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Agronomic and Climate Benefits of Basalt Rock Dust: A Review of Silicate Rock Applications in Agriculture

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Abstract:
A freshly derived and ground mafic igneous rock called basalt represents a sustainable alternative for enhancing the fertility of agricultural soils and improving the sequestration of atmospheric CO_2. Minerals like feldspar, micas, zeolites, and major oxides with 37.76–59.64% (SiO_2), 11.77–14.32% (Al_2O_3), 5.57–14.75% (CaO), 5.37–9.15% (MgO), 10.1–20.93% (Fe_2O_3), 1.7–6.69% (K_2O), 1.4–3.34% (Na_2O), and 1.81–3.73% (TiO_2) are reported as its constituents. Through the process of mineral weathering, nutrients are released slowly and consistently from basalt dust, thereby improving soil nutrient structure and availability. For most agronomic trials involving mafic silicate rocks, particularly in highly weathered tropical soils, yield improvements are reported as a result of basalt incorporation. The amendments with basalt increase plant height, stem diameter, biomass, and accumulation of plants' macronutrients such as phosphorus, potassium, calcium, and magnesium in tropical cropping systems. According to this review, other elemental compositions and chemical parameters of soil, such as potassium, calcium, magnesium, and pH, were reported to be improved significantly as a result of basalt addition. The climate benefits of basalt addition through the process of enhanced weathering and 0.3 t CO_2 t^{-1} carbon capturing potential were emphasized. Despite the promising reports on the soil, agricultural, and climate benefits of basalt in tropical regions, limited studies under temperate conditions remain a challenge.

Keywords - Enhanced weathering; Soil mineralization; Carbon sequestration; Tropical Soil

1. INTRODUCTION

A crucial agricultural challenge is to increase or maintain yields without further degrading the Earth's environmental systems, particularly soil. Global soil degradation, of which agriculture is a major driving force, proceeds at alarming rates with about 10 million ha of cropland rendered unproductive each year. Simultaneously, additional arable land is limited, trends in crop yields decline or have reached plateaus in many countries [1], and climate change is expected to further constrain future food production. On the other hand, agricultural intensification would result in considerable pressure on existing

farmlands and requires profound advancements in soil sustaining crop production [2]. Among the major contributors to enhanced crop production are mineral nutrients, which are extracted from the soil with every harvest and must be adequately replaced by fertilizers, manures, or other amendments. In many countries however, food production currently depends on depleting large quantities of soil mineral nutrients without adequate replacement, resulting in substantial global rates of nutrient mining [3].

The physical and chemical properties and changes to the soil are important understudied dimensions of rock dust impacts on soil health and agricultural systems.

Basalt rock dust releases inorganic macronutrients (P, K, Ca, and Mg) and micronutrients (Mn, B, Cu, and Zn), which are essential for crops due to their roles in chemical signaling, protein structures, cellular structures, enzyme co-factors and many other roles in plants and humans [4;5]. Inorganic macronutrients and micronutrients are sourced from the dissolution of minerals present in basalt rock dust, specifically olivine, augite, diopside, apatite, and anorthosite [6;7]. These minerals contain important inorganic macro and micronutrients as major structural components, or they are isomorphically substituted within the minerals at trace concentrations. Lastly, elements, such as B, may be present within additional trace accessory minerals [4]. Field trials and greenhouse studies have shown mixed effects on agricultural soils. In sorghum (*Sorghum bicolor*) field trials, [6] found basalt rock dust addition had significantly higher soil Si and Mg but not Ca or soil pH. In a greenhouse study conducted by [7], soil and soil leachate, Ca, Mg, and K significantly increased with the addition of basalt rock dust, but soil pH was not affected. The weathering of basalt rock dust can also promote the precipitation of secondary Al and Fe oxy-

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hydroxide minerals that may immobilize nutrients, particularly phosphate [8].

