*Article*

# Biorestorer: Synthetic Succession for Soil Restoration in Arid and Degraded Regions

**Jan Chvojka**

chvojka191@gmail.com

**Abstract:** Soil degradation in arid and semi-arid regions poses a critical threat to global ecological stability and food security. This paper introduces Biorestorer, a systems-based framework for initiating synthetic succession and synthetic pedogenesis in highly degraded or sterile substrates where natural recovery is infeasible. The Biorestorer concept integrates dual-temperature biochar, rock-solubilizing bacteria (RSB), and acidic minerals into a modular platform designed to lower pH, retain water, and promote microbial colonization—effectively jump-starting early-stage soil formation. Rather than focusing on reintroducing native vegetation or nutrients, Biorestorer reimagines soil as a biotechnological interface assembled and calibrated for extreme environmental contexts. Each module has empirical support from the literature, and although the full system has not yet been piloted in the field, its design allows validation through component-based experimentation. The approach is intended as a scalable tool for practical soil reclamation, ecological restoration, and land management in challenging environments. In addition, Biorestorer may offer a foundational approach for controlled extraterrestrial environments, such as Martian biospheres or lunar habitats, where resource-efficient and scalable pedogenic systems are essential. By merging ecological theory with engineered soil processes, this framework opens new possibilities for accelerated recovery of soil functions and regenerative land management both on Earth and beyond.

**Keywords:** soil regeneration; biochar; microorganisms; acidic rocks; soil degradation; desertification; arid regions; ecological restoration

## 1. Introduction

Soil degradation, particularly desertification, is one of the most serious environmental issues of our time, threatening billions of people and ecosystems worldwide. The deterioration of soil quality—caused by unsustainable agriculture, climate change, soil erosion, and improper land use—leads to a loss of soil fertility, which in turn decreases productivity and threatens food security [1]. This process is especially pronounced in arid and semi-arid regions, where a lack of water and organic matter essential for soil stabilization and recovery further exacerbates degradation. Studies from various environments, including forest ecosystems, have highlighted the role of stable carbon forms such as charcoal in improving soil resilience and long-term fertility [2], which may inform restoration strategies in dryland contexts [3].

### *1.1. Desertification as a Global Problem*

According to estimates by the UNCCD (United Nations Convention to Combat Desertification), approximately 40% of the world's land is affected by various forms of degradation. In arid regions, the problem is further exacerbated due to the lack of sufficient water reserves, and as a result of unsustainable agricultural practices, the soil often becomes biologically inactive. Traditional soil restoration methods—such as irrigation, composting, or synthetic fertilizers—can be ineffective or costly [3], and in arid environments, they have not proven to be sustainable.

### *1.2. The Potential of Biological and Mineral Regeneration*

In response to this challenge, Biorestorer was developed—an innovative approach to soil regeneration that combines biochar, microbial processes, and acidic rocks to sustainably improve soil structure, lower pH, and support microbial activity. This bio-mineral system is designed to function in low-carbon, structurally poor soils under limiting environmental conditions [4]. It serves as both a carrier for microorganisms and as a structural enhancer that improves soil texture, increases water retention, and reduces temperature fluctuations.

Research shows that biochar can enhance soil fertility by retaining nutrients and creating a stable environment for soil microflora. The combination of RSB bacteria and acidic rocks offers an additional benefit—controlled acidification of the soil, which increases the availability of nutrients and minerals for plants [5,6], thus accelerating the colonization of degraded areas.

### *1.3. Aim of the Article*

This article proposes a new framework for soil restoration—one that focuses not on revitalizing existing soil, but on its synthetic creation: a soil starter capable of initiating fundamental pedogenetis processes in sterile and inhospitable conditions.

The system is designed to:

- optimize soil pH [6] and increase nutrient availability [5,7],
- activate microbial processes within the soil, and improve soil structure and water retention capacity over the long term [8].

The article further analyzes the application procedure, expected outcomes, and the potential for global deployment of this method in regions facing desertification and land degradation.

Pedogenesis is inherently linked to geodiversity, as soil formation depends on the mineral composition, structure, and weathering of geological substrates. By initiating synthetic pedogenesis using geologically informed materials, the Biorestorer system applies geodiversity as a foundational tool for ecosystem regeneration.

