite adsorbs N and P to improve water quality during straw decomposition and then gradually releases them for reuse (A-i). Based on these findings and conventional field designs, the use of 20 t/ha of zeolite in the field can not only reduce excess N but also recycle N and P for better crop growth. (A-d), (A-f), (A-g). This study provides a sustainable and more economical development method to reduce water quality degradation caused by straw returning to the field (A-l), (A-v). However, limitations of this study design include the use of indoor simulations and pot experiments. It is suggested that future experiments extend this study to detect soil and physiological growth indicators.

Heavy metals can negatively affect the growth, yield, and quality of cereal crops. Heavy metal excess can be reduced in two ways: by using organic matter that can reduce heavy metals, and microorganisms that can bind heavy metals with plants. The organic matter used includes manure, compost, and biochar that adsorbs heavy metals in the soil and reduces their levels (A-k), (A-u), (A-y) (Buswar et al. 2024). Biochars and zeolites are highly suitable for soil restoration due to their ability to improve soil structure, improve nutrient and water retention, regulate pH levels, and remove various impurities (A-c), (A-d), (A-e), (A-x). Both materials effectively transform degraded soils into productive land, offering significant benefits for soil management and environmental health. In a literature review (Kukowska and Szewczuk-Karpisz 2024), the effects of biochars and zeolites on the sorption capacity of different soil types towards metal ions, drugs, pesticides, and pollutants were compared. Based on recent reports, it was concluded that the incorporation of biochar and zeolite into soil amendment practices is a promising strategy to improve soil quality and promote environmental sustainability. Based on the available data, it can be said that both biochars and zeolites generally have good sorptive properties that contribute to a better accumulation of nutrients or immobilization of pollutants (A-d), (A-k). Among the zeolites identified as soil improvers, those prepared from struvite-added fly ash and zeolite showed the greatest potential. That is, they allowed the removal of mobile forms of heavy metals and bioavailable molecules (A-y). Scientists have identified many cases where the addition of one substance alone was not effective enough to immobilize pollutants or nutrients. These cases required the simultaneous use of two solids with different properties, for example, biochar + zeolite, biochar + polymer (A-u). The combined use of biochar, zeolite, and/or polymers offers great opportunities to improve soil health and agricultural productivity (A-c). The synergistic effect of these materials is due to their unique and complementary properties. Biochar improves soil aeration, WR, and provides a habitat for soil microorganisms due to its porous structure. In contrast, the high CEC of zeolite facilitates nutrient retention and slow release (A-d), (A-i). Polymers can improve soil structure and WR. (Rahmi et al. 2023) found that pink zeolite gave very good results as a carrier containing biochar and sorbent materials. The mechanism allowed the efficient use of zeolite and biochar (A-k), (A-t), (A-y).

(Schnackenberg et al. 2023) conducted an experimental study to study the short- and long-term distribution and mobility of metals in soils amended with a self-produced compost, when added alone or together with different doses of natural zeolite. To reduce

metal translocation and prevent metal migration to plants, zeolite was added to metal-contaminated mature compost to be mixed into the soil. When zeolite was added to compost alone, it tended to reduce the extractability of Cd and Zn by 25% and Pb by 15% better (A-k), (A-y). Self-produced compost showed an increase in ryegrass biomass when applied to soil at these doses alone or together with zeolite (A-f), (A-g). In the selected experimental conditions, the study recommends mixing self-produced compost with 15% zeolite (A-u).

Another field condition where zeolite can be effective is its relationship with water resources. A sensitive approach to water resources emerges as a component of primary importance for plant and fruit development. For these reasons, zeolite-soil application has been investigated in many studies where the effects on field hydraulic capacities were established (A-c) (Ibrahim-Saeedi and Sepaskhah 2013). (de Campos Bernardi et al. 2013) indicated that the incorporation of zeolitic sedimentary rocks in Brazil could increase their WR capacity (A-c). These hydrated tectoaluminosilicates of alkaline earth elements (Srilai et al. 2019) are emerging as important natural inorganic soil improvers that can enhance the physical/chemical properties of the land (i.e., infiltration rate (Nakhli et al. 2017), CEC (Zijun et al. 2021), and saturated hydraulic conductivity (Aslani et al. 2021)) (A-c), (A-i). It has been extensively demonstrated that soil adaptation using zeolitic equipment improves WR and minimizes infiltration, which reduces water application in agricultural management (A-c) (Méndez Argüello et al. 2018; Wu et al. 2019; Ibrahim and Alghamdi 2021; Szatanik-Kloc et al. 2021).

Meteorological extremes during the ripening season, such as heat waves and water restrictions, can negatively affect grapevine ecophysiology and fruit metabolism, resulting in lower yields per vine. (Cataldo et al. 2023a) aimed to compare two different soil treatments, Zeowine (30 t/ha; a soil conditioner made with clinoptilolite and compost from wine IW) and compost (20 t/ha), with a control without any treatment during two growing-production seasons (2021 and 2022) in Italy (A-u). In general, compost applied together with zeolite can alleviate the negative effects of water stress and improve PG, yield, and quality (A-c), (A-f). The use of zeolite minimizes the need for vine irrigation thanks to the good retention of water in the zeolite structure, and can positively affect both the physiological profiles and the fruit peel metabolism (sugar and size) of the vines (A-h).

Optimizing composting methods in closed-loop institutional chains can skillfully solve the problem of waste (lentils, stems, and pruning residues) in vineyards (A-n). Due to ongoing global warming, many wine-growing regions have experienced uneven ripening with difficult harvests. Extreme temperatures reduce the anthocyanin content of the must, while severe water deficits do not allow the fruit to develop properly, halting growth processes. (Cataldo et al. 2023b) conducted to improve soil management and grape quality through the application of a new soil conditioner (Zeowine) obtained from the composting processes of industrial wine, waste, and zeolite. Three applications were conducted in the vineyard: Zeowine (30 t/ha), Zeolite (10 t/ha), and Compost (20 t/ha). The Zeowine and Zeolite treatments were among the most balanced in terms of water potential, net photosynthesis, grape quality (sugar and anthocyanin content), and berry weight (A-c), (A-f), (A-g).

The use of zeolite has gained momentum in the recent past due to its numerous benefits. Significant research has been conducted worldwide to harness the potential of zeolites for the sustained maintenance of SF (Sangeetha and Baskar 2016). However, the rational and profitable utilization of these zeolites requires a systematic and comprehensive research effort. The most important aspects of future research include: (1) characterization of available zeolite deposits in each country (A-b), (2) determination of physical stability of zeolites in various soil environments (A-z), (3) development of methodologies for low-cost and efficient organo-zeolite fertilizers (A-c), (A-v), (A-r) (Ramesh and Reddy 2011).

2.2. Sulfur wastes

S is an essential nutrient for the proper functioning of living organisms, both plants and animals. However, after many years of environmentally friendly activities, there is a deficiency of S in the soils of many countries (Lisowska et al. 2022b). S is primarily used in the production of sulfuric acid required for the fertilizer industry and in pesticides (B-o), (B-r) (URL-1). According to the US Environmental Protection Agency (USEPA), S is used as an organic pesticide dose to protect crops, especially fruits and vegetables such as apples, strawberries, and potatoes (B-o). S, which has long been used as a fungicide and phytoalexin, is being considered for use in nanoparticle form due to increased fungal pathogenicity and fungicide resistance (Shankar et al. 2021). S nanoparticles and S quantum dots were found to have significant bactericidal effects compared to elemental S, which makes them particularly useful in the treatment of fungal and bacterial diseases. The effect of S nanoparticles on the growth response and seed production of typical steppe phytocenoses was determined in a dose-dependent manner (B-c) (Ryabinina et al. 2017). S nanoparticles reduced the number of pathogenic organisms in the soil and prevented agricultural diseases (B-k). Moreover, the growth of a pumpkin plant was also improved, and organic S compounds were produced, which could provide the potential nutrient source of the plant (B-d), (B-f) (Salem et al. 2016). These studies show the potential of nano-sized S as a fungicide and PG regulator in agriculture. Although many studies have been conducted on S nanoparticles, which show better activity than elemental S, it has been concluded that the smaller the particle size, the higher its activity (Priyadarshi et al. 2023).