[7;9] reported that in order to limit global warming to well below 2°C, model projections indicate that both rapid decarbonisation and negative emission technologies (NETs) will be required. Hence, in addition to conventional mitigation there is an urgent need for development of scalable NETs that safely remove CO_2 from the atmosphere. A promising, yet poorly studied NET, is enhanced weathering (EW) of silicate minerals, which is particularly of interest due to its application potential in agriculture [10;11]. This technique aims to accelerate natural weathering, a process that has been responsible for stabilizing climate over geological timescales, which naturally captures 1.1 Gt of CO_2 per year (or ca. 3% of current global CO_2-emissions) [12;13]. The idea behind EW is to speed up this natural process by grinding silicate rocks to powder, hence increasing the surface area [10] and bringing these in a moisture-retaining environment favorable to weathering, e.g., agricultural soils.

In addition to its atmospheric CO_2 removal potential, applying silicate minerals to soils holds promise for improving agricultural practices, Agricultural enhanced weathering is considered a promising NET because co-utilization of surface area with agricultural land is possible and competition with food production is avoided (in contrast to some other NETs such as afforestation). Soil acidification and nutrient leaching are pervasive issues in agriculture, and EW can (in this way) contribute to soil health and improve crop growth [14]. Additionally, even though not considered an essential plant nutrient, the process of EW releases silicon (Si), which can improve plant resistance to pests and diseases, thereby improving crop health and productivity in general [5;16]. Because of these benefits, silicate rock powder has been used as a fertilizer for many years [17], particularly in tropical regions, where the release of base cations from these rocks can significantly enhance crop productivity [5]. Nonetheless, EW also holds certain risks that need to be considered. Silicate materials typically contain toxic trace elements that are released into the environment during weathering, posing the risk of uptake by plants. The amount of toxic trace elements varies strongly among rocks and industrial silicates [17;18]. For instance, basalt, a naturally occurring and globally abundant silicate rock, generally exhibits lower concentrations of potentially harmful metals such as nickel (Ni) and chromium (Cr) compared to other silicate rock types and is, therefore, a preferred rock source to consider in agriculture [6].

Despite the growing interest in basalt rock dust as a soil amendment, existing studies are often fragmented, varying in experimental design which limits generalization and practical guidance. Research has documented the potential of basalt rock dust in improving soil fertility, enhance crop yields, and increase nutrient use efficiency, fewer studies have systematically and simultaneously reviewed the underlying mechanisms, long-term soil impacts, and associated climate co-benefits of basalt rock dust, such as carbon sequestration through enhanced silicate weathering. A comprehensive synthesis of these effects is therefore essential to bridge the gap between the reviewed experimental findings and field application, providing evidence-based recommendations for farmers, agronomists, and policymakers. This review aims to critically evaluate the current literature on basalt rock dust, focusing on its mechanisms of action in soils, agronomic benefits across different crops, and environmental co-benefits. By consolidating knowledge on co-benefits of basalt rock dust, this study provides a multidisciplinary perspective that integrates soil science, agronomy, and climate mitigation, highlights existing knowledge gaps, and offers practical insights for sustainable agricultural management.

2.LITERATURE RVIEW

2.1 Soil Benefits of Basalt Rock Dust

Basalt rock is a proposed alternative silicate, containing at least six plant-essential nutrients (K, P, Ca, Mg, Fe and Mn) and very low concentrations of Cr and Ni [10; 19; 20]. Rock dust (RD) is a soil amendment comprising rock quarry byproducts [21], from gravel to clay-sized particles, and may improve soil health. Rock dust can compose of materials with varying particle size distributions and lithologies, ranging from igneous rocks (e.g., granites, dunites, and feldspathoids) to metamorphic rocks (e.g., serpentine, gneiss, and metabasalts). The neo-formed secondary Al and Fe oxyhydroxides due to basalt rock addition can help promote and protect soil organic carbon (SOC). All of these coinciding processes altering SOC, pH, inorganic nutrients, micronutrients, aggregation, and other soil health properties from rock dust can affect soils and crop production and have been understudied in temperate organic farming systems. Before rock dust can be applied at scale, field trials in organic farms in temperate regions are needed to evaluate if rock dust does have the intended effects.