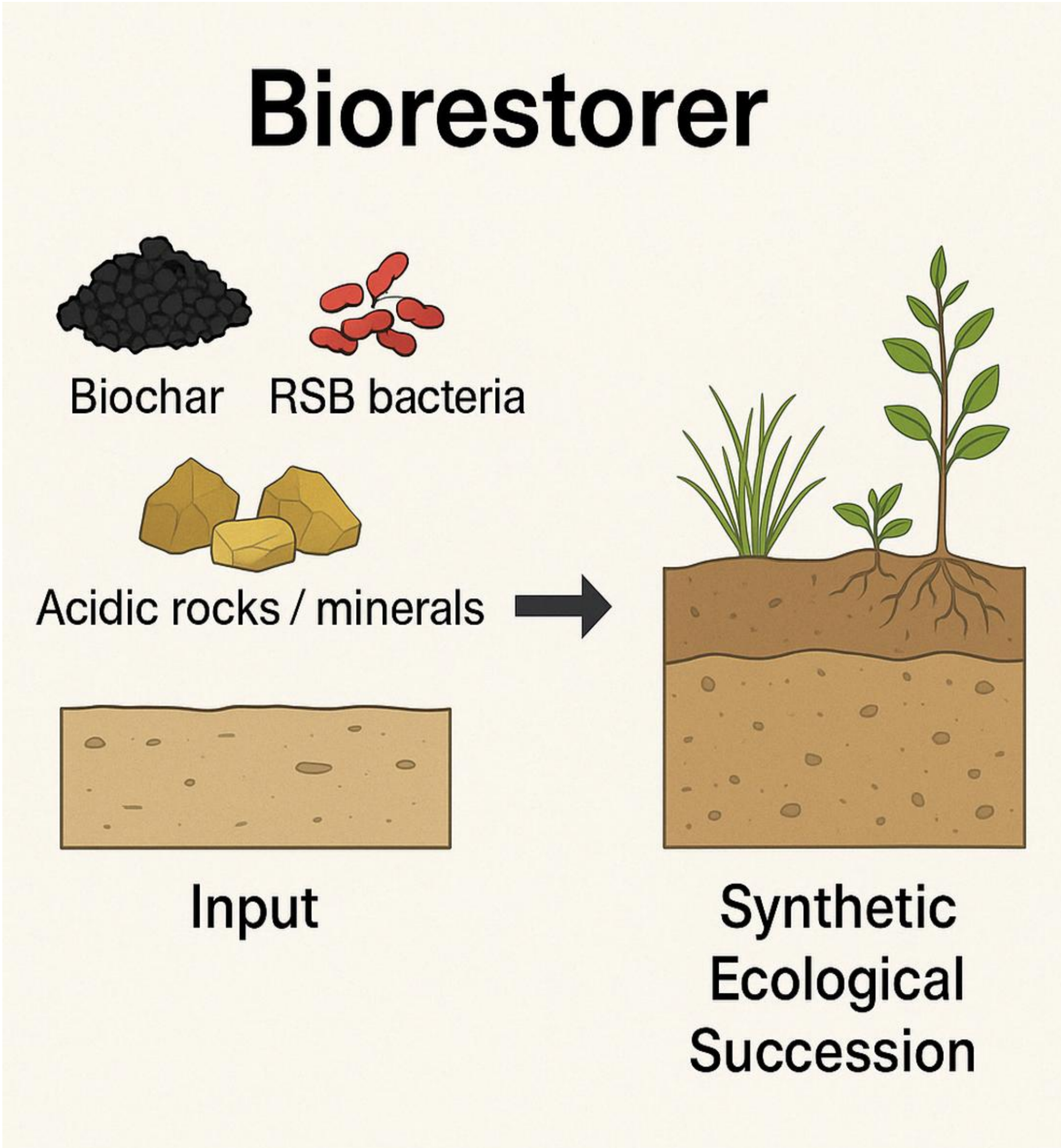


**Figure 1.** Graphical abstract illustrating the process of synthetic succession initiated by the Biorestorer platform.

## 2. Materials and Methods

Bacteriolite is a biological soil stimulant composed of microbial inoculants (often including redox-active bacteria and mycorrhizal fungi [9]), enriched with humic substances, clay minerals, or other natural carriers. Its primary function is not to supply organic matter, but to activate soil life and accelerate microbial colonization. Unlike compost, it contains a lower amount of stabilized carbon but exhibits higher biological activity and a greater capacity to colonize sterile or degraded soils. Within the Biorestorer platform, it plays a key role in initiating life within the substrate and stabilizing pioneer succession.

For the regeneration of alkaline and desertified soils, a substrate based on biochar, rock-solubilizing bacteria (RSB), and acidic rocks was developed. These components together form a bio-mineral substrate that enhances water retention [5], regulates pH through microbial action [6], and contributes to improved soil structure over time.

When using biochar produced at 800 °C, its strongly alkaline pH (9.5–11.5) must be taken into account. A high proportion of such carbon can disrupt microbial balance in the substrate, particularly during the initial activation phase of the system. Therefore, it is recommended to combine different types of biochar (e.g., 600 °C + 800 °C) or to supplement the substrate with acidic and biologically active components. Since the main acidifying effect in the Biorestorer system is provided by RSB bacteria, higher pH values can be tolerated as long as the component ratios are appropriately adjusted.

Even when using high-temperature biochar (e.g., 800 °C), which has a high pH and strong chemical stability, the functionality of the system can be maintained through simple compensatory mechanisms. Reducing the dosage of 800 °C biochar, combining it with lower-temperature biochar (~600 °C), increasing the proportion of acidic rocks, or pre-acidifying the substrate (e.g., via fermentation) allows the substrate pH to be maintained within a tolerable range for RSB bacteria. Stable carbon alone does not actively increase the pH of the substrate, especially after exposure to outdoor conditions. The key is the proper composition of the matrix, which enables RSB to create localized microclimatic and pH zones essential for their activity. This maintains the biological effectiveness of the system even when using technically advantageous but more alkaline biochar.

Within the Biorestorer system, biochar produced at 600 °C is primarily used, as its higher porosity and lower pH support microbial activity in the short to medium term. Biochar produced at 800 °C is used as a supplementary fraction, mainly to ensure the long-term structural stability of the substrate. Although it has a lower capacity to retain water and nutrients, it contributes to the system's durability [6,8]. Combining both types allows for an optimized balance between biological activity and long-term stability across different application zones.

Even high-temperature biochar (~800 °C) tends to lower its pH by 1–2 units after exposure to air, moisture, and microorganisms. This natural aging process—known as "biochar aging"—results in the neutralization of alkaline components, oxidation of the carbon surface, and gradual colonization of the substrate by microorganisms that produce weak organic acids. This natural aging process—described in detail in biochar studies [10]—results in the neutralization of alkaline components and microbial colonization, making it compatible with RSB bacteria without risk of disrupting the substrate environment [11].

### *2.1. Biochar Production*

The biochar was produced from organic materials (wood, agricultural residues) using pyrolysis at temperatures of 600 °C and 800 °C. The lower-temperature fraction (600 °C) has high porosity and water-holding capacity, enhancing the substrate's ability to retain moisture. The higher-temperature fraction (800 °C) is chemically stable and provides long-term structural integrity, meaning that this biochar remains effective in soil without decomposing.

Flexibility in Biochar Feedstock: Although the ideal material for producing biochar is woody biomass (both hardwoods and softwoods) with high carbon content and low ash content, in field conditions or developing regions, it is also possible to use alternative, locally available materials such as: agricultural waste (husks, straw, corn cobs), plant residues, cane processing waste, uncontaminated organic municipal biowaste.

These sources may be of lower quality (higher ash content, lower porosity), but they allow for increased substrate volume and enable the solution to be expanded into areas where wood is scarce or unavailable.

A suitable compromise is the combination of: High-quality biochar (e.g., from hardwood, 800 °C) as a stable carrier for microorganisms, supplemented by volume-extending additives from simpler sources that improve water retention but do not take over the carrier function. Such additives may include straw, plant residues, nutshells, crushed zeolite, light pumice, or other local materials that increase the porosity and volume of the substrate without negatively affecting microbial performance. This combination enhances the availability of the solution even in resource-limited environments, as supported by restoration strategies in drylands [3] and field-oriented evaluations of biochar use [12].

*2.2. Rock-Solubilizing Bacteria (RSB)*

Types of Microorganisms: RSB bacteria release nutrients from minerals and lower pH, which is key to improving nutrient availability [6]. These bacteria are selected for their ability to produce acids that support the mobilization of phosphorus, calcium, and other mineral elements essential for plant growth. They are incubated within a biochar matrix, which protects them from desiccation and optimizes their activity in the soil.

RSB form the foundation of biological activity in the Biorestorer substrate. These microorganisms are capable of releasing nutrients from the soil's mineral components through the production of organic acids (e.g., citric, gluconic, oxalic acids), chelating agents, or enzymes. A key advantage of RSB is their ability to survive and function in environments with minimal or no organic matter.

Many representatives (e.g., Bacillus, Pseudomonas, Acinetobacter) utilize inorganic substrates as sources of nutrients and carbon, and do not require humus or compost to be active. This makes them particularly suitable for extremely degraded soils where organic matter content is less than 0.5%. In combination with biochar, not only is their survival ensured, but also their ability to actively function after irrigation [6]. Biochar creates favorable microhabitats that support microbial persistence and reactivation under field conditions [7].

*2.3. Acidic Rocks*

The most suitable acidic rocks in terms of calcium content are andesite, basalt, and granodiorite, which contain $Ca^{2+}$ bound in plagioclase minerals [13] as part of the soil sorption complex. In contrast, rocks such as granite or rhyolite contain very little calcium [13].

If acidic rocks (e.g., basalt, andesite, phonolite, or certain types of granite) are not available, they can be partially or completely replaced by locally available rocks with neutral to slightly alkaline pH. Although these minerals do not contribute significantly to pH reduction, they can provide a broad spectrum of nutrients (e.g., calcium, magnesium, potassium, micronutrients) that are often lacking in sandy or highly weathered soils. Moreover, acidification of the substrate is primarily achieved by RSB bacteria, which produce organic acids independently of the type of mineral fraction. Thus, even when neutral rocks are used, localized acidification and nutrient mobilization can still occur. This approach increases the flexibility of Biorestorer application across different geological conditions without compromising functionality.

Crushed acidic rocks, such as granite or phonolite, were used for soil acidification. These rocks weather slowly and release mineral elements like potassium, calcium, and magnesium. They play an important role in stabilizing soil pH [13] and supporting long-term acidification, which is essential for improving conditions for plant growth in alkaline soils.

Flexibility in the Use of Covering Mineral Fractions: In dry and windy regions where acidic rocks may be scarce, locally available rocks with neutral or slightly alkaline pH can also be used as a protective cover layer over the substrate. Mineral amendments can improve soil structure in arid areas [3]. In such cases, their primary purpose is not chemical soil adjustment, but mechanical protection of the substrate against wind erosion, desiccation, and overheating.

