BioCarbon Earth

Biominerals – A White Paper **12/2024**

Biominerals, a new class of soil amendments

Biominerals are a new class of soil amendments that combines rock dust, pyrogenic carbon (a.k.a., biochar) and non-GMO organic biomass that produces plant growth promoting microbial communities. Through this unique combination and processing, biominerals can be used as a soil conditioner, biofertilizer and nutrient delivery system to enhance crop growth and sequester soil carbon.

Currently, there are several nature-based strategies being explored individually as methods to capture carbon, improve soil health and fertility, and reduce reliance on inorganic chemical fertilizers for crop production. The most prominent strategies utilize either biochar[1,2], biologicals (e.g., nitrogen-fixing bacteria)[3], the addition of organic matter through regenerative agriculture and composting[4], or enhanced rock weathering (ERW)[5].

Biominerals are a way to consolidate the benefits from each of these strategies into one framework which synergistically improves the efficacy of each individual method. Not only are biominerals produced in a low-cost, energy efficient way and can be done virtually anywhere, but they are also easily applied to any agronomic system using existing on-farm application methods.

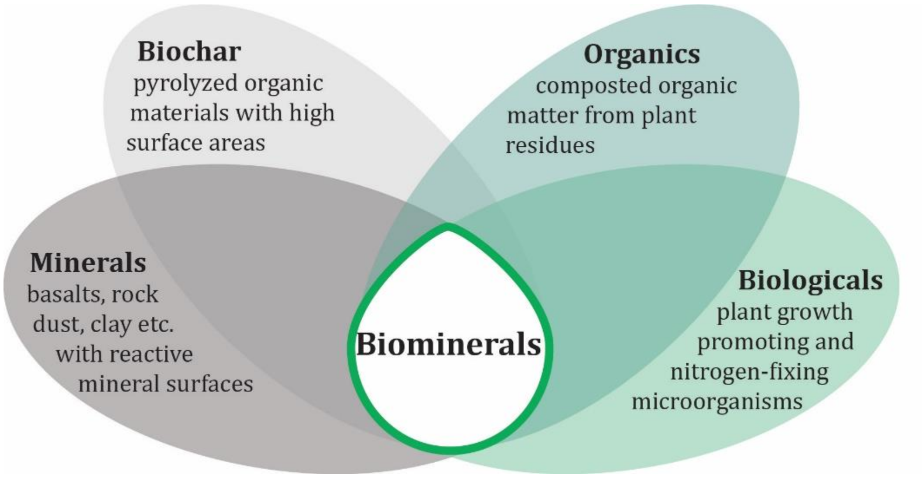

Figure 1. Conceptual diagram of biomineral components.

How do organics, biochar, minerals, and microbes synergistically interact to produce biominerals?

Compost and biochar both have long histories as soil amendments to improve crop production. Composting relies on biological decomposition of organic wastes that produces a material rich in carbon and nutrients that can be reapplied to soils to improve soil organic matter stocks, soil aggregation and moisture retention[6].

Biochar, "terra preta" or black earth, has also been used to improve soil fertility in a more rudimentary form for 2,500 years and has only more recently been refined from using charcoal from natural fires to producing charcoal under low oxygen and high temperature conditions[7]. Biochar also improves soil structure by promoting soil aggregation which improves moisture retention as well as water infiltration of soil[7]. Furthermore, biochar has been explored in bioremediation efforts as it has the capacity to sorb pollutants and toxins, such as PFAS and PFOS and plastics. Biochar can also be used in municipal waste remediation and agricultural liquid waste remediation. Additionally, pyrolysis of solid wastes (manure) is a potential waste management solution for large agriculture systems.

In addition to the soil health and environmental remediation benefits, biochar has been explored as a nature-based climate change mitigation tool because once the organic input materials are pyrolyzed, inorganic, highly condensed aromatic carbon compounds are formed. These compounds are difficult for microorganisms to degrade, therefore the carbon contained in them is expected to remain in soil for centuries to millennia. Not only does biochar store carbon for long periods of time, but it is also highly porous with a large surface area. The large surface area of biochar is covered in reactive binding sites for adsorption of nutrients, metals, and organic carbon compounds[8–10]. It has been shown that the highly adsorptive physical properties of biochar aid in soil fertility because the adsorbed nutrients, metals, organics and the microbial biofilms that colonize the biochar surfaces are released into the rhizosphere of roots[9–11]. Biochar also functions as an electron shuttle between microorganisms and iron-bearing minerals, resulting in the reduction of iron oxyhydroxides and thereby potentially forming organic-mineral complexes to further stabilize soil carbon[12]. Biochar's ability to shuttle electrons and adsorb metabolites in soil indirectly promotes plant growth through modulation of plant growth hormones in response to soilborne pathogens[9,13].