Plant fertilization with S is an important part of agricultural practices, as is the systematic increase of soil organic matter content. Waste-derived materials are a source of soil organic matter as well as plant-available S (Lisowska et al. 2022c) assumed that incorporating waste S pulp and its mixtures with organic materials allows simultaneous enrichment of soil with readily available S and organic matter, and conducted a 240-day incubation experiment in two different soils to verify the hypothesis (B-u). Two doses of S were applied to each soil (20 and 40 mg S/kg for very light soil and 30 and 60 mg S/kg for heavy soil) (B-s). The sulphate S content in the incubated soil material treated with the addition of S dough and its mixtures with organic materials increased significantly up to day 60 and then decreased.

The application of these materials significantly increased the available S content and decreased the pH of the incubated material (B-d). The use of waste S significantly increased the soil sulphate S content. A factor to be kept in mind when using waste S is its significant potential for soil acidification.

Waste S has a high fertilizing potential due to the high content of this element. The problem of using this waste for fertilizing purposes is its physical properties. These properties make it impossible to granulate this material and make its application much more difficult. Therefore (Lisowska et al. 2022a) designed a granulated fertilizer based on waste element S. To improve its properties and effects on soil properties, humic acids and halloysite were used. Granular fertilizers (with component weights given as percentages) were prepared as fertilizer A (waste S (%95) + halloysite (%5)), fertilizer B (waste S (%81) + halloysite (%5) + humic acids (%14)), fertilizer C (waste S (%50) + halloysite (%50)) and fertilizer D (waste S (%46) + halloysite (%46) + humic acids (%8)) (B-s), (B-u). In addition, the effects of the addition of the prepared fertilizers on soil pH, electrolytic conductivity, and sulphate content were investigated in a 90-day incubation experiment. Enrichment with humic acids and use of higher amounts of halloysite (especially the share of larger granules and bulk density) increased fertilizer properties. It also stabilized soil pH and increased S content in soil (B-d), (B-e). (Lisowska et al. 2022b) investigated the effect of application of waste S element and its mixtures with organic matter (cattle manure, digestible product, and biochar) on Mn and Zn availability in soils (B-u). The presented findings showed that there were significant relationships among soil pH value, S-SO₄, Zn, and Mn contents, dehydrogenase activity, and experimental period. The results of regression analysis revealed that applied substances had a more significant effect on zinc content than Mn content during the incubation period. Soil pH is a predictive variable of Zn availability in light and heavy soils and Mn content in heavy soil. Sulphate S content itself also seems to be a significant predictor of Zn content in heavy soil, but it is less significant than the pH value (B-e), (B-y).

(Tabak and Filipek-Mazur 2018) analyzed the application method of waste elemental S and ground Pm rock by adding 20 and 40 mg S, 40 and 80 mg/kg P to medium soil, 30 and 60 mg S and 60 and 120 mg/kg P to heavy soil (B-s), (B-u). The (technologically unprocessed) S waste used in this study, despite its significant fertilizer potential, is problematic in terms of its effect on soil properties, i.e., due to its chemical form. The material used is muddy, and there is no effective method on the market today to apply it. Elemental S added to the soil must be oxidized to the sulfate form, because only this form can be taken up by plants. The combination of ground Pm rock with S pulp created a product that could be a suitable material for granulation after thorough homogenization (B-r). During the experiment, the pH of the medium soil varied between 4.99 and 5.74, which corresponded to an acidic and slightly acidic reaction. The pH of the heavy soil varied between 4.42–4.75, which indicated a very acidic reaction. Application of waste S pulp increased the sulfate S content in both soils. In addition, application of a double dose of ground Pm rock increased the soil abundance in terms of P (B-c), (B-r).

(Tozsın et al. 2014c) investigated the usability of WP and sulfuric acid produced from WP for the reclamation of calcareous Na soils (B-x). Displacement of Na from an exchange

complex and its replacement with Ca, a decrease in pH, and exchangeable Na percentage, and an improvement in soil structure were also aimed. Since WP can be rich in various micronutrients, SF can also be increased with this technique. An additional advantage of this strategy is that, unlike gypsum, WP is cheap and readily available in large quantities (B-m), (B-v). In this study, column washing tests were conducted to evaluate the change in soil properties when gypsum and PW additives were added from a Cu concentration plant (B-u). The availability of micronutrients (Fe, Cu, Zn, and Mn) required for PG and the hazardous potential of PW in terms of heavy metal pollution were considered (B-h). Gypsum, powdered WP, and sulfuric acid produced from WP were applied to the soil by taking the gypsum requirement of the soil as a reference. The results showed that the application of WP at a dose of 44.74 mg/ha was superior to gypsum at a dose of 55.20 mg/ha in terms of exchangeable Na% at 42 weeks (B-s). In addition, the application of all concentrations of sulfuric acid produced from WP also decreased the exchangeable Na percentage values. The best values were obtained with sulfuric acid at a dose of 35.31 mg/ha at 26 weeks. It was observed that the content of all micronutrients in the soil increased significantly with the applications of WP and sulfuric acid (B-d). The levels of micronutrients after applications can be classified as sufficient for PG except for the Fe level, when the minimum dose of sulphuric acid application was 17 mg/ha. The heavy metal content in the soil after application with WP was found to be lower than the legal limit values (B-k). Application of WP or sulphuric acid to the soil resulted in increased availability of Fe, Cu, Zn, and Mn, which are essential for PG (B-h). WP has not been found to cause pollution or toxic problems in the soil. With these data, it has been determined that the use of pyrite as a product or waste from Cu concentration plants can provide a useful improvement in calcareous Na soils and can be an effective fertilizer (B-c), (B-r).

S has also been an active ingredient in antibacterial agents since ancient times, especially for the treatment of skin diseases. The antibacterial properties of S have been studied in agricultural applications to treat plant diseases (B-f) (Paralikal and Rai 2018). Besides chemical methods, biological techniques for S nanoparticle synthesis using plant extracts have also been applied in an environmentally friendly manner (Priyadarshi et al. 2022b). Additionally, various research reports have shown that the dispersion potential of S nanoparticles coated with hydrophilic macromolecules such as chitosan is greatly enhanced (Shankar et al. 2018). In addition to enhancing the dispersibility, these biopolymer coatings increase the biocompatibility of S nanoparticles, facilitating their interaction with biological membranes (B-f). This strategy not only reduced the toxicity of S nanoparticles (B-k) but also enhanced their antibacterial activity by improving their uptake by microbial cells (Priyadarshi et al. 2022a). This feature improves the biological function of S and makes it usable in food, agriculture, biomedicine, and medicine. Many S-containing substances produced by plants, such as thionine, defensins, glucosinolates, phytoalexins from the cruciferous family, alliin, and glutathione, are directly or indirectly linked to plant defense systems against microbial diseases (M-o) (Cooper and Williams 2004). They are also used as nutrient supplements and soil pH regulators to produce sulfate and promote P uptake by