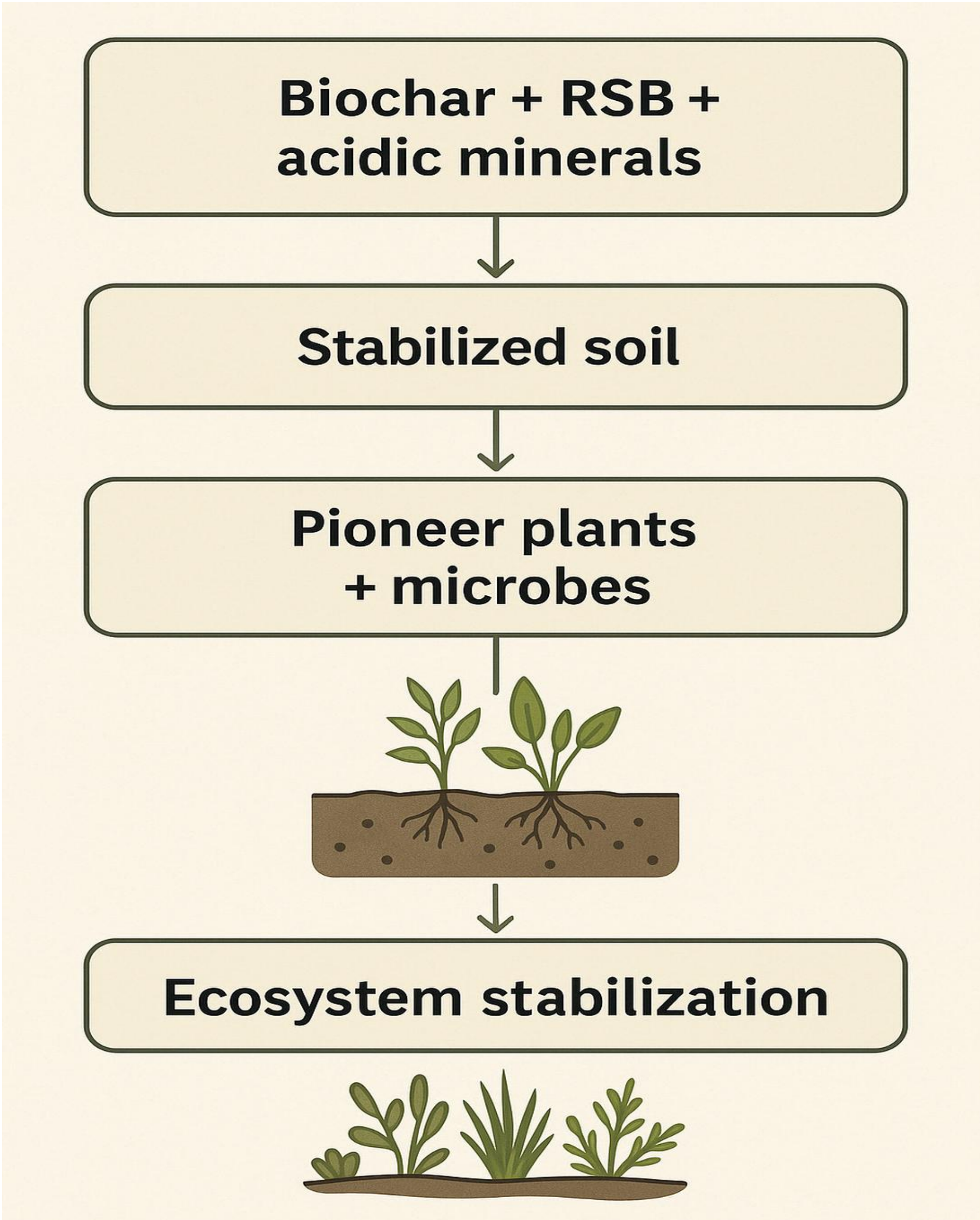


**Figure 2.** Synthetic succession as the core principle of the Biorestorer system. Phase 1 involves the formation and stabilization of the substrate through a mixture of biochar, RSB, and acidic minerals. In Phase 2, the biologically prepared matrix supports microbial colonization and the establishment of pioneer vegetation, leading to long-term ecological functionality and succession.

Although these rocks do not significantly contribute to substrate acidification, their impact on pH will be minimal—mainly because the substrate is applied below the surface, and climatic conditions (such as dryness) limit solubility and chemical interaction. The biological activity of RSB within the substrate can compensate for the slower pH change caused by using a less reactive cover layer. This approach also improves the economic efficiency and local applicability of the solution, as it eliminates the need to import specific minerals over long distances.

Biorestorer relies on the strategic use of geodiversity components, including the mineral substrate and the protective cover layer, which consist of locally available rocks and other geogenic materials. These layers are designed not only to adjust soil pH and improve structure but also to replicate and enhance abiotic diversity. In this way, Biorestorer leverages geodiversity to support ecosystem restoration, foster microbial and plant establishment, and restore ecosystem functions in degraded or arid soils.

### *2.4. Substrate Pre-Treatment*

Biochar has also been shown to improve plant resilience under abiotic stress conditions, such as drought and temperature extremes, by enhancing the soil microenvironment and supporting beneficial microbial interactions [14].

Before application, biochar can be: Washed with a solution of ferrous sulfate (green vitriol), or soaked in a mildly acidic solution (e.g., sulfuric acid, citric acid, or extracts from acidic pyrolytic fractions), or mechanically treated and inoculated without any chemical additives.

These pre-treatment methods are optional and implemented depending on local conditions. Their purpose is to lower the initial pH of the substrate to facilitate faster system activation. However, they are not strictly necessary—some RSB strains can survive and remain active even at pH levels up to 9 [15]., which preserves their viability even without acidification.

Pre-acidification before application may also serve to temporarily lower the substrate's pH, creating a more favorable microenvironment for triggering microbial activity prior to stabilization through the action of rocks and biochar.

After the substrate is applied, it is important to monitor soil pH development, particularly in the first few weeks following irrigation or rainfall. However, the surrounding soil usually possesses a natural buffering capacity that dampens changes in pH caused by the substrate’s acidic components. As a result, large-scale acidification is highly unlikely.

A temporary localized drop in pH may occur, especially in areas where soluble organic or inorganic acids from acidic rocks or pyrolytic fractions accumulate. However, this effect typically stabilizes quickly under natural conditions.

Acidification of the substrate through pre-treatment (e.g., with green vitriol, organic acids, or acidic pyrolytic extracts) is supplementary and should be applied only when local conditions permit. It is not essential.

Some strains of rock-solubilizing bacteria (RSB) are capable of surviving and maintaining basic metabolic activity even at pH levels up to 9. This trait allows them to persist in alkaline soils until the system is activated (e.g., after rainfall), without the need for immediate acidification.

Biochar also creates microenvironments with different pH values, where these bacteria are protected from the extreme conditions of the macroenvironment. Their activation occurs after irrigation, when the water regime shifts and the pH within the microenvironment gradually stabilizes.

### 2.5. Application Strategy

In areas with steep terrain or extremely low water infiltration, the Biorestorer application matrix can be supplemented with semi-circular bunds, which concentrate rainfall directly at the application points. These bunds are oriented with their openings facing upslope, capturing rainwater and retaining it in the substrate zone. When combined with pit-based application methods (e.g., the Zaï technique), they enable efficient moistening of the substrate, reduce erosion, and support the rooting of pioneer shrubs or trees. This technique is optional, but it increases the likelihood of successful ecological restoration, especially in sloped or severely desiccated areas—although it may slightly increase costs and labor intensity.