Nutrients are released into the soil when rock weathers. Silicate rocks such as basalt release nutrients like magnesium, calcium, and silicon which enhance soil fertility and support plant growth [6;10]. By releasing

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nutrients into the soil and promoting plant growth, rock amendments may reduce the need for synthetic fertilizers and help to rebuild eroded soils. The illustration to the left depicts how pulverized rock may store carbon and release nutrients into the soil when applied as an amendment. Since many growers already apply granular fertilizers or lime to their fields, rock amendments can be applied using existing equipment. For centuries farmers have been amending the soil with rock minerals to improve fertility. Rock minerals especially silicate rock like basalt are rich in nutrients that are needed to support healthy soils and can benefit soil water availability for crops. Some of the vital nutrients found naturally in rocks include calcium, magnesium, potassium and phosphorus, and micronutrients like zinc and iron. Recently, farmers have been exploring how different rock minerals can be applied to the soil to improve soil health [22].The components of basalt are freshly ground and mixed into fine particles and they contain feldspar, micas and zeolites. Basalt mass contents are; SIO_2 (37.76 to 59.64%), Al_2O_3 (11.77 to 14.32%), CaO (5.57 to 14.75%), MgO (5.37 to 9.15%), Fe_2O_3 (10.1 to 20.93%), K_2O (1.7 to 6.69%), Na_2O (1.4 to 3.34%) and TiO_2 (1.81 to 3.73%) [23]. Basalt powder is used to restore the fertility of poor soils and to restore the nutritional balance of crops. Natural mineral fertilization increases plant growth, total yield, fruit quality and certain chemical constituents and chlorophyll rates of pepper fruits and cucumbers [23]. One of the options that was pointed out has been the use of rock dust for mineralization of agricultural soil. Rocks normally contain essential nutrients needed by plants to grow well while the quantities and availability of their mineral composition vary. Therefore, these rocks have been used in agronomic studies to investigate their potential as alternative source for the supply of nutrients to plants [24]. There is a wide diversity of igneous, metamorphic, or sedimentary rocks with potential for agricultural use. These rocks have a wide range of minerals, and considerable levels of potassium (K), calcium (Ca), magnesium (Mg) and phosphorus (P), among other essential nutrients for plants. This rock powder when applied to the soil is solubilized and promotes the availability of its nutrients to plants [24]. Several studies have reported that the application of rock powder such as basalt, has resulted in the improvement of chemical characteristics and fertility of different types of soil [25].

2.2. Agronomic Benefits of Basalt Rock Dust

Basalt is a mafic igneous rock that contains substantial amounts of Ca- and Mg-rich silicate minerals. In the review of Swoboda et al. (2022), all trials with (ultra)mafic rocks on agricultural soils improved yields. Recent studies further corroborate these findings; [26], for instance, documented improved corn biomass upon basalt application in both clay and sandy clay loam soils. Similarly, basalt addition led to notable increases in dry mass, height, and stem diameter as well as the accumulation of macronutrients (nitrogen, N; phosphorus, P; potassium, K; sulfur, S, Ca, and Mg) in corn and beans grown on tropical soils [27]. Most EW experiments have been conducted in tropical regions on highly weathered, acidic soils, while studies in a temperate climate are still scarce [5].

[28] Demonstrated an increase in spring oat yield after application of basalt on direct-drill and ploughed plots in a temperate climate. These increases were assigned to a modest increase in pH that resulted in reduced manganese (Mn) and iron (Fe) uptake. This study also reported higher tissue Ca content and increased grain and tissue K upon basalt application. Contrastingly, the addition of volcanic rock dust to soils did not influence wheat growth in a mesocosm experiment in Sweden [29]. Furthermore, the aboveground biomass of potato plants tended to increase with basalt application in a mesocosm experiment in Belgium, growing on an alkaline soil [7]. Nonetheless, it is important to keep in mind that the apparent dominance of positive EW effects on crop growth might be affected by publication bias, as negative or non-significant results are less likely to be published compared to positive and expected outcomes [30].