plants (B-e), (B-h) (Griffith et al. 2015). Therefore, the two main applications of elemental S in agriculture are pesticides/microbicides and fertilizers (Priyadarshi et al. 2023). Fungi and soil bacteria are vital for organic matter decomposition and biogeochemical cycles, but excessive use of synthetic fertilizers contributes to soil degradation and loss of biodiversity. (Maffia et al. 2024) tested a fertilizer made from S-based agro-industrial waste stabilized with synthetic fertilizer, composted olive pulp, and bentonite clay on two-year-old hazelnut seedlings (B-u). The present study shows that the combined application of chemical and organic fertilizers (especially an innovative mixture of composted olive pulp and mineral components such as S and bentonite) is a promising strategy to increase soil biodiversity. The findings highlighted the importance of organic fertilization in improving soil microbial health, providing a sustainable approach to improve soil quality and hazelnut productivity (B-c), (B-f). The findings showed that even a very low level (5%) of organic matter addition to S-based fertilizers could significantly increase both bacterial and fungal diversity, providing effects similar to those observed with all-organic fertilizers (B-p). These results highlighted the potential of mixed fertilization strategies to maintain soil health and promote PG by optimizing microbial diversity and functionality (B-o). Microbial biodiversity improved with organic inputs, with more than 20% increased species richness and diversity compared to unfertilized soils.

2.3. Dunite wastes

The use of remediation to immobilize metals in contaminated soils is a widely accepted remediation approach. In the framework of the circular economy, remediation produced from mining and/or biomass waste has gained importance. In this direction (Díaz et al. 2024) proposed the combination of nanoscale zero-valent Fe nanoparticles with dunite MW and compost for the remediation and restoration of soil affected by high concentrations of As and metals (C-m), (C-x), (C-u). For this purpose, the authors conducted combinations of dunite, compost, and zero-valent Fe nanoparticles in pots containing contaminated soil for 75 days. The pH, available P, and CEC were also determined. The application of dunite led to the immobilization of metals and provided Mg (C-y). Thus, it improved the CEC. On the other hand, the compost increased the nutrient content and also promoted PG (C-f) and (C-h). However, this change caused a dramatic increase in As accumulation in plants. Finally, the application of Fe nanoparticles in combination with the other two amendments was found to be the most suitable strategy, as it not only inhibited As mobilization and accumulation but also promoted PG by adding nutrients to the soil. Thus, the combination of zero valent Fe nanoparticles with dunite MW and compost proved to be effective in remediating soil contaminated by As and metals simultaneously (C-c), (C-u), (C-y).

(Crusciol et al. 2019) conducted the effects of dunite rates on Mg, Si, reducing sugars, sucrose, and leaf starch, soil chemical properties, and maize yield in two soil types. The treatments consisted of five dunite rates (0, 42, 208, 542, and 1542 mg/kg) in clayey soil and

five dunite rates (0, 150, 238, 411, and 933 mg/kg) in sandy soil (C-s). Dunite application to clayey and sandy soils resulted in positive increases in Mg and Si contents and pH improvements in plants and soil (C-d), (C-e). However, higher Mg nutrition resulted in lower sucrose and leaf starch levels. Increasing rates resulted in better partitioning of metabolites in the plant for the maize crop. This led to better development and yield of maize grains (C-f), (C-g). (Moretti et al. 2019) evaluated the effect of dunite rates on Mg, Si, reducing sugars, sucrose, and leaf starch, soil chemical properties, and soybean yield in two soil types. The treatments consisted of five dunite rates (0, 42, 208, 542, and 1542 mg/kg) in clay soil and five dunite rates (0, 150, 238, 411, and 933 mg/kg) in sandy soil (C-s). In both crops and soils, Mg and Si contents, reducing sugars and leaf glucose, soil pH, Mg and Si, and yield components increased (C-d), (C-e), (C-f). Mg nutrient element provided lower starch levels in the leaf. Therefore, the best distribution of metabolites to the plant provided better growth and better yield of soybean.

2.4. Serpentinite wastes

(Pekarskas et al. 2017) investigated the effect of processing crushed waste extracted from a serpentinite quarry on soil agrochemical properties, phytotoxicity of spring barley, barley plant biomass, and chemical composition (D-m). Ground and granulated serpentinite soil had different effects on plants. Application of serpentinite fertilizers significantly increased the contents of Ca, Fe (227.95–376.75 and 5.05–9.62 mg/kg), total and plant-derived Mg (0.34–0.52 and 1.19–2.16 mg/kg), Pb, and Ni, while the contents of Cu and Mn significantly decreased (D-d), (D-y). Application of ground serpentinite resulted in a significant increase in plant-derived Mg and a much higher alkalization of the soil compared to granulated (D-e). The effect of serpentinite increased the yield of green and dry mass of spring barley plants by 0.65–3.41 and 1.19–2.59%. The yield of green and dry mass of spring barley under the effect of ground serpentinite was higher than that of granulated serpentinite fertilizer, and the dry matter was also significantly higher than that of unfertilized spring barley plants (D-f), (D-g).

Mg is one of the essential elements for PG. However, when only Mg supply is required, few economically viable options are available. One of these options is the use of serpentinite as an alternative Mg source, although little is known about its potential and efficiency in tropical soil conditions. (Viana et al. 2021) evaluated the use of serpentinite as a soil remineralizer and Mg fertilizer. The study was conducted in a greenhouse using a completely randomized design with seven treatments (controls with three levels of serpentinite, serpentinite with phonolite mixture, and dolomitic limestone without fertilization) and four replications (D-u). Two plant species (corn hybrid bean variety) and two contrasting soils (clayey and sandy texture) were used in the pots. The results showed that the free silica and toxic element contents of serpentinite met the legal requirements (D-k), (D-u). No statistically significant difference was observed for plant dry matter weight production in serpentinite

and dolomitic limestone control and pure serpentinite and phonolite mixture treatments. Chemical and mineralogical analysis showed that serpentinite presented high MgO content. Thus, serpentinite could meet the Mg requirements for the growth and development of corn and bean plants (D-f), (D-g).

2.5. Nickel mining wastes

TM, a by-product of Ni ore mining, can be considered as a more environmentally friendly alternative to traditional fertilizers as a source of Mg and Si in agriculture (E-m). TM positively affects soil properties and provides nutrients that can be taken up by plants. However, information on the effects of TM on plant physiology in cropping systems is limited. (Crusciol et al. 2022) analyzed the effects of increasing doses of TM on crop yield; soil chemical properties; and leaf Mg, Si, reducing sugars, sucrose & starch contents in a soybean-maize crop rotation system (E-s). The study was conducted under rain-fed conditions in three consecutive cropping seasons, 2018/2019 (soybean), 2019 (maize), and 2019/2020 (soybean). The greatest increases in grain yield for both crops were obtained at 1,050 kg/ha TM dose, with increases of 1,068 and 3,658 kg/ha in soybean and maize, respectively. According to these results, the persistent effect of TM application on Mg and Si fertilization and improvement of soil acidity was proven (E-d), (E-e) (Souza et al. 2007; Crusciol et al. 2022). Similarly, (Bossolani et al. 2021) investigated whether TM, a by-product of Ni ore mining, is an effective fertilizer for maize. The effects of TM on soil pH, Si and Mg availability to soil and plants, carbohydrate metabolism, grain filling, and yield were evaluated in two simultaneous experiments conducted under greenhouse conditions. Five TM doses were applied to two soil textures: clayey (0, 55, 273, 709, and 2,018 mg/kg) and sandy (0, 293, 410, 645, and 1,260 mg/kg). In general, the best results in soil and maize plants occurred at the highest TM dose for both soil textures (2018 mg/kg for clayey and 1,260 mg/kg for sandy). The results showed that in both soils, Mg and Si concentrations in maize leaves increased with TM dose, similar to that in the soil. Interestingly, in clayey soil, soil pH increased linearly, while in sandy soil, pH reached its maximum value between the two largest TM doses. The concentration of reducing sugars increased at the highest TM dose, while sucrose and starch concentrations decreased. Improvement of carbohydrate partitioning resulted in higher maize growth, grain filling, and yield (E-f), (E-g). This study confirmed that TM is another suitable and clean alternative fertilizer for agricultural systems, which can improve soil pH and actively provide Si and Mg to soil and plants, regardless of soil texture, especially when applied in larger doses (E-d), (E-e), (E-q).