For effective substrate application, three main techniques are used Zonation:

- zones: In areas intended for intensive substrate application and plant growth, the substrate is applied as full-surface coverage;
- Buffer zones: In these areas, the substrate is applied at medium density (often in a 2×2 m or 3×3 m Productive grid), optimizing input use while allowing gradual vegetation expansion;
- Non-productive zones (grid): These zones are essential for protecting surrounding areas and preventing the spread of degradation. The substrate is applied in regular grids (1×1 m) to minimize costs.

Grid-based application: Applying the substrate in a grid pattern (1×1 m to 3×3 m) ensures efficient material use and even coverage of the soil with the biological substrate. Application costs are minimized because the matrix allows the substrate to cover only specific points, achieving high effectiveness with lower material input.

Application depth: The substrate is applied at a depth of 5–10 cm in soils with low organic matter content. For woody plants, the substrate is applied deeper (up to 15–25 cm) to ensure proper root anchoring and nutrient availability even under low moisture conditions.

A mineral layer (acidic rocks or inert materials) is applied over the substrate matrix to reduce water evaporation, protect the substrate from wind erosion, and stabilize soil temperature. This layer also shields the substrate from direct sunlight, improving conditions for microbial activity and increasing the success rate of plant growth. Additionally, the surface cover plays a critical role in hydrological management by reducing surface runoff during rainfall events, enhancing water infiltration, and supporting dew condensation and retention. These functions contribute to more efficient water use in arid environments and help maintain moisture availability in the root zone for longer periods.

Planting of pioneer species takes place only after the soil and substrate have stabilized, which is a key condition for successful root establishment. Stabilization occurs following the application of the Biorestorer substrate—when the pH balances, structure improves, and microbial activity is activated in the soil. The planting process is targeted—bacteriolite is applied directly to the plant root zone to ensure rapid contact with the microbial community.

After planting, simple but effective protective measures are used: a shade net protects the plant from solar stress during the rooting phase, and a support stake stabilizes the plant against wind, minimizing mechanical damage and the risk of uprooting.

### 2.6. Pilot Testing

Biorestorer is tested on controlled plots where the following factors are monitored:

- Soil pH [6] before and after substrate application;
- Microbial biomass (number of microbial colonies);
- Soil moisture and water retention capacity;

- Plant rooting success, growth rate, root penetration, and organic matter content in the soil.

Pilot tests provide critical information about the system's effectiveness and serve to optimize application strategies for various soil types and climatic conditions.

Use of Generative AI: During the preparation of this manuscript, the author used ChatGPT-4 (OpenAI, 2024) to assist in language editing, literature synthesis, and the technical restructuring of content. The system was not used to generate original scientific concepts or data. All content has been reviewed and verified by the author, who takes full responsibility for its accuracy.

## 3. Expected Results

### *3.1. Long-Term Reduction of Soil pH and Improved Soil Reaction*

One of the main expected outcomes of Biorestorer application is a reduction in soil pH [6], which is often the root cause of low fertility in alkaline and desertified regions. The use of acidic rocks and rock-solubilizing bacteria (RSB) should lead to a long-term decrease in pH, creating optimal conditions for the growth of plant species that prefer slightly acidic to neutral soils.

Acidic rocks will weather slowly, ensuring gradual and sustained pH regulation over time. This will also improve the availability of essential nutrients for plant growth, such as potassium, calcium, magnesium, and trace elements required for development [13].

### *3.2. Increased Microbial Diversity and Activity*

The application of biochar and RSB bacteria will have a direct effect on soil microbial diversity. RSB bacteria, which activate nutrient release, will act as catalysts for microbial processes, thereby increasing microbial activity in the soil [16,17,18,19]. As a result, soil structure and water retention will improve, which is crucial for maintaining fertility in dry and degraded areas [8,6]. Biochar serves as a carrier for microorganisms, providing protection [10] and stability in the soil, which allows long-term support for microbial communities [19,20].

### *3.3. Increased Water Retention*

Applying biochar to soil is known for its ability to retain moisture, which is especially important in regions with low rainfall [5,21]. Biochar can trap moisture in the soil and prevent rapid evaporation. This directly improves the soil's water balance and reduces the impact of drought on plants. After Biorestorer is applied, it is expected that the soil will exhibit enhanced water retention, allowing plant growth even during dry periods. This effect will be reinforced by the presence of RSB bacteria, which help reduce water loss and stabilize the soil.

### *3.4. Stabilization of Soil Structure and Plant Colonization*

Biorestorer application is expected to lead to the successful colonization of pioneer plants [3], which are capable of growing under more challenging soil conditions. These pioneer species are essential for initiating the process of ecological succession in degraded soils, as they create the conditions needed for the development of additional plant species and microbial communities.

In the first years following application, soil structure is expected to stabilize, improving the environment for root growth. The increase in organic matter during succession will further enhance fertility and strengthen the connection between microbial communities and vegetation.

### *3.5. Long-Term Increase in Fertility and Improvement of Soil Structure*

Over the long term, the Biorestorer substrate undergoes biological and chemical maturation, where microbial acidification (RSB) [6,] and the gradual weathering of mineral components lead to increased system efficiency without the need for repeated application [22,23].

The application of Biorestorer will lead to long-term improvement in soil fertility, as biochar and mineral additives provide stability and protect the soil from erosion and degradation [24,25]. Acidic rocks will also release essential nutrients needed to support plant growth over many years. As a result, soil structure will improve, and its capacity to support diverse plant species will increase [26].

The combination of microbial processes, mineral sources, and biochar leads to enhanced soil fertility and creates self-regenerating conditions that ensure sustainable restoration even under extreme conditions. The effectiveness of biochar in improving the fertility of sandy soils has been confirmed in soils along the southeastern coast of the United States [27]. The combination of biochar with organic amendments has proven to be an effective strategy for increasing soil fertility and agricultural yields in various conditions [28]. This effect has also been observed in increased tomato yields following biochar application [24,29].

Biochar significantly influences the structure and function of soil biota [30]. The concept of the "charosphere" highlights the unique microbial habitat created by biochar [31].

Systematic reviews emphasize the importance of biochar for long-term soil health [32]. Meta-analyses also indicate that biochar improves soil function and crop performance in temperate climates [33].

Biochar is also used in the reclamation of contaminated and degraded soils [34].

Pyrogenic carbon has proven to be a stable form of carbon with broad applicability in agriculture [35].

Biochar has been shown to be an effective tool for improving soil quality and increasing agricultural productivity [20,28].

Review studies confirm the positive effects of biochar on the physical and chemical properties of soil [36].

### *3.6. Long-Term Ecological Benefits*

The application of Biorestorer can bring significant long-term ecological benefits, particularly in the area of biodiversity restoration. As soil regeneration progresses, improvements in water retention, nutrient cycling, and microbial activity are expected to create conditions favorable for the colonization of pioneer and secondary plant species. These vegetation dynamics will contribute to the reestablishment of local ecosystems and ecological functions [3].

This effect is not limited to small-scale projects. The modular and adaptive nature of the Biorestorer system allows for its application across large degraded areas where traditional soil restoration methods—such as composting or fertilization—have proven ineffective or economically unsustainable. In these contexts, Biorestorer can initiate synthetic ecological succession, promoting both structural and biological recovery [22].

The increased microbial activity induced by the RSB component plays a central role in soil bioproductivity and supports a diverse range of microbial and plant communities. Over time, this interaction stabilizes the soil environment and facilitates the gradual return of native biodiversity [3,17].