Basalt powder significantly increased cocoa plant growth and in situ soil solution concentration of Ca, Mg, K, Na and Si, while Al and Mn concentrations were effectively reduced to non-toxic levels [31]. Soil pH and CEC increased with application amounts, whereas the best agronomic effectiveness was obtained by mixing basalt with rice husk compost at 5 t ha^{-1} each. [32] Reported that ground basalt alleviated Fe-deficiency (chlorosis) of peanuts grown on a calcareous soil with equal efficiency as the commonly applied synthetic organic chelate FeEDDHA. [33] Mixed 'Eifelgold', a commercial rock powder with basaltic composition, with cattle manure, which significantly reduced the NH_3 emissions of the manure after field application. Grass and maize growth increased and the apparent nitrogen recovery (ANR) was 2–3 times higher compared to the unamended manure. An ultramafic mining by-product substantially enhanced (up to 3- fold compared to control) rice (cv. Curinga) yield and shoot concentrations of K, Zn, Cu and Ni at non-toxic levels [34]. A significant increase in pH was reported for applying a basalt-diabase-bentonite mixture to three forest soils in Austria [35].

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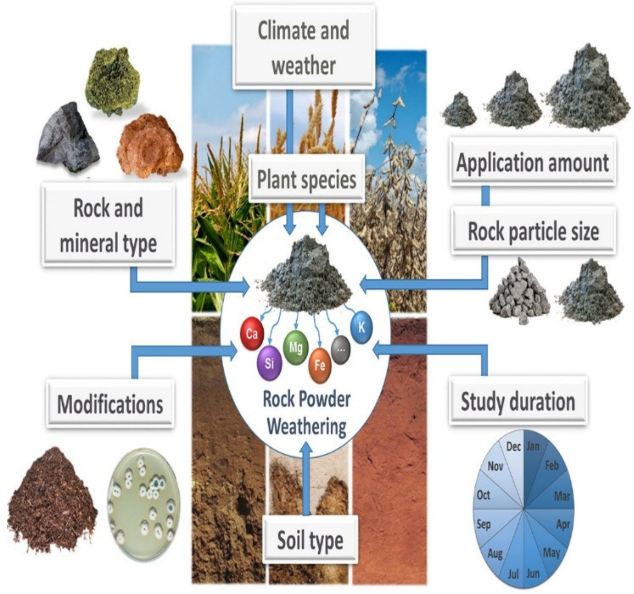

Fig1: Relevant parameters to consider for basalt co-benefits for soil, plant, and climate [5]

2.3. Review on Climate Benefits of Basalt Rock Dust

Significant potential exists for deployment at scale to remove atmospheric CO_2 with ground basalt. A maximum carbon capture potential of ~0.3t CO_2 t^{-1} is suggested for basalt, assuming a sufficiently fine particle size for effective dissolution on decadal time scales [20]. The actual particle size will depend upon the mineralogy of the basalt, climate and biological activity, and requires further investigation and verification, but initial calculations suggest particles of 10-30 µm diameter. On this basis, basalt applications of 10 to 50 t ha^{-1} yr^{-1} to 70 × 106 ha of the annual crops corn/soy in the corn-belt of North America could sequester 0.2–1.1 $PgCO_2$, up to 13% of the global annual agricultural emissions, in the long run. Theoretical estimates of CO_2 capture and sequestration schemes involving global croplands and silicate rocks are very uncertain. [36] reported that provisional estimates (suggest that amending two thirds of the most productive cropland soils (9 × 108 ha) with basalt dust at application rates of 10-30 t ha^{-1} yr^{-1} could perhaps extract 0.5-4 $PgCO_2$ yr^{-1} by 2100 depending on climate, soil and crop type.

A key issue affecting carbon capture efficiency is the energy cost associated with mining, grinding and spreading the ground rock, which could reduce the net carbon drawdown by 10- 30%, depending mainly on grain size [37]. Enhanced weathering accelerates CO_2 reactions with minerals contained in globally abundant, Mg- and/or Ca-rich rocks, a process that naturally moderates atmospheric CO_2 and stabilizes climate on geological time scales. In soils, chemical breakdown of carbonate and silicate rocks is accelerated during aqueous reactions with the elevated soil CO_2 environment, releasing base cations (Ca^{2+} and Mg^{2+}) and delivering bicarbonate ($HCO^{3\ -}$), and to a lesser extent carbonate (CO_3^{2-}) anions via runoff to surface waters and eventually the ocean. Enhanced weathering, therefore, uses the oceans to store atmospheric CO_2 as these stable dissolved inorganic alkaline forms. Given the oceans worldwide store around 38,000 Pg C, >45 times the mass of C in the current atmosphere, their future storage capacity is not an issue [11]. The residence time of dissolved inorganic carbon in the global ocean is around 100,000 – 1,000,000 years, making it essentially a permanent C-storage reservoir on human timescales. Weathering on land can also sequester atmospheric CO_2 without involving the oceans, if soil pore water chemistry results in precipitation of secondary carbonate minerals from base cation release [11].