(de Melo et al. 2022) evaluated the relationship between TM particle size and agronomic productivity. The study was conducted in a crop rotation system during the seasons 2018/2019, 2019, and 2019/2020 for soybean, maize, and soybean, respectively. The effects of two different particle sizes of TM (20 and 100 mesh) on soil chemical properties, leaf nutrient

content, leaf sugar concentration, leaf pigments, grain weight, and yield were evaluated with eight replications. Positive responses of chlorophyll a, carotenoids, and total chlorophyll to both TM particle sizes were observed (E-c). In particular, TM treatment at 100 mesh increased leaf concentrations of reducing sugars and sucrose in the first soybean crop and maize, but not in the second soybean crop. TM treatment reduced leaf starch concentrations regardless of crop or particle size. Increases in 100 mesh grain weight were observed in soybean and maize at both particle sizes under TM treatment at 100 mesh. Application of 100 mesh TM increased the grain yield of the first soybean crop and corn, while no effect of TM application on the grain yield of the second soybean crop was observed. Although additional studies on particle size are needed, it is concluded that TM can be considered as a suitable source of Mg and Si for crops, especially when ground to a particle size of 100 mesh. This study showed that TM is an agronomically viable source of Mg and Si, especially in tropical acidic soils that are typically Mg and Si-deficient (E-d), (E-f), (E-h).

2.6. Boron wastes

Boron has many areas of use (F-w). One of them is the agricultural sector (Tombal et al. 2016). Boron is a very important element for efficient PG and development (F-f) (Saleem et al. 2011; Shireen et al. 2018; Figueira et al. 2024). Boron-deficient plants include tuber crops (especially sugar beet), rough alfalfa, fruit trees, grapes, olives, coffee, tobacco, and cotton. Boron-based fertilizers are often used in the soil to eliminate the effects of boron deficiency in plants (F-j). Various boron-based fertilizers have therefore been developed for agricultural purposes. In cases of boron deficiency, a mixed fertilizer containing anhydrous borax and borax pentahydrate is used. It is applied by spraying highly water-soluble Na pentaborate or disodium octaborate on the crop (F-r). Boron, together with compounds such as Na chlorate and bromosol, is also used when weeding or soil sterilization is required (F-c), (F-o) (Figueira et al. 2024; URL-1).

The need for boron-based fertilizers for agricultural use is continuously increasing as a result of world population growth. The global market for boron-based fertilizers is expected to grow to ~\$6.3 billion by 2032. Hence, the demand for boron resources will also increase. Due to the increasing demand for boron in a wide range of applications, the recovery of boron from secondary sources is of great importance (F-b). At this point, boron recovered from waste streams can be a low-cost source for fertilizer application (F-r), (F-v). (Figueira et al. 2024) analyzed the recovery of boron from various waste streams. It also reviewed the application of boron-based fertilizers in agriculture. Boron recovered from waste streams can be used to tailor a slow-release boron fertilizer for agriculture (Degryse 2017) (F-a), (F-i).

BW with high boron and Mg content can be used as fertilizer in boron and Mg-deficient soils. In addition, the bioavailability of heavy metals in compost is of critical importance for their agricultural value. (Wang et al. 2016) proposed a new disposal method of BW by

composting and investigated the effect of BW additions (2.5%, 5.0%, and 7.5% on a dry weight basis) on the bioavailability of boron and Mg during aerobic pig manure composting (F-m), (F-n), (F-s), (F-u). The results showed that BW additions increased both boron and Mg contents in different fractions (F-d). The addition of BW improved the bioavailability of boron to plants and reduced the proportion of Mg in the exchangeable fraction. (Wang et al. 2021) evaluated the effect of inorganic additives on Cu and Zn bioavailability during co-composting of pig manure and rice straw (P_m rock and BW) using the sequential extraction procedure (F-m), (F-n), (F-u). The results showed that both additives applied at 2.5%–7.5% could promote the conversion of exchangeable Cu and reducible Cu to oxidizable Cu, thereby reducing the bioavailability factors by 15.5%–47.2% (F-k), (F-s), (F-u). Although the additives did not provide a significant reduction in the bioavailability factors of Zn, the transition from exchangeable Zn to reducible Zn could reduce the mobility of Zn. P_m and BW could provide some nutrients to humus chelated with Cu and Zn, which enhanced organic matter decomposition (F-d). Thus, P_m rock and BW promoted the passivation of Cu by chelation with humus, mainly enhancing organic matter decomposition. These findings can be used to reduce the ecological risk of heavy metal contamination during land application of manure compost (F-k), (F-y).

In one experiment, the amount of boron had a significant effect on first pod height, grain boron content, germination rate, grain weight and grain yield (F-f) (Gülümser et al. 2005). In another study, boron deficiency or excess in the medium did not affect the germination rate of sunflowers. At the end of four weeks, it was reported that boron deficiency caused an increase in root length and indole acetic acid content, and a decrease in shoot length and pigment content. It was also reported that excessive boron during this period caused a decrease in root length and indole acetic acid content, and an increase in shoot length and pigment content (F-c), (F-f), (F-g) (Akçam-Oluk et al. 2004). Boron had no significant effect on the shoot and root growth of sunflowers. However, it caused a decrease in root fresh weight (Ortaca 2005). Excess boron caused a decrease in the growth of wheat (Rerkasem and Jamjod 2004). However, it was found that boron caused a decrease in the dry weight of some varieties and an increase in the dry weight of some varieties (F-f). Excess boron caused a decrease in the root and shoot length of barley and wheat (Taban and Erdal 2000; Ayvaz 2002). However, excessive boron reduced the fresh weight of roots and shoots of maize (Güneş et al. 2000). The common feature of these studies is that there was a decrease in seedling characteristics due to the increase in boron. The effects of boron on plants varied according to plant species and applied boron concentrations (Akçam-Oluk and Demiray 2004). (Onaran and Yücedağ 2013) analyzed the effects of two different boron concentrator wastes on the germination and growth of beans and chickpeas. For this purpose, species seeds were applied to petri dishes containing pure water (control) and varying concentrations of two different wastes in three repetitions. At the end of three days, root and shoot lengths, fresh and dry weights of one-week-old seedlings grown from germinated seeds were measured. At the end of three days, most of the bean and chickpea seeds had germinated. This result showed that BWs did not have any inhibitory effect on the germination of the seeds of the mentioned plants (F-f).

In addition, it was found that both BWs at concentrations of 600 ppm and above reduced the root and shoot lengths, fresh and dry weights of the seedlings.