*3.7. System Resilience to Soil Salinity*

One of the advantages of the Biorestorer system is its natural resilience to soil salinity [37,12,38], meaning it can survive and function even under higher concentrations of $Na^+$ and $Cl^-$ ions [12]. Additionally, the biochar used in the substrate has a high cation exchange capacity [20], which facilitates the replacement of sodium ions with more beneficial cations such as $Ca^{2+}$ and $Mg^{2+}$ [39].

The zonal and grid-based application of the substrate further enables the formation of microzones with improved water and ion dynamics, contributing to localized improvements even in highly saline soils [40]. In cases of extreme salinity, the substrate can also be supplemented with gypsum ($CaSO_4$), a traditional remediation material used in solonchak (saline) areas. Thanks to these properties, Biorestorer is suitable for soils affected by secondary salinization and represents a functional foundation for ecological restoration even under these specific conditions.

*3.8. Monitoring Effectiveness and Practical Evaluation*

A key factor for the success of Biorestorer will be the long-term monitoring of its effectiveness and evaluation under real-world conditions. The system is expected to be continuously assessed based on soil parameters (pH, organic matter), microbial activity, and plant growth success. This evaluation will be essential for making adjustments and optimizing application strategies, ensuring the system's successful implementation in diverse environments.

## 4. Discussion

In extreme or logistically challenging conditions, Biorestorer is applied based on the principle of availability: each component can be replaced with a functionally similar alternative in order to preserve the system's integrity. It is not a rigid recipe, but an adaptable platform—where granite is unavailable, dolomite may be used; where there is no oak, reed can be substituted. The core principle remains: to activate microbial recovery within a mineral–biochar matrix.

The logic of the Biorestorer system mirrors the natural process of ecological succession, as observed during the colonization of new lava fields or volcanic islands. In both cases, the foundation involves the introduction of pioneer species, creation of microclimatic niches, stabilization of water and substrate, and gradual layering of biological complexity. Thus, the platform represents not only a technical solution but also a concept of synthetic pedogenesis—a biologically inspired initiation of a soil ecosystem where the basic conditions for natural formation are absent.

Even when high-quality biochar is not available in large volumes, the Biorestorer system is designed to allow substitution with other available carbon fractions or temporary reduction of biochar input without loss of functionality. In agroecosystems, such as rice paddies, the application of biochar has been linked not only to yield increases but also to the reduction of methane and nitrous oxide emissions [11]. In real-world applications—particularly those involving large-scale land restoration (e.g., thousands of hectares)—it is natural for the project to include supporting technological infrastructure such as mobile or locally based pyrolyzers, biomass collection logistics, and on-site production of inputs. The solution is therefore deployable immediately and designed to integrate with capacity-building efforts as part of long-term landscape restoration programs.

In developing regions, biochar can also be produced from by-products of wastewater treatment plants or sludge—where the pyrolysis process allows the production of stable carbon material while simultaneously recovering nutrients [41].

The substrate developed within the Biorestorer platform is, by itself, a complete solution with significant ecological impact. It is capable of functioning independently as an activator of soil life, a pH regulator, and a water-retentive nutrient carrier—even under extreme conditions. It can therefore be applied on its own—as an initial phase of ecological restoration or as a product for agricultural regeneration. In combination with locally sourced materials, the substrate remains viable even in settings without full technological infrastructure, thus maintaining both practicality and universal applicability.

It is also important to consider the different functions of biochar based on its pyrolysis temperature. Biochar produced at 800 °C possesses exceptional chemical stability and is therefore best suited for non-productive or buffer zones, where frequent management or regular input replenishment is not expected. In these areas, long-term effectiveness and minimal intervention are required, and carbon stability ensures the durability and resilience of the substrate. In contrast, in productive areas that are regularly fertilized and cultivated, it is appropriate to use biochar produced at lower temperatures (500–600 °C), which has a higher capacity to retain nutrients and water, and can be applied periodically along with standard agricultural practices. This differentiation allows for optimal use of materials depending on soil type and application goals.

The cost-effectiveness of application depends on the availability of local raw materials, the chosen application technique, and the condition of the soil. However, thanks to the modular architecture of the Biorestorer system, the design can be adapted to conditions with limited budgets or infrastructure. This approach allows for cost optimization without significantly compromising the system's functionality.

When designing and applying the Biorestorer system, it is also important to consider the economic efficiency of the solution. While the complete substitution of acidic rocks or high-quality biochar may lead to a slight decrease in effectiveness, the system remains functional due to the synergy of its components—particularly RSB and microbial acidification. This flexibility allows the solution to be adapted to local conditions without significantly reducing its ecological impact. The final cost-to-effectiveness ratio is optimized precisely because Biorestorer works even in "sub-optimal" conditions—which is a key advantage in arid regions compared to rigid systems.

Biorestorer represents a comprehensive and innovative approach to the regeneration of alkaline and desertified soils. Its use combines biochar, microbial processes, and acidic rocks to achieve long-term improvement in soil structure, water retention [19], and fertility in areas affected by land degradation [6]. This approach, distinct from conventional organic methods, enables successful application in extreme conditions where typical soil restoration strategies are either too costly or ineffective.

Advantages of Biorestorer

Efficiency with low inputs: One of the main advantages of Biorestorer is that it does not require the regular application of expensive organic materials. The system relies on microbial activity, which allows for cost-effective soil regeneration—making it ideal for areas with limited access to high-quality organic fertilizers.

Long-term stability: The use of biochar provides long-lasting structural enhancement to the soil. The 800 °C biochar fraction decomposes much more slowly than typical organic materials, ensuring the stability of the system for decades. Additionally, acidic rocks support sustained acidification, which is crucial for the successful colonization of plants in alkaline soils.

Modular and Adaptable Application: Zoning and matrix-based application enable flexible use of Biorestorer in various regional conditions. This approach allows for the adaptation of the application according to available resources and specific environmental conditions, optimizing input use.

### 4.1. Improvement of Microbial Diversity

RSB bacteria support the presence and activity of microorganisms that are essential for prolonging the soil life cycle and maintaining ecological processes. These bacteria act as catalysts that enhance nutrient availability for plants and lower soil pH [6], thereby improving conditions for the growth of additional plant species.

### 4.2. Challenges and Limitations

Availability of Acidic Rocks: For successful implementation of Biorestorer, access to acidic rocks such as granite is necessary. Their availability may be limited in some regions, which can increase the cost of application. In such cases, it will be necessary to look for alternatives or rely on inert rocks, which have lower effectiveness but can be used as a fallback option.

Monitoring pH and Long-Term Effectiveness: The application of acidic rocks in combination with RSB bacteria can be highly effective in lowering soil pH [6], but excessive acidification may harm soil microflora or affect plant species that are sensitive to low pH levels. Therefore, it is essential to regularly monitor soil pH [6] and track its dynamics during and after application.

After the substrate is applied, monitoring soil pH development is particularly important in the initial stages following irrigation or rainfall. The surrounding soil typically has a natural buffering capacity that mitigates changes in pH caused by the substrate. Thus, the likelihood of widespread acidification is low, even when acidic components are used.

Acidification may occur only locally and temporarily—mainly after heavy irrigation, when acids are released from rocks or residual pyrolytic fractions. However, this effect generally stabilizes within a few days to weeks due to interactions with the surrounding soil environment.

Under normal conditions—without extreme water input—over-acidification is unlikely. We recommend monitoring pH development at intervals of 2–4 weeks after application in order to determine the optimal pace of mineralization and microbial activity.