A step further towards the marriage of agricultural use and climate mitigation use of agrominerals is BECCS, bio-energy carbon capture and storage [38]. This strategy calls for growing biomass feedstocks on an additional 0.5 billion hectares of land worldwide. The growth of fast and hardy crops extracts atmospheric CO_2. Relatively high energy costs for grinding, as influenced by rock mineralogy and crushing processes, call for innovation in the industrial sector, such as grinding and milling technology powered by renewable energy sources (solar, wind, water), to significantly increase the net CO_2 benefit. The benefit will increase as future energy sources are decarbonized, the grinding process becomes more energy efficient, and by utilizing already ground waste silicate materials previously or currently produced by the mining industry. By driving down costs for grinding in this way, carbon sequestration costs would be correspondingly cheaper. Current cost estimates are uncertain and vary widely, and better understanding the economics involved is a priority. The most detailed analysis for operational costs drawn-up for using a basic rock, such as basalt, gives values of US$52-480 tCO_2^{-1}, with comminution and transport [20].

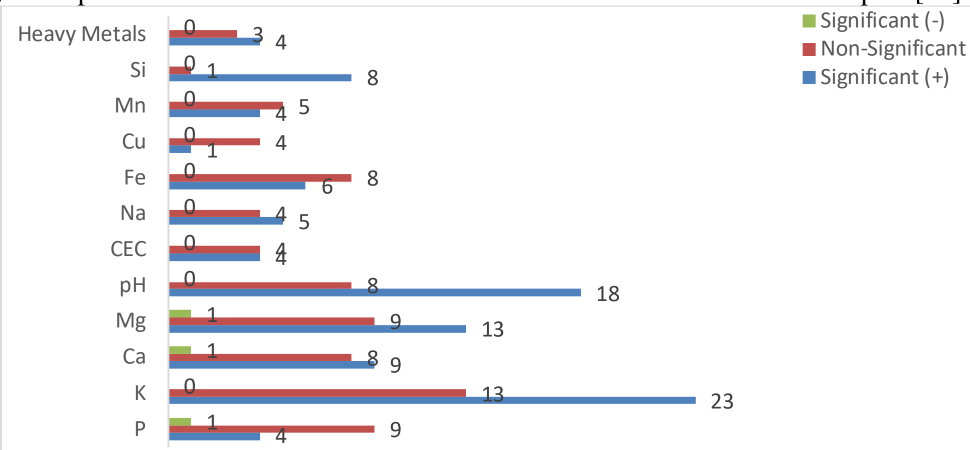

Fig2: Global review on the significance of silicate rock powder on soil minerals

3. CONCLUSION

The possibilities for using basalt rock powders are vast; part of this is soil fertilization which requires a simple procedure and can be rapidly scaled to the regional level. The rocks are widely distributed and readily available as a cheap byproduct. In general, these by-products are abundant in mining sites and are already in crushed and powdery form, a fact that does not require extra energy and new technology to obtain them. The use of basalt rock powder in agriculture provides a sustainable natural means to remineralize soils, improve crop agronomic values, and clean climate on a large scale. In tropical countries, with crucial agricultural sectors and great geo-diversity for food and income generation, the use of stone meal like basalt becomes a crucial productive alternative, particularly as these countries are struggling with the importation of chemical fertilizers. Furthermore, the increase in atmospheric CO_2 sequestration in agricultural soils may require an innovative approach, as it considers the potential of incorporating pre-industrial revolution levels to atmospheric CO_2 removal through the projected use of the global agricultural land. In addition to providing soil revitalization, the global atmospheric CO_2 can be reduced to a safe level for a better climate. Therefore, the different basalt dust application rates, particle sizes, remeniralization periods, and their synergy should be a crucial area of focus of future studies for improved soil fertility, crop productivity, and climate.

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