2.7. Perlite wastes

Perlite is used as a “substrate” to improve the physical properties of the soil in field agriculture, horticulture, greenhouse cultivation (such as seedling cultivation, and culture cultivation), and grass sports fields (G-c), (G-w) (URL-1). E.g., soil amendment with PW from the wine industry can improve some soil properties closely related to SF, such as organic matter content and nutrient (P and K) concentration. (Rodríguez-Salgado et al. 2016) analyzed the effect of PW from a winery on general soil properties and Cu adsorption. The studied soil was amended with different concentrations of PW corresponding to 10, 20, 40, and 80 mg/ha (G-s). Addition of PW to soil increased the amount of organic matter as well as soil nutrients such as P and K, and these increases remained stable over time (G-d), (G-h). An increase in Cu retention and adsorption capacity was detected in soils amended with PW. In terms of sustainable agricultural practices, addition of PW to agricultural soils can lead to a significant decrease in Cu mobilization, thus minimizing the harmful effects of Cu-based fungicides used to combat fungal diseases in plants (G-k), (G-x), (G-y). Similarly, (Nóvoa-Muñoz et al. 2008) conducted the agricultural benefits of PW from the wine industry. In this context, the natural characteristics of the waste were measured, followed by monitoring the chemical characteristics of acidic soils and their effects on grape PG. Considering that heavy metals associated with the waste (e.g., Cu, Zn, and Mn) could cause problems when used as a regulator, changes in their total levels and soil fractionation were studied together with the total contents of the plant. The high contents of C (214 g/kg), N (25 g/kg), P (534 mg/kg), and K (106 g/kg) of PW made it a suitable amendment to increase SF and also solved the disposal problem (G-c), (G-m). Direct addition of PW to soil contributed to increasing soil pH (by 2 pH units) and CEC (G-e). However, potential Cu phytotoxicity was reduced due to a change in Cu distribution towards less soluble fractions (G-k), (G-y). High Cu content and electrical conductivity positively affected seed germination and/or PG (G-f). All these changes in acidic soils provide agronomic benefits without undesirable environmental side effects. It was concluded that soils dedicated to vineyards may be the best target for large amounts of PW application due to the high K levels required by vineyards (G-g), (G-h).

3. Conclusions

3.1. Number of sustainable criteria contributed by MW

A summary of the contribution to sustainable criteria of the use of MWs in agriculture is presented in Table 1. In Table 1, a “✓” sign is placed for each waste’s (detected) contribution

Table 1. Summary of contributions to sustainable criteria of the use of MWs in agriculture

Tabela 1. Podsumowanie wkładu w zrównoważone kryteria stosowania MW w rolnictwie

MW types / sustainable contribution criteria		A	B	C	D	E	F	G
The flow and cycle of the elements that make up the basic nutrients of soils	(a)	(A-a) N/A	(B-a) N/A	(C-a) N/A	(D-a) N/A	(E-a) N/A	(F-a) ✓(1)	(G-a) N/A
The relationship between soil mineral needs and mineral reserves	(b)	(A-b) ✓(2)	(B-b) N/A	(C-b) N/A	(D-b) N/A	(E-b) N/A	(F-b) ✓(1)	(G-b) N/A
Contribution to soil improvement	(c)	(A-c) ✓(21)	(B-c) ✓(4)	(C-c) ✓(1)	(D-c) N/A	(E-c) ✓(1)	(F-c) ✓(2)	(G-c) ✓(2)
Eliminating the lack of organic matter in the soil	(d)	(A-d) ✓(9)	(B-d) ✓(4)	(C-d) N/A	(D-d) ✓(3)	(E-d) ✓(3)	(F-d) ✓(2)	(G-d) ✓(1)
Use as a soil regulator & pH balancer in acidic lands	(e)	(A-e) ✓(4)	(B-e) ✓(3)	(C-e) N/A	(D-e) ✓(3)	(E-e) ✓(2)	(F-e) N/A	(G-e) ✓(1)
Contribution to PG/development	(f)	(A-f) ✓(15)	(B-f) ✓(3)	(C-f) ✓(1)	(D-f) ✓(4)	(E-f) ✓(2)	(F-f) ✓(5)	(G-f) ✓(1)
Contribution to food production	(g)	(A-g) ✓(11)	(B-g) N/A	(C-g) N/A	(D-g) ✓(3)	(E-g) ✓(1)	(F-g) ✓(1)	(G-g) ✓(1)
Increasing the nutritional value and quality of the plant	(h)	(A-h) ✓(5)	(B-h) ✓(3)	(C-h) ✓(1)	(D-h) N/A	(E-h) ✓(1)	(F-h) N/A	(G-h) ✓(2)
SRFs & The ability to provide slow release of minerals into the soil	(i)	(A-i) ✓(5)	(B-i) N/A	(C-i) N/A	(D-i) N/A	(E-i) N/A	(F-i) ✓(1)	(G-i) N/A
Providing sustainable mineral needs of soils & facilitating this supply	(j)	(A-j) ✓(6)	(B-j) N/A	(C-j) N/A	(D-j) N/A	(E-j) N/A	(F-j) ✓(1)	(G-j) N/A
Contributions to reducing environmental risks (such as preventing toxic formation)	(k)	(A-k) ✓(6)	(B-k) ✓(3)	(C-k) N/A	(D-k) ✓(1)	(E-k) N/A	(F-k) ✓(2)	(G-k) ✓(2)
Effect of protecting the ecological environment & reducing negative environmental impacts	(l)	(A-l) ✓(9)	(B-l) N/A	(C-l) N/A	(D-l) N/A	(E-l) N/A	(F-l) N/A	(G-l) N/A
Contribution to MW reduction	(m)	(A-m) N/A	(B-m) ✓(1)	(C-m) ✓(1)	(D-m) ✓(1)	(E-m) ✓(2)	(F-m) ✓(2)	(G-m) ✓(1)
Contribution to reducing domestic or IW	(n)	(A-n) ✓(8)	(B-n) N/A	(C-n) N/A	(D-n) N/A	(E-n) N/A	(F-n) ✓(2)	(G-n) N/A
Contribution to sustainable agriculture	(o)	(A-o) ✓(7)	(B-o) ✓(4)	(C-o) N/A	(D-o) N/A	(E-o) N/A	(F-o) ✓(2)	(G-o) N/A

MW types / sustainable contribution criteria		A	B	C	D	E	F	G
Reducing the use of chemical fertilizers	(q)	(A-q) ✓(2)	(B-q) N/A	(C-q) N/A	(D-q) N/A	(E-q) ✓(1)	(F-q) N/A	(G-q) N/A
The effect of reducing the amount of fertilizer used and preventing excessive mineral fertilizer consumption	(p)	(A-p) ✓(3)	(B-p) ✓(1)	(C-p) N/A	(D-p) N/A	(E-p) N/A	(F-p) N/A	(G-p) N/A
Feasible use as fertilizer in agriculture	(r)	(A-r) ✓(4)	(B-r) ✓(4)	(C-r) N/A	(D-r) N/A	(E-r) N/A	(F-r) ✓(2)	(G-r) N/A
Application of MWs to soils in mixtures of different percentages	(s)	(A-s) ✓(6)	(B-s) ✓(4)	(C-s) N/A	(D-s) ✓(2)	(E-s) ✓(1)	(F-s) ✓(2)	(G-s) ✓(1)
Feasible use in the production of technosols for the reclamation of soils degraded by mining	(t)	(A-t) ✓(1)	(B-t) N/A	(C-t) N/A	(D-t) N/A	(E-t) N/A	(F-t) N/A	(G-t) N/A
Suitability of MW (such as domestic, agricultural and industrial) for use by mixing with other wastes or special fertilizers	(u)	(A-u) ✓(16)	(B-u) ✓(6)	(C-u) ✓(2)	(D-u) ✓(2)	(E-u) N/A	(F-u) ✓(3)	(G-u) N/A
Cost reduction and positive contribution to feasibility	(v)	(A-v) ✓(5)	(B-v) ✓(1)	(C-v) N/A	(D-v) N/A	(E-v) N/A	(F-v) ✓(1)	(G-v) N/A
Ability to use in different sectors as well as agriculture	(w)	(A-w) ✓(4)	(B-w) N/A	(C-w) N/A	(D-w) N/A	(E-w) N/A	(F-w) ✓(1)	(G-w) ✓(1)
Its use in the soil rehabilitation process	(x)	(A-x) ✓(4)	(B-x) ✓(1)	(C-x) ✓(1)	(D-x) N/A	(E-x) N/A	(F-x) N/A	(G-x) ✓(1)
Reducing harmful elements of the soil	(y)	(A-y) ✓(8)	(B-y) ✓(1)	(C-y) ✓(2)	(D-y) ✓(1)	(E-y) N/A	(F-y) ✓(1)	(G-y) ✓(2)
Improving the geotechnical parameters of the soil	(z)	(A-z) ✓(1)	(B-z) N/A	(C-z) N/A	(D-z) N/A	(E-z) N/A	(F-z) N/A	(G-z) N/A