Dependence on Microbial Activity: Soil microbial activity, supported by the action of RSB microorganisms [17], is critical to the system's effectiveness [16]. However, if the microorganisms are not sufficiently activated (e.g., due to very low temperatures or lack of water), the system's performance may decline. Therefore, it is essential to ensure that Biorestorer is applied under conditions that favor microbial activation.

Soil Response to Different Application Types: Different soil types may respond differently to acidic rocks and biochar, which can affect the long-term success of the application. It is therefore important for Biorestorer to be tested across various soil types in order to determine the best conditions and application methods for each region.

### 4.3. Global Potential of Biorestorer

Biorestorer has global potential [29] and can be applied in various regions where soil is degraded due to alkalinity, poor structure, or contamination. Its low cost and high effectiveness in arid zones make it an excellent tool for regions facing desertification and land degradation. The implementation of Biorestorer could significantly improve soil quality and support the restoration of ecosystems that are currently in a critical state.

Biorestorer operates on the principle of accelerated ecological succession, similar to the development of soil on newly formed volcanic islands. In nature, soil forms very slowly—starting with rock weathering, microbial colonization, mineral release, and the subsequent emergence of pioneer plants. This process can take decades or even centuries. Biorestorer compresses this sequence into an engineered system in which each component corresponds to a specific phase of succession: acidic rocks simulate weathering, RSB bacteria initiate microbial colonies and nutrient cycles, biochar provides structure, retention, and microclimate, and pioneer plants are intentionally introduced after substrate stabilization. In this way, new soil is created where none previously existed—not just an amendment of degraded soil, but a complete synthesis of pedogenesis.

This approach is supported by long-term studies confirming the impact of biochar on soil formation and plant growth [22,42].

The Biorestorer system enables the synthetic creation of soil from the ground up, with deliberately configured physical, chemical, and biological parameters that would otherwise take decades or centuries to develop through natural succession. In this way, it is possible to produce a substrate with optimized pH, water retention, microbial activity, and nutrient availability—even before planting begins—fundamentally changing the possibilities for soil restoration under extreme conditions.

## 5. Validation of the Concept Without Pilot Testing

Although the Biorestorer solution has not yet been tested in its entirety under real-world conditions, its individual components and application strategies are based on scientifically confirmed findings and long-documented results in soil research. The concept uses a modular validation approach—"verification of parts instead of the whole"—which allows the system's performance to be predicted with a high degree of confidence.

### *5.1. Validated Components of the Solution*

The Biorestorer system is composed exclusively of components whose functionality has been demonstrated in scientific literature or practical deployment. These elements were selected to work synergistically in supporting ecological soil restoration even under extreme conditions.

Biochar: Proven to improve soil structure, water retention, and nutrient binding.

RSB microorganisms: Include primarily halotolerant and alkalitolerant bacteria—ideal for alkaline and arid soils—that enhance phosphorus availability [6,15], some strains may also contribute to nitrogen fixation under specific conditions [6].

- Acidic silicate rocks: A source of calcium and magnesium [13], contributing to pH reduction;
- Zonal substrate application: Leads to stabilization of the substrate's microenvironment [3], creating stable conditions even in inhospitable areas [7] ;
- Grid-based nutrient distribution: Optimizes the spatial layout of active zones across the landscape;
- License-free system design: An open methodology that allows localization and adaptation based on regional conditions.

Each of these components has been validated in scientific literature, and their combination has been deliberately designed to produce mutually reinforcing and synergistic effects. This ensures not only the functionality of the solution but also its replicability and scalability.

### *5.2. Systemic Logic and Integration*

The individual components of the solution do not operate in isolation—they are integrated into a synergistic system where their effects complement and enhance one another:

- Biochar protects RSB and provides a microenvironment with higher moisture levels;

- RSB activate nutrient release from acidic rocks, even without organic inputs;
- Acidic rocks provide long-term pH stabilization, preventing the decline of microbial activity;
- Zoning reduces costs and increases application efficiency, even across large areas.

The system is intentionally designed not to depend on a single "weak link," but to remain functional even when implemented partially.

### *5.3. Minimization of Failure Risk*

Thanks to the exclusive use of known, well-tested components and their logical integration, it can be stated that:

- The risk of systemic failure is low, as there are no unknown or untested components involved;
- Every step is grounded in existing studies or agricultural practice, and even partial implementation (e.g., just RSB + biochar) brings ecological benefits;
- The system is adaptable to local conditions, which further increases its robustness.

### *5.4. Justification for Pre-Pilot Publication*

Given the validated inputs, clearly defined mechanisms, and absence of hypothetical components, the Biorestorer concept is ready to be published as a theoretical system design with a high probability of functionality in practice, with pilot verification recommended as the next step.

Although Biorestorer is primarily designed for soils threatened by desertification and alkalization, its core design principles—biological activation, zonal application [3]. In developing regions, biochar can also be produced from by-products of wastewater treatment plants or sludge—where the pyrolysis process allows the production of stable carbon material while simultaneously recovering nutrients [43]. Thus, the solution is not only a specialized tool, but also a platform for general landscape restoration.

Even without full-scale pilot testing, the Biorestorer system can be considered ready for deployment, as each component has been individually validated, and the overall design has been optimized for flexibility, risk mitigation, and long-term functionality in the field. The system is capable of operating across a wide range of conditions—including drought, alkaline soils, low organic matter, and high pH inputs. Its readiness for implementation arises not only from its design logic but from the deep synergy between its components, which together form a functional and resilient whole.

Biorestorer was not designed as a laboratory-optimized system, but rather as a practical, ecologically robust platform capable of functioning even under suboptimal conditions. Its greatest strength is not just its effectiveness in ideal scenarios, but its resilience to variability, material limitations, and climatic stress. The principle of "work with what you have" is the foundation of its usability in developing, arid, and crisis-affected regions.

## 6. Conclusion

Biorestorer represents a systems-based approach to ecological soil restoration, integrating microbiology, geology, and bioengineering into a functional whole. Unlike traditional methods that attempt to amend existing soils, this concept creates a new soil substrate—functionally, chemically, and biologically prepared for succession.

By combining biochar, RSB microorganisms, and mineral components, an environment is created that can support plant growth even in sterile, dry, or alkaline soils with minimal organic content. The system's modular architecture allows it to be adapted to local resources, climatic conditions, and restoration goals—ranging from agriculture to ecological rehabilitation.

The solution is designed to be applicable in suboptimal conditions and across vast, infrastructure-poor regions, with an emphasis on openness, low cost, and scalability. The principle of synthetic succession also enables a significant acceleration of natural pedogenetic development, opening new possibilities for soil regeneration in desertified regions.

The next step is pilot testing the complete system under diverse geographic conditions. This will help verify its effectiveness, identify limitations, and optimize application methods for different soil types. As such, Biorestorer is not only a technical solution but a new approach to soil creation—based on the synthesis of fundamental soil functions. This system is designed to act as an initiator of ecological succession, capable of creating functional soil where natural pedogenesis fails or is absent.

Although originally designed for the restoration of alkaline, degraded soils, Biorestorer's architecture also allows for full adaptation to acidic soils. The key to this adjustment lies in replacing acidic rocks with alkaline materials such as dolomite, limestone, basalt, or industrial by-products with alkaline pH (e.g., certain types of ash) [19,29].

The remaining system components—biochar (for structure and retention) and RSB bacteria (for nutrient mobilization)—maintain their function. In extremely acidic soils, microbial consortia can be adjusted to suit the environment, ensuring pH tolerance and functionality.