It is important to note that the archeological "terra preta" soils were rich assemblies of highly carbonized biomass (pyrogenic carbon, often derived from low fire "smoldering" woody biomass) combined with ceramic terracotta (shards of low fired clays, perhaps "chamber pots" rich in microbial colonies from containing biomass)[14,15].
The ceramics contain abundant metals, including base cations, manganese rich magnetite iron oxides and numerous other elements useful to microbiology and plant nutrient exchange. Recently researchers have explored co-pyrolyzing organic materials with nitrogen- or phosphorous-rich compost (derived from animal waste) or crushed minerals to mimic historic "terra preta" production[10,11,16,17]. These recent studies have demonstrated the beneficial effects of biochar are largely due to the elements sorbed to the biochar surfaces, making it an ideal component of any nature-based fertilizer amendment.

Rock dust, or natural pulverized rock mineral fines, are often derived from commodity aggregate production by-product streams including the alkaline aluminum silicates containing magnesium and calcium (e.g., primary magma such as the basalt), or feldspathic igneous rock such as K-feldspar granite, or metamorphic or sedimentary geologic materials derived from alluvial or deep-sea sediments such as black shale, or placers derived from sand and gravel pits. Currently the traditional use of the broad-spectrum rock dusts for remineralization has evolved into a Nature Based System (NBS) Carbon Dioxide Removal (CDR) technology for negative emissions strategy to mitigate climate change called enhanced rock weathering (ERW)[18,19]. Although basalt and olivine are the primary rock types for this purpose, numerous other geologic types have this potential while also delivering abundant mineral nutrients to living systems. Rock dust has a rich history globally to regulate soil pH (carbonate lime, gypsum) as well as to replenish depleted soil with macro and micronutrients, such as calcium, iron, magnesium, manganese, sodium, and silicon as well as important trace elements such as zinc, nickel, molybdenum, selenium and boron, essential for cellular metabolism[20]. While many of the metals released from rock dust enable necessary cellular functions, it is the microbially solubilized calcium and magnesium ions that have the potential to react with carbon dioxide to form carbonates that persist for long periods of time in terrestrial and aquatic environments[15,21,22].

Microorganisms are the drivers of all biogeochemical cycles on Earth. Improvements in technology have deepened our understanding of how bacteria and fungi function in the soil. Microorganisms have numerous survival strategies ranging from the ability to obtain energy from inorganic compounds (such as minerals) to gaining energy from decomposing organic compounds. Because of their wide range of metabolic functions, microorganisms have a large influence on plant growth, as either pathogens or plant growth promoting bacteria. Plant growth promoting bacteria directly and indirectly aid in plant growth through numerous pathways[23,24] – with nitrogen fixation being a popular mechanism being explored today. Microorganisms cultured in biominerals are not a “one trick pony” of providing nitrogen to plants through conversion of nitrogen gas to the plant available ammonium ($N_2 \rightarrow NH_3$). The microbial community in biominerals consists of a wide consortium of bacteria including mineral solubilizing bacteria, such as nitrogen and iron oxiders, and organic matter decomposers. Together these microorganisms work to release trace elements from the supplied minerals that stimulate the activity of the organic matter decomposers which further releases plant nutrients (N, P, K) for optimal growth.

When combined, these four individual strategies have the potential to provide plants with essential trace elements and nutrients that are retained on reactive surfaces of the biochar and mineral surfaces, while improving soil properties (moisture retention, pH and organic carbon stocks), and fostering a diverse microbial community that promotes plant growth.

How does the microbial community in biominerals improve soil health and crop growth?

Biominerals are produced by combining organic (i.e., crop residues) and inorganic (i.e., basalt rock dusts and biochar) feedstocks in a unique way that cultivates a microbial community that is capable of withstanding harsh environmental conditions (e.g., drought, high salinity, alkaline conditions, etc.), and functions in a beneficial mutualistic capacity. The microorganisms cultivated during the production of biominerals are generally gram-positive bacteria, meaning they lack outer cell membranes and are generally known for developing unique survival strategies in response to extreme environmental conditions. The mutualistic relationships of the microorganisms cultured in biominerals is distinct from what is currently commercially available. Instead of one or a few microorganisms that perform one function, such as nitrogen fixation, the microbial community cultivated in biominerals works together to perform numerous functions that are beneficial for plant growth and result in carbon mineralization.