A – Zeolite wastes, B – Sulfur wastes, C – Dunite wastes, D – Serpentine wastes, E – Nickel MWs, F – BWs, G – PWs.

to different sustainable criteria, and a “N/A” sign is placed for those whose contribution cannot be determined. In addition, the number of references to each code in the text is given in Table 1. These numbers indicate that different studies have contributed to the sustainable criteria that meet this code. Thus, it is shown which sustainability criteria MW types contribute to. The mineral that contributes the most among the 26 sustainable criteria determined is presented in Figure 1. Of course, it can be said that some types of additives,

such as code “c” in Table 1 and Figure 1, are more comprehensive or important in soil improvement and agriculture as fertilizer than others. This shows that the quality of the type of contribution is more important than the number of contributions to sustainable criteria. In other words, the results do not indicate the superiority of MW in terms of sustainable contribution to their use in agriculture. Rather, these numbers show the extent to which the contribution of selected MWs to sustainability criteria has been determined by considering the literature.

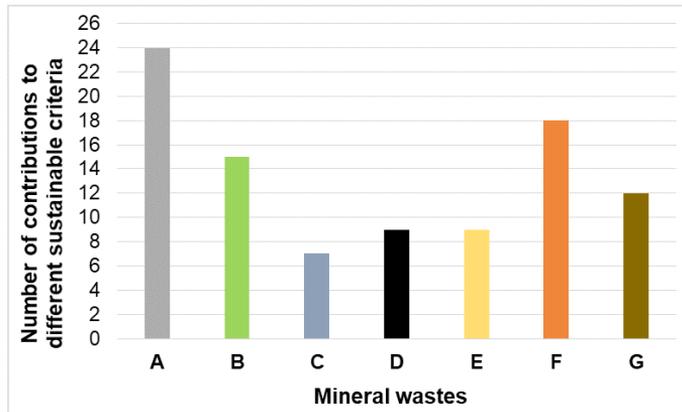


Fig. 1. Number of contributions to sustainable criteria for the use of MW in agriculture

Rys. 1. Liczba wkładów w zrównoważone kryteria stosowania MW w rolnictwie

The results show the sustainability criteria to which the MW examined in the current study predominantly contribute. Accordingly, the contribution numbers to the sustainable criteria among the wastes reviewed in the study are as follows, from largest to smallest: Zeolite > BWs > sulfur > PWs > serpentinite = Nickel MWs > dunite wastes. On the other hand, these results do not mean that the wastes in question do not have other sustainability contributions. Although the “N/A” marks indicate that the contribution of the MW specified in Table 1 to the sustainability criteria could not be determined in this study, it may be determined that these waste types contribute to different sustainability criteria in the future with new studies.

3.2. MWs contributing to each sustainable criteria

This study has proven that the use of these MWs in soil improvement and as fertilizer in agriculture can provide significant benefits in terms of sustainability. As mentioned above, almost every MW can provide different positive and sustainable contributions to different soil types. When the codes in Figure 1 are considered in reverse, that is, it can be understood from Table 1 which types of waste were analyzed specifically to support sustainability

contributions. The following conclusions criteria regarding which MWs contribute to each sustainable criteria (Figure 2):

- ◆ (a): Studies were conducted on BWs (1) that contribute to the (a) criterion.
- ◆ (b): Studies were conducted on zeolite wastes (2) and BWs (1) that contribute to the (b) criterion.
- ◆ (c): Studies were conducted on zeolite (21), sulfur (4), dunite (1), nickel MWs (1), BWs (2), and PWs (2) that contribute to the (c) criterion.
- ◆ (d): Studies were conducted on zeolite (9), sulfur (4), serpentinite (3), nickel MWs (3), BWs (3), and PWs (1) that contribute to the (d) criterion.
- ◆ (e): Studies were conducted on zeolite (4), sulfur (3), serpentinite (3), nickel MWs (2), and PWs (1) that contribute to the (e) criterion.
- ◆ (f): Studies were conducted on zeolite (15), sulfur (3), dunite (1), serpentinite (4), nickel MWs (2), BWs (5), and PWs (1) that contribute to the (f) criterion.
- ◆ (g): Studies were conducted on zeolite (11), serpentinite (3), nickel MWs (1), BWs (1), and PWs (1) that contribute to the (g) criterion.
- ◆ (h): Studies were conducted on zeolite (5), sulfur (3), dunite (1), nickel MWs (1), and PWs (1) wastes that contribute to the (h) criterion.
- ◆ (i): Studies were conducted on zeolite (5) and BWs (1) that contribute to the (i) criterion.
- ◆ (j): Studies were conducted on zeolite (6) and BWs (1) that contribute to (j) criterion.

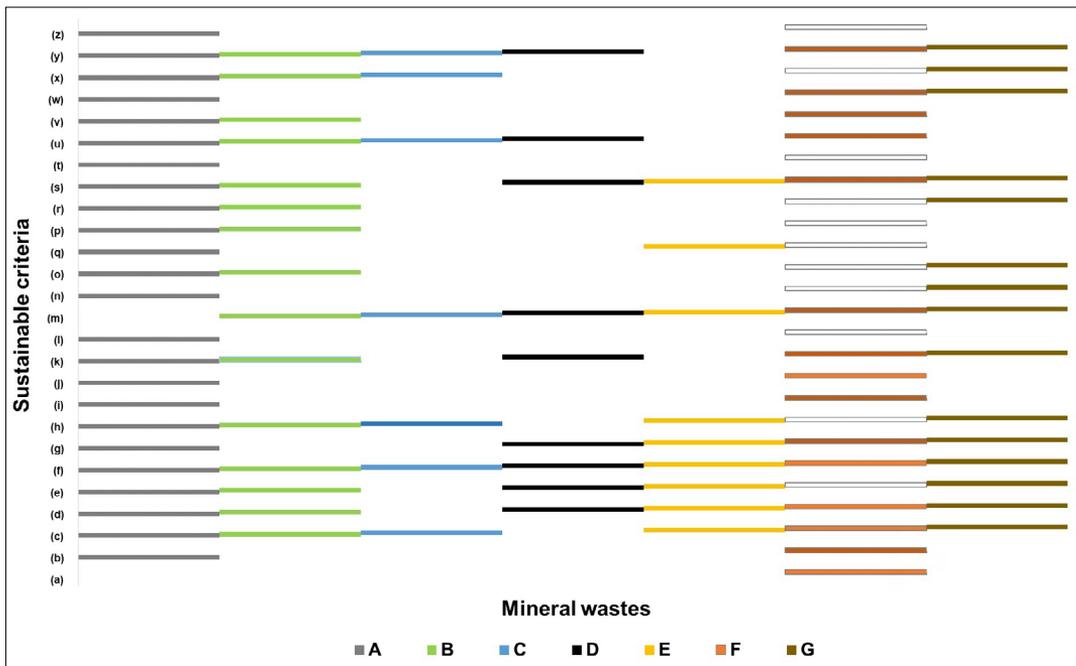


Fig. 2. MWs that contribute to every sustainable criterion

Rys. 2. MW, które przyczyniają się do spełnienia wszystkich kryteriów zrównoważonego rozwoju