Such a modified substrate allows for:

- raising the pH of acidic soils ($pH < 5.5$) toward optimal levels [12] ;
- reducing the toxicity of aluminum and manganese [19] ;
- improving the availability of phosphorus, calcium, and magnesium [6], and
  restoring soil structure even in severely degraded areas [8].

Thanks to its modular design logic, Biorestorer is universally applicable to a wide range of soil types, significantly enhancing its global relevance and usability.

**Author Contributions:** Conceptualization, methodology, writing—original draft preparation, writing—review and editing: author.

**Funding:** This research received no external funding.

**Conflicts of Interest:** The author declares no conflict of interest.

**Data Availability Statement:** Not applicable.

# 7. Appendix / Tables

**Table 1.** Comparison of Solutions: Biorestorer vs. Biochar + Compost

| Criterion | Biorestorer | Biochar + Compost |
|---|---|---|
| Composition | Biochar + RSB bacteria + acidic minerals | Biochar + compost (organic matter) |
| Nutrient sources | Mineral weathering + microbial nutrient mobilization | Organic matter and humic substances |
| Microbial activity | High (RSB initiates microbial succession) | Medium to high (depends on compost quality) |
| pH regulation | pH reduction via acidic rocks and RSB | Neutralization (if compost is acidic), often no pH adjustment |
| Water retention | High (biochar + structured substrate) | High (biochar + organic matter) |
| Long-term stability | High (800 °C biochar + minerals) | Medium (compost decomposes faster) |
| Ecological succession | Yes (synthetic succession, pioneer species) | Limited (depends on compost and soil conditions) |
| Input flexibility | High (locally available substitutions possible) | Low to medium (depends on compost and biochar availability) |
| Salinity resistance | High (biochar + Ca/Mg cation exchange) | Low to medium (compost has low exchange capacity) |
| Initial nutrient availability | Medium (requires RSB activation and mineral weathering) | High (compost provides immediate nutrients) |
| Suitability for arid soils | High (designed for extreme conditions) | Medium (compost may degrade faster in dry climates) |
| Potential for soil recovery without organics | Yes (does not require organic matter) | No (requires organic input) |
| Risk of over-acidification | Low (except for localized and temporary acidification) | Low |
| Cost and material availability | Medium (depends on local availability of minerals and biochar) | Low to medium (compost is widely available, biochar varies) |

Note: The following table summarizes the key differences between the proposed Biorestorer system and the commonly used combination of biochar and compost. The comparison includes aspects such as biological activity, long-term stability, ecological succession potential, and suitability for various soil types. The table is intended as an informative overview to guide understanding of the functional advantages of each approach.

## References


1. Lehmann, J.; Joseph, S. Biochar for Environmental Management: Science and Technology; *Earthscan*: London, UK, **2009**. https://doi.org/10.4324/9781849770552
2. DeLuca, T.H.; Aplet, G.H. Charcoal and carbon storage in forest soils of the Rocky Mountain West. *Front. Ecol. Environ.* **2008**, *6*, 18–24. https://doi.org/10.1890/070070
3. Aronson, J.; Floret, C.; Le Floc'h, E.; Ovalle, C.; Pontanier, R. Restoration and rehabilitation of degraded ecosystems in arid and semi-arid lands. I. A view from the South. *Restor. Ecol.* **1993**, *1*, 8–17. https://doi.org/10.1111/j.1526-100X.1993.tb00004.x
4. Singh, B.; Cowie, A.L. Long-term influence of biochar on native organic carbon mineralization in a low-carbon clayey soil. *Sci. Rep.* **2014**, *4*, 3687. https://doi.org/10.1038/srep03687
5. Basso, A.S.; Miguez, F.E.; Laird, D.A.; Horton, R.; Westgate, M. Assessing potential of biochar for increasing water-holding capacity of sandy soils. *GCB Bioenergy* **2013**, *5*, 132–143. https://doi.org/10.1111/gcbb.12026
6. Uroz, S.; Calvaruso, C.; Turpault, M.-P.; Frey-Klett, P. Mineral weathering by bacteria: Ecology, actors and mechanisms. *Trends Microbiol.* **2009**, *17*, 378–387. https://doi.org/10.1016/j.tim.2009.05.004
7. Agegnehu, G.; Srivastava, A.K.; Bird, M.I. The role of biochar and biochar-compost in improving soil quality and crop performance: A review. *Appl. Soil Ecol.* **2017**, *119*, 156–170. https://doi.org/10.1016/j.apsoil.2017.06.008
8. Schmidt, H.-P.; Kammann, C.; Hagemann, N.; Leifeld, J.; Bucheli, T.D.; Sánchez Monedero, M.A.; Cayuela, M.L. Biochar in agriculture – A systematic review of 26 global meta-analyses. *GCB Bioenergy* **2021**, *13*, 1708–1730. https://doi.org/10.1111/gcbb.12889
9. Warnock, D.D.; Lehmann, J.; Kuyper, T.W.; Rillig, M.C. Mycorrhizal responses to biochar in soil – concepts and mechanisms. *Plant Soil* **2007**, *300*, 9–20. https://doi.org/10.1007/s11104-007-9391-5
10. Novotny, E.H.; Maia, C.M.; Carvalho, M.T.M.; Madari, B.E. Biochar: pyrogenic carbon for agricultural use—a critical review. *Rev. Bras. Ciênc. Solo* **2015**, *39*, 321–344. https://doi.org/10.1590/01000683rbcs20140818
11. Zhang, A.; Liu, Y.; Pan, G.; Hussain, Q. Effect of biochar amendment on yield and methane and nitrous oxide emissions from a rice paddy from Tai Lake plain, China. *Agric. Ecosyst. Environ.* **2012**, *139*, 469–475. https://doi.org/10.1016/j.agee.2010.09.003
12. Verheijen, F.G.A.; Jeffery, S.; Bastos, A.C.; van der Velde, M.; Diafas, I. *Biochar Application to Soils – A Critical Scientific Review of Effects on Soil Properties, Processes and Functions*; European Commission – Joint Research Centre: Ispra, Italy, **2010**. https://doi.org/10.2788/472
13. Wilson, M.J. Weathering of the primary rock-forming minerals: Processes, products and rates. In *Treatise on Geochemistry*; Drever, J.I., Ed.; Elsevier: Oxford, UK, **2004**; Volume 5, pp. 113–155.
14. Spokas, K.A.; Reicosky, D.C. Impacts of sixteen different biochars on soil greenhouse gas production. *Ann. Environ. Sci.* **2009**, *3*, 179–193.
15. Janati, W.; Mikou, K.; El Ghadraoui, L.; Errachidi, F. Isolation and characterization of phosphate solubilizing bacteria naturally colonizing legumes rhizosphere in Morocco. *Front. Microbiol.* **2022**, *13*, 958300. https://doi.org/10.3389/fmicb.2022.958300
16. Elad, Y.; Cytryn, E.; Meller Harel, Y.; Lew, B.; Graber, E.R. The biochar effect: plant resistance to biotic stresses. *Phytopathol. Mediterr.* **2011**, *50*, 335–349.
17. Biederman, L.A.; Harpole, W.S. Biochar and its effects on plant productivity and nutrient cycling: a meta-analysis. *GCB Bioenergy* **2013**, *5*, 202–214. https://doi.org/10.1111/gcbb.12037
18. Lehmann, J.; Rillig, M.C.; Thies, J.; Masiello, C.A.; Hockaday, W.C.; Crowley, D. *Biochar effects on soil biota – A review. Soil Biology and Biochemistry* **2011**, *43*, 1812–1836. https://doi.org/10.1016/j.soilbio.2011.04.022
19. Beesley, L.; Moreno-Jiménez, E.; Gomez-Eyles, J.L. A review of biochar's potential role in the remediation, revegetation and restoration of contaminated soils. *Environ. Pollut.* **2011**, *159*, 3269–3282. https://doi.org/10.1016/j.envpol.2011.07.023
20. Liang, S.; Wang, S.-N.; Zhou, L.-L.; Sun, S.; Zhang, J.; Zhuang, L.-L. Combination of biochar and functional bacteria drives the ecological improvement of saline–alkali soil. *Plants* **2023**, *12*, 284. https://doi.org/10.3390/plants12020284