Table 1. Commonly abundant bacteria species identified using 16S rRNA amplification sequencing in biominerals.

Bacteria (Genus Species)	**Plant growth promoting characteristics**
Bacillus species	Nitrogen fixation, phosphate solubilzation, siderophore production, plant growth hormone production, urease production, microbial induced calcite precipitation (MICP)[22,25,26]
Brachybacterium paraconglomeratum	Protects plant against salinity, mediates phytohormones, bioremediation of toxins and pollutants, urea and organic matter decomposition, ammonium production[27–29]
Glutamicibacter nicotianae	Degradation of antibiotics, cadium and plasticizers, urea degradation, dissimilatory nitrate reduction, ammonification[30,31]
Saccharomonospora viridis	Forms mutualistic relationships with other bacteria via production of cobalamin, resistant to abiotic stess[32]
Nocardiopsis species	Production of metabolites and enzymes, bioremediation of soil heavy metals and pollutants, symbiotic relationships with nitrogen-fixing bacteria[33–37]
Actinomadura species	Production of plant growth promoting hormones such as indole-3-acetic acid (IAA), siderophore production, phosphate solubilization[38]
Pseudogracilibacillus endophyticus	Nitrogen fixation, solubilization of inorganic phosphorus, production of plant growth regulators (IAA), and siderophore production for iron acquisition[39]
Sporosarcina pasteurii	Urease production, calcite precipitation (MICP), soil aggregate formation via carbonate production[40,41]

These functions include metabolism related to the nitrogen cycle such as the production of ammonium (plant available nitrogen) through urease-catalyzed hydrolysis of urea, nitrification of ammonium, dissimilatory nitrate reduction to ammonia (DNRA) and nitrogen fixation. The identified species in biominerals (Table 1) have also been shown to improve plant growth through several different other mechanisms. These mechanisms include the solubilization of nutrients (e.g., phosphorous) from the soil, production of siderophores which scavenge for Fe^{3+} uptake into the bacteria cell, thus depriving pathogenic fungi of available iron, secretion of metabolites and hormones that signal plant growth/release of simples sugars via roots, and the production of auxins (e.g., indoleacetic acid, (IAA)) which promotes germination, root growth and mediates plant responses to environmental stressors[42]. Microorganisms also decompose organic matter, which releases carbon and nutrients, prevention of root uptake of toxins and pollutants via cellular assimilation and induction of plant defenses against diseases such as root rot.

Overall, the microbial assemblage in biominerals promotes plant growth and sequesters carbon (discussed below) through numerous mechanisms. This multi-functional microbial community is also cultivated in a low-technology way that is energy and cost efficient and does not rely on aseptic culturing of individual bacteria species or gene editing, which are commonly used to create “biological” fertilizers or “bioinoculants”. Not only are biological fertilizers or inoculants costly to produce, but their ability to solely replace chemical fertilizers is unlikely given the physiological traits of bacteria and environmental conditions (e.g., oxygen availability or nitrate concentrations) that govern a microorganism’s ability to fix nitrogen. Furthermore, whether the applied inoculants can even survive or become dominant enough to produce enough nitrogen for crops is in question[43]. In fact, a 2023 review of biofertilizers conducted by North Dakota State University (NDSU) found that out of 61 on-farm trials, only 3 trials had greater yield in the treated plots compared to the control[44]. Lastly, the application of bioinoculants, when sprayed in aqueous solutions in agronomic systems, has a proclivity to develop biofilms on irrigation systems which causes unintended consequences the growers must confront when using these types of products.

Can biominerals improve carbon dioxide removal (CDR) strategies?

Not only do the cultivated microorganisms promote plant growth, but they are also primed to mineralize organic carbon into inorganic, long-lasting, carbon compounds – such as carbonates. This process is known as microbially induced calcite precipitation (MICP) and is when microorganisms produce carbonic acids (CO_3^{2-}) that react with calcium (Ca^{2+}) or magnesium (Mg^{2+}) ions to form carbonate precipitates ($CaCO^3$ or $MgCO_3$)[22]. This process can also happen abiotically via enhanced rock weathering, where carbon dioxide in soils reacts with $Ca^{2=}$ and Mg^{2+} ions released from crushed basalt rock dust[5]. What makes biominerals unique is that in addition to the abiotic mechanism that sequesters inorganic carbon, the microbial community cultivated during biomineral production is primed to induce carbonate production and releases Ca^{2+} and Mg^{2+} at faster rates than natural chemical weathering processes. Ultimately, the bacteria species in the biomineral material are suited for carbonate production themselves, and they also oxidize the reactive rock dust to solubilize nutrients and trace metals – a process known as microbial mediated plant nutrient exchange.