- ◆ (k): Studies were conducted on zeolite (6), sulfur (3), serpentinite (1), BWs (2), and PWs (2) that contribute to the (k) criterion.
- ◆ (l): Studies were conducted on zeolite wastes (9) that contribute to the (l) criterion.
- ◆ (m): Studies were conducted on sulfur (1), dunite (1), serpentinite (1), nickel MWs (2), BWs (2), and PWs (1) that contribute to the (m) criterion.
- ◆ (n): Studies were conducted on zeolite (8) and PWs (2) that contribute to the (n) criterion.
- ◆ (o): Studies were conducted on zeolite (7), sulfur (4), and PWs (2) that contribute to the (o) criterion.
- ◆ (q): Studies were conducted on zeolite (2) and nickel MWs (1) that contribute to the (q) criterion.
- ◆ (p): Studies were conducted on zeolite (3) and sulfur wastes (1) that contribute to the (p) criterion.
- ◆ (r): Studies were conducted on zeolite (4), sulfur (4), and BWs (2) that contribute to the (r) criterion.
- ◆ (s): Studies were conducted on zeolite (6), sulfur (4), serpentinite (2), nickel MWs (1), BWs (2), and PWs (1) that contribute to the (s) criterion.
- ◆ (t): Studies were conducted on zeolite wastes (1) that contribute to the (t) criterion.
- ◆ (u): Studies were conducted on zeolite (16), sulfur (6), dunite (2), serpentinite (2), and BWs (3) that contribute to the (u) criterion.
- ◆ (v): Studies were conducted on zeolite (5), sulfur (1), and BWs (1) that contribute to the (v) criterion.
- ◆ (w): Studies were conducted on zeolite (4), BWs (1), and PWs (1) that contribute to the (w) criterion.
- ◆ (x): Studies were conducted on zeolite (4), sulfur (1), dunite (1), and PWs (1) that contribute to the (x) criterion.
- ◆ (y): Studies were conducted on zeolite (8), sulfur (1), dunite (2), serpentinite (1), BWs (1), and PWs (2) that contribute to the (y) criterion.
- ◆ (z): Studies were conducted on zeolite wastes (1) that contribute to the (z) criterion.

Discussion and suggestions

Soil degradation poses a serious threat to global agricultural productivity. Current statistics show that degraded soils constitute 24% of the Earth's land mass (Ball et al. 2007). Soil degradation encompasses various types, including imbalance of soil nutrients, soil salinization, soil acidification, soil organic matter depletion, and microbial diversity reduction. In this case, researchers should make more efforts to treat MW as a soil amendment to solve this problem. The evaluation of soil quality generally requires considering three aspects of soil physics, chemistry, and biology (Tian et al. 2015). At this point, soil sample monitoring analysis in mines and surrounding agricultural areas is useful to know the concentrations of

various parameters present in soil samples (Paramasivam and Anbazhagan 2019). In today's world, the introduction of a new fertilization product to the market should be linked to the creation of a technology for its application and the analysis of its precise effect on soil properties in both long-term and short-term contexts (Tabak and Filipek-Mazur 2018).

One of the most important factors limiting the use of waste in agriculture is its physical form, which is not suitable for the machines currently used. It is also important that the elements are in chemical forms that cannot be directly taken by plants (Tabak and Filipek-Mazur 2018). E.g., some MWs, such as S, cannot be used alone in their natural state due to their physical forms. In addition, it is noteworthy that S and zeolite wastes were used, especially with biochar or other compost materials, in the study. This indicates that minerals or MWs should not be considered alone, but can give better results as a soil conditioner or fertilizer when mixed with other materials.

Compost is seen as an environmentally sound way to dispose of household and garden waste while improving soil quality. Composting can transform organic waste into a valuable soil amendment that can improve physical, chemical, and biological soil quality. Many home-made composts contain various metals in varying concentrations that could potentially contaminate plants grown in compost-improved soils. Therefore, compost amendments can also contribute to the remediation of areas anthropogenically degraded by metals (Schnackenberg et al. 2023). The use of additives that improve the properties and increase the effectiveness of waste-based fertilizers also corresponds to the modern approach to creating waste-free technologies observed in agriculture and other branches of the economy (Lisowska et al. 2022a).

Sustainable agriculture is based on practices that consider the need to protect the environment and natural resources by meeting increased production targets by taking advantage of the opportunities brought by technological development. The aim is to limit the use of chemical plant protection products and mineral fertilizers in favor of organic fertilizers and to minimize the use of fossil fuels (Lisowska et al. 2022b). In this study, the use of selected wastes in agriculture was reviewed. On the other hand, according to field conditions, not only the MWs but also the minerals themselves can be used in agriculture at certain rates when economically feasible. In other words, it has been determined in this study that there are feasible applications where the minerals & wastes in question can be used in agriculture together with domestic & IWs. These applications can be preferred in cases where the use of minerals in other industrial applications is not feasible.

The combined use of MWs and IWs can serve as a soil amendment in the agro-ecosystem to maximize synergy to increase land productivity. Moreover, such practices can create a revenue stream that can partially offset the cost of dry disposal of MWs. This can be a strong incentive for mining companies to adopt such practices. According to (Babla et al. 2022), before the production of waste-based soil conditioners and their immediate commercialization, further research should be conducted in the following areas:

- a) The values added to wastes/by-products should be quantified to provide positive environmental and economic benefits compared to conventional soil conditioners/

fertilizers. The potential commercial value of soil conditioners should be examined not only in terms of soil amendment and improved product performance but also in terms of their affordability for end users.

- b) Improvement in soil properties should be investigated in both greenhouse and field trials to increase crop production.
- c) Depending on the crop type, the optimal application rate of soil conditioners needs to be determined for specific agricultural lands (acidic or alkaline) and/or soil types (e.g., sand, silt, clay). (A rate that is too high may cause phytotoxicity in crops).
- d) Value-added products from waste (e.g., pellets or granules) should be properly produced to ensure long-term availability of nutrients compared to traditional fertilizers or soil conditioners.
- e) Optimal moisture content and heavy metal leaching potential for soil conditioners should be examined. Soil conditioners should not contaminate the agricultural ecosystem with excessive heavy metals. They should also minimally interfere with natural microbial activity and have minimal impact on the environment.
- f) Residual toxicity in all edible parts of plants should be within limits and meet relevant food safety standards.
- g) Regulatory, social, and commercial perceptions should be changed to ensure feasible and sustainable use of MWs with agricultural/IWs.