21. Novak, J.M.; Busscher, W.J.; Laird, D.L.; Ahmedna, M.; Watts, D.W.; Niandou, M.A.S. Impact of biochar amendment on fertility of a southeastern coastal plain soil. *Soil Sci.* **2009**, *174*, 105–112. https://doi.org/10.1097/SS.0b013e3181981d9a
22. Glaser, B.; Haumaier, L.; Guggenberger, G.; Zech, W. The 'Terra Preta' phenomenon: A model for sustainable agriculture in the humid tropics. *Naturwissenschaften* **2001**, *88*, 37–41. https://doi.org/10.1007/s001140000193
23. Lehmann, J.; Rondon, M. Bio-char soil management on highly weathered soils in the humid tropics. In *Biological Approaches to Sustainable Soil Systems*; Uphoff, N., Ed.; CRC Press: Boca Raton, FL, USA, **2006**; pp. 517–530.
24. Calcan, S.I.; Petrescu, C.; Voicu, G.; Paraschiv, G.; Chereji, A.; Popescu, C.; Nistor, E. Effects of biochar on soil properties and tomato growth. *Agronomy* **2022**, *12*, 1824. https://doi.org/10.3390/agronomy12081824
25. Hussain, M.; Farooq, M.; Nawaz, A.; Al-Sadi, A.M. Biochar for crop production: Potential benefits and risks. *J. Soils Sediments* **2017**, *17*, 685–716. https://doi.org/10.1007/s11368-016-1360-2
26. EL-Sayed, M.M.; Mahdy, A.Y.; Gebreel, M.; Abdeen, S.A. Effectiveness of biochar, organic matter and mycorrhiza to improve soil hydrophysical properties and water relations of soybean under arid soil conditions. *Eurasian Soil Sci.* **2023**, *56*, 1055–1066. https://doi.org/10.1134/S1064229323600276
27. Ding, Y.; Liu, Y.; Liu, S.; Li, Z.; Tan, X.; Huang, X.; Zeng, G.; Zhou, L.; Zheng, B. Biochar to improve soil fertility: A review. *Agron. Sustain. Dev.* **2016**, *36*, 36. https://doi.org/10.1007/s13593-016-0372-z
28. Lehmann, J. A handful of carbon. *Nature* **2007**, *447*, 143–144. https://doi.org/10.1038/447143a
29. El-Naggar, A.; Lee, S.S.; Rinklebe, J.; Farooq, M.; Song, H.; Sarmah, A.K.; Zimmerman, A.R.; Ahmad, M.; Shaheen, S.M.; Ok, Y.S. Biochar application to low fertility soils: A review of current status and future prospects. *Geoderma* **2019**, *337*, 536–554. https://doi.org/10.1016/j.geoderma.2018.09.034
30. Palansooriya, K.N.; Wong, J.T.F.; Hashimoto, Y.; Huang, L.; Rinklebe, J.; Chang, S.X.; Bolan, N.; Wang, H.; Ok, Y.S. Response of microbial communities to biochar-amended soils: A critical review. *Biochar* **2019**, *1*, 3–22. https://doi.org/10.1007/s42773-019-00009-2
31. Thomas, S.C.; Gale, N. Biochar and forest restoration: A review and meta-analysis of tree growth responses. *New For.* **2015**, *46*, 931–946. https://doi.org/10.1007/s11056-015-9491-7
32. ELsaman, N.K.; Amin, A.E.A.Z.; Abd El-Razek, M.; Roshdy, N.M.K. Comparative effects of different types and doses of biochar on soil quality indicators and arugula growth under saline conditions. *Sci. Rep.* **2025**, *15*, 10046. https://doi.org/10.1038/s41598-025-92816-w
33. Jeffery, S.; Verheijen, F.G.A.; van der Velde, M.; Bastos, A.C. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agric. Ecosyst. Environ.* **2011**, *144*, 175–187. https://doi.org/10.1016/j.agee.2011.08.015
34. Quilliam, R.S.; Glanville, H.C.; Wade, S.C.; Jones, D.L. Life in the 'charosphere'–Does biochar in agricultural soils provide a significant habitat for microorganisms? *Soil Biol. Biochem.* **2013**, *65*, 287–293. https://doi.org/10.1016/j.soilbio.2013.06.004
35. Niraula, S.; Choi, Y.-K.; Payne, K.; Muir, J.P.; Kan, E.; Chang, W.-S. Dairy Effluent-Saturated Biochar Alters Microbial Communities and Enhances Bermudagrass Growth and Soil Fertility. *Agronomy* **2021**, *11*, 1794. https://doi.org/10.3390/agronomy11091794
36. Anderson, C.R.; Condron, L.M.; Clough, T.J.; Fiers, M.; Stewart, A.; Hill, R.A.; Sherlock, R.R. Biochar induced soil microbial community change: Implications for biogeochemical cycling of carbon, nitrogen and phosphorus. *Pedobiologia* **2011**, *54*, 309–320. https://doi.org/10.1016/j.pedobi.2011.07.005
37. El-Ramady, H.; Prokisch, J.; Mansour, H.; Bayoumi, Y.A.; Shalaby, T.A.; Veres, S.; Brevik, E.C. Review of crop response to soil salinity stress: Possible approaches from leaching to nano-management. *Soil Syst.* **2024**, *8*, 11. https://doi.org/10.3390/soilsystems8010011
38. Machado, R.M.A.; Serralheiro, R.P. Soil salinity: Effect on vegetable crop growth. Management practices to prevent and mitigate soil salinization. *Horticulturae* **2017**, *3*, 30. https://doi.org/10.3390/horticulturae3020030
39. Luizao, F.J.; Petersen, J.; et al. Black carbon increases cation exchange capacity in soils. *Soil Sci. Soc. Am. J.* **2006**, *70*, 1719–1730. https://doi.org/10.2136/sssaj2005.0383

40. Gul, S.; Whalen, J.K.; Thomas, B.W.; Sachdeva, V.; Deng, H. Physico-chemical properties and microbial responses in biochar-amended soils: Mechanisms and future directions. *Agric. Ecosyst. Environ.* **2015**, *206*, 46–59. https://doi.org/10.1016/j.agee.2015.03.015
41. Racek, J.; Sevcik, J.; Chorazy, T.; Kucerik, J.; Hlavinek, P. Biochar – Recovery material from pyrolysis of sewage sludge: A review. *Waste Biomass Valorization* **2019**, *10*, 1–17. https://doi.org/10.1007/s12649-019-00679-w
42. Joseph, S.; Cowie, A.; Van Zwieten, L.; Bolan, N.; Budai, A.; Buss, W.; Cayuela, M.L.; Graber, E.R.; Ippolito, J.A.; Kuzyakov, Y.; et al. How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar. *GCB Bioenergy* **2021**, *13*, 1731–1764. https://doi.org/10.1111/gcbb.12885
43. Bridle, T.R.; Pritchard, D. Energy and nutrient recovery from sewage sludge via pyrolysis. *Water Sci. Technol.* **2004**, *50*, 169–175. https://doi.org/10.2166/wst.2004.0562