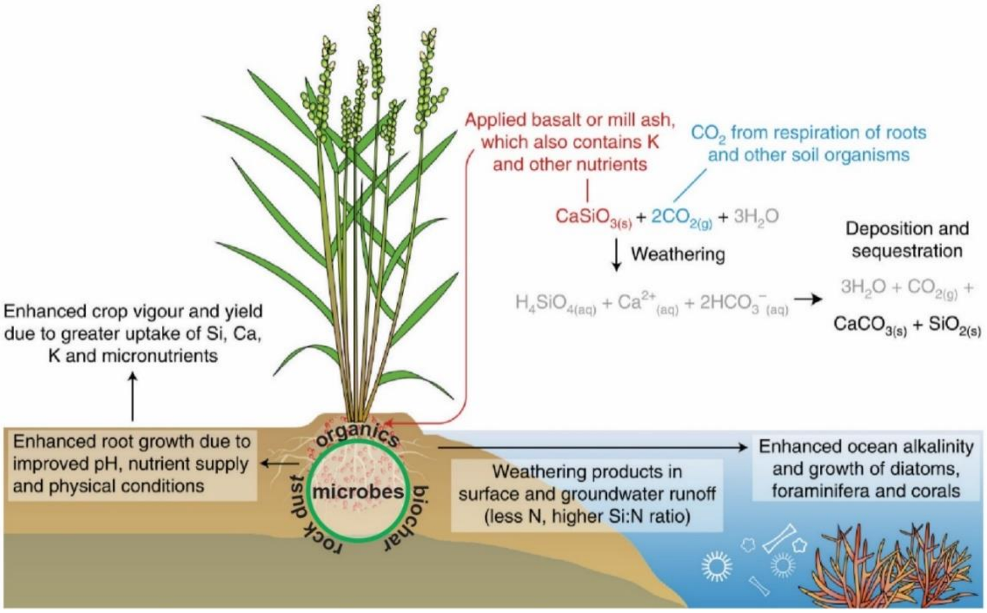

Figure 2. Diagram of enhanced rock weathering processes modified from Beerling et al., 2018: "Summary of the potential effects of weathering of crushed basalt or silicate-rich wastes, such as sugarcane mill ash, applied to croplands. As silicate rocks weather, they release nutrients that can improve soil conditions and support crop production, and also generate alkaline leachate, ultimately leading to export of dissolved inorganic carbon forms to the oceans." These processes are expected to be further enhanced from the basalt rock dust, organics, biochar and microbial community components of biominerals compared to applications of rock dust alone.

Through cultivating rock dust and organics together, the microorganisms can work symbiotically to release the calcium and magnesium ions that react with the carbon dioxide and carbonic acids produced during microbial respiration. This process is expected to happen naturally when rock dust is applied to the soil surface, however the pre-cultivation of the rock dust allows the optimal microbial species to become abundant to accelerate the process of enhanced rock weathering when applied to soil. Furthermore, the supplied organic materials and rock dust promote a close association between the microorganisms and the mineral surfaces while the biochar can mediate electron shuttling to and from the mineral surfaces. These mechanisms, when working together, can increase the rate of carbonate formation (inorganic carbon compounds) and can promote microbial decomposition of organic matter. It is now well established that old carbon in soil is predominantly composed of organic matter that has been microbially processed which have a higher affinity to be chemically bound to mineral surfaces and therefore can persist in soils for longer periods of time[45]. By promoting the formation of long-lasting inorganic compounds and organic-mineral complexes, biominerals have the potential to improve upon the existing ERW model supporting the nature-based CDR strategy.

Biominerals provide for a whole-systems, nature based strategy to adapt and mitigate climate related insecurities while providing for economic agronomic alternatives for crop production, maintenance and environmental restoration methods including providing for steep reductions in applied synthetic soluble fertilizers, reductions in applied toxic pesticides and fungicides, mitigation of legacy environmental toxins while increasing the carrying capacities and stability of global top soils.

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