The majority of the studies reviewed in this paper emphasize the need for further research. The wastes listed in this article should not be considered in isolation. These wastes can be mixed with each other and with other types of wastes or minerals to improve the soil. These will continue to increase with new studies. As can be seen from the examples shared in the study, the possibilities of producing soil improvement materials from MWs and other industrial, organic, or domestic wastes in different mixtures are very rich. These examples will increase further over the years. What is important here is to ensure the environmental sensitivity of these applications and to produce soil improvers feasibly. E.g., the possible presence of REE and other precious metals in the MWs mentioned indicates that their recovery may also contribute to feasibility. If these wastes feasibly contain REE and other valuable metals, they should not be used as fertilizer; instead, the recovery of these metals should be considered.

Open-pit mining leads to large-scale land degradation, including land abandonment and reduction of agricultural land, resulting in serious environmental problems. Rehabilitation of mines and farmland is therefore vital. Ecological restoration of mines is a long-term, complex process and a worldwide challenge. As an important indicator of mineral reclamation, the essence of soil reclamation is the fertilization, reclamation, and maturation of the soil (Xu et al. 2023). Our study has demonstrated how effective the mixture of MWs with other wastes can be in the reclamation and fertilization of soil. In this study, only the sustainable contribution of selected MWs to agriculture and soil improvement was demonstrated. In future studies, it would be beneficial to develop regional studies on the feasible use of MWs with other IWs. Further studies may reveal the sustainable contributions of the MWs selected in this study or other MWs that were not identified in Table 1.

There is a need for feasible practices in the agriculture sector to ensure access to clean food at affordable prices to sustain the necessities of life for people around the world. Accordingly, the use of mineral wastes in agriculture as part of environmentally sound mining can not only reduce waste and reduce the environmental impact of wastes but also enable feasible fertilizer production in agriculture and the improvement of soils to be reclaimed. Not all mineral wastes can be used in soil near or far away with the same feasibility. Focusing on feasibility and R&D studies for these uses will enable the feasible use of these mineral wastes in agriculture and soil improvement in certain regions. Agriculture is an important investment alternative in terms of production diversification and food security in settlements with mineral-based economies. Agricultural activities can benefit from improvements in infrastructure and the availability of resources from the mining industry, the adoption of technological innovations in production systems, and the expansion of market opportunities. (de Loureiro et al. 2023) examined whether the main mining municipalities in the states of Pará and Minas Gerais, Brazil's largest ore producers, exhibit growth in agricultural production and production systems at a higher technological level. In mining regions, agriculture and mining activities can be carried out together (Yıldız et al. 2021). In addition, mining companies pay various costs to the Indigenous people of the mining region and the state in the form of royalties and land use costs (Yıldız 2020b; 2020c; 2022a; 2022b; 2023). Some of these costs could be used for the benefit of the public, especially in the agricultural sector. Studies on the use of MWs in agriculture and soil improvement in or near mining areas could be encouraged with the support of mining companies and the state. Being able to use it in different sectors or discovering these uses can also make a positive contribution to the environmental costs and feasibility of the use of MWs. The use of MWs in agriculture and soil improvement will also have a positive impact on the feasibility of mining operations. For this reason, it would be beneficial for the R&D departments of mining enterprises to intensify their work on the use of MWs generated in their operating areas in agriculture and soil improvement. It would be beneficial for states to encourage these activities of mining enterprises.

The findings in our study are consistent with the findings and suggestions of (Tian et al. 2015; Tabak and Filipek-Mazur 2018; Paramasivam and Anbazhagan 2019; Babla et al. 2022; Schnackenberg et al. 2023; Xu et al. 2023) mentioned above. To eliminate the mineral deficiencies of plants, it is recommended that R&D projects be directed towards the use of industrial slag wastes, which are rich in these minerals, as fertilizers. In this direction, new studies to be conducted in the future on the use of not only MWs but also industrial slag wastes together with other IWs in agriculture and soil improvement can complete the deficiency in this study.

No funding sources were used for this article.

The Author has no conflicts of interest to declare.

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A REVIEW OF THE SUSTAINABLE CONTRIBUTIONS OF THE USE OF SOME MINE WASTES IN SOIL IMPROVEMENT AND AS FERTILIZER IN AGRICULTURE

Keywords

agriculture use, natural soil fertilizers, organic fertilizer, mine soil, sustainable agriculture

Abstract

Mining wastes pose environmental risks. Additionally, storage & disposal costs of waste are high. Studies on the utilization of mine wastes in soil improvement and agriculture can significantly contribute to reducing the environmental risks and the feasible utilization of these wastes. Considering the latest developments in the literature, the number of published review articles on the use of mine wastes in soil improvement and as fertilizer in agriculture is extremely limited. Taking into consideration this deficiency in the literature, this study reviewed the sustainable contributions of the use of zeolite wastes, sulfur wastes, dunite wastes, serpentinite wastes, nickel mining wastes, boron wastes, and perlite wastes in soil improvement and as fertilizers in agriculture. In this evaluation, it was determined which of the selected mine wastes contributed to the sustainable criteria corresponding to the codes created. In this way, it was aimed to contribute to the sustainable, environmentally friendly, and feasible use of mine wastes and to raise awareness for all stakeholders. The results of this study can guide guidance to R&D organizations and recycling businesses considering financing the use of these mine wastes in soil improvement and agriculture as fertilizer in the future. It is also a guide for other stakeholders considering the use of these mine wastes in soil improvement and agriculture as fertilizer in specific regions, considering contributions to sustainability criteria.

PRZEGLĄD ZRÓWNOWAŻONEGO WKŁADU WYKORZYSTANIA NIEKTÓRYCH ODPADÓW GÓRNICZYCH DO ULEPSZANIA GLEB I JAKO NAWOZÓW W ROLNICTWIE

Słowa kluczowe

wykorzystanie w rolnictwie, naturalne nawozy glebowe, nawóz organiczny, gleba kopalniana, zrównoważone rolnictwo

Streszczenie

Odpady górnicze stanowią zagrożenie dla środowiska. Ponadto wysokie są koszty ich składowania i utylizacji. Badania nad wykorzystaniem odpadów górniczych do ulepszania gleb i w rolnictwie mogą znacząco przyczynić się do zmniejszenia zagrożeń dla środowiska i opłacalnego wykorzystania tych odpadów. Biorąc pod uwagę najnowsze osiągnięcia w literaturze, liczba opublikowanych artykułów przeglądowych na temat wykorzystania odpadów górniczych do ulepszania gleb i jako nawozów w rolnictwie jest bardzo ograniczona. Biorąc pod uwagę ten niedobór w literaturze, w niniejszym badaniu dokonano przeglądu zrównoważonego wkładu wykorzystania odpadów zeolitowych,

odpadów siarkowych, odpadów dunitowych, odpadów serpentynitowych, odpadów górniczych niklu, odpadów borowych i odpadów perlitowych do ulepszania gleb i jako nawozów w rolnictwie. W niniejszej ocenie określono, które z wybranych odpadów górniczych przyczyniły się do spełnienia kryteriów zrównoważonego rozwoju odpowiadających utworzonym kodom. W ten sposób starano się przyczynić do zrównoważonego, przyjaznego środowiska i wykonalnego wykorzystania odpadów kopalnianych oraz wzrostu świadomości wszystkich zainteresowanych stron. Wyniki niniejszego badania mogą stanowić wskazówki dla organizacji badawczo-rozwojowych i przedsiębiorstw recyklingowych rozważających finansowanie wykorzystania tych odpadów kopalnianych w celu poprawy jakości gleby i w rolnictwie jako nawozu w przyszłości. Stanowią one również przewodnik dla innych zainteresowanych stron rozważających wykorzystanie tych odpadów kopalnianych w celu poprawy jakości gleby i w rolnictwie jako nawozu w określonych regionach, uwzględniając wkład w kryteria zrównoważonego rozwoju.