Biorestorer: A Framework for Synthetic Succession with a Qualitative System-Level Illustration

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Abstract: Ecosystem restoration in severely degraded or soil-absent environments requires approaches that operate independently of natural soils and make effective use of locally available resources. The Biorestorer platform introduces synthetic succession as a systems-based eco-engineering framework structured in sequential functional phases and aligned with in situ resource utilization (ISRU) principles, understood here as the use of locally available resources independent of terrestrial or extraterrestrial setting. Its core element, the soil initiator, is a prototype soilless, mineral-dominated substrate engineered to support early soil-like functionality under low-organic conditions by integrating mineral components, porous carbon scaffolds, and targeted microbial inoculants. In the initial phase, locally available mineral materials are configured to achieve targeted physical and geochemical properties, including porosity, pH buffering, and potential nutrient accessibility. These are combined with microorganisms associated with mineral nutrient mobilization, such as rock-solubilizing bacteria (RSB), to support biological colonization. Subsequent phases introduce vegetation and plant-associated microbial communities, enabling organic matter accumulation and increasing system complexity. A qualitative engineering test of a defined prototype configuration was conducted to assess system-level behavior rather than to isolate causal mechanisms. The prototype supported plant establishment and continued growth in a mineral-dominated substrate without compost, humus, or conventional fertilizers. Observations included stabilization of substrate pH, visible structural changes, and growth of two successive plant generations (*Sinapis alba and Phaseolus vulgaris*). The inclusion of a cultivated species in the second generation is consistent with multi-stage plant establishment under the tested prototype conditions. As no control treatments or quantitative chemical or microbiological analyses were included, these findings should be interpreted as qualitative indicators of system-level feasibility, not as evidence of specific underlying mechanisms or validated process-level performance. Further controlled studies are required to resolve component contributions, process dynamics, reproducibility, scalability, and operational performance.

Keywords: synthetic succession; synthetic pedogenesis; biochar scaffold; rock-solubilizing bacteria; mineral-dominated substrate; soil-like functionality; ecological restoration; in situ resource utilization

I. Introduction

Biorestorer presents a systems-based framework for synthetic pedogenesis, in which soil is treated not as a material input but as an emergent, engineerable function arising from controlled pedogenetic processes. The framework integrates mineral components forming a soilless substrate, targeted microbial activation, and functional carbon scaffolds within a structured, staged system design, forming a configuration potentially applicable in environments where natural soil formation is absent or operationally infeasible, including terrestrial restoration and in situ resource utilization (ISRU) contexts. The theoretical foundation and system-level conceptual design of the framework are described in an earlier preprint [1], and were subsequently presented in poster form at an international conference focused on dryland systems [2].

Severely degraded, arid, or soil-absent environments—including mine tailings, exposed bedrock, desert crusts, and extraterrestrial regolith analogues—pose a fundamental challenge to ecological restoration, sustainable agriculture, and bioregenerative life-support systems. In such contexts, natural soil formation is extremely slow or suppressed due to minimal organic matter, limited biological activity, unfavorable pH conditions, and poor water retention. Conventional restoration approaches typically assume the presence of residual soil functionality and are therefore ineffective where soil is biologically inactive or entirely absent [3].

Comparable constraints arise in controlled environments and extraterrestrial settings, where soils do not exist by definition and must be functionally generated from mineral parent materials. This perspective is directly relevant to in-situ resource utilization (ISRU), where the mobilization of nutrients and the establishment of biologically functional interfaces from locally available mineral resources represent a critical limitation for long-duration missions and closed-loop life-support architectures.

In natural systems, early soil development occurs during primary succession, when initially sterile mineral substrates are colonized by microorganisms, leading to the formation of a proto-soil (protopedon). A central driver of this process is the activity of rock-solubilizing and lithotrophic microorganisms, which mobilize essential nutrients through mineral weathering long before significant organic matter accumulation occurs [4,5]. In engineered analogues of this process, early microbial colonization may be supported by transient, low-intensity organic stimulation acting as a mild activator, without constituting a sustained external carbon source.

Most existing restoration technologies focus on accelerating secondary succession and therefore rely on pre-existing soil functionality. However, plant establishment depends not on soil as a material entity, but on a set of functional services, including mechanical support, access to water and nutrients, gas exchange, and a biologically active rhizosphere. These services can be delivered through engineered systems, effectively decoupling plant growth from natural soils [6].

Building on this functional view, synthetic succession has been proposed as a controlled analogue of natural primary succession. Rather than improving degraded soils, it focuses on the deliberate creation of a synthetic parent material designed to support microbial activation, mineral weathering, and early aggregation. Biorestorer implements this concept as a controllable pedogenetic platform, whose core element is a soil initiator—an engineered mineral–biochar substrate providing water retention, pH buffering, nutrient mobilization, and rhizosphere support.

Within this framework, biochar is not treated merely as a stable carbon additive, but as an active microbial–mineral interface. The concept of the charosphere describes the unique microbial habitat created by biochar, characterized by elevated microbial density, altered community composition, and intensified biochemical activity relative to the surrounding mineral matrix [7,8]. Biochar particles provide porous microenvironments that promote close spatial coupling between microorganisms and mineral surfaces, and have been associated in the literature with processes such as localized mineral weathering, ion exchange, and nutrient mobilization at the mineral–biochar substrate, particularly during early stages of soil formation.

A key design feature of the Biorestorer system is the use of dual-temperature biochar. Lower-temperature biochar (~500–600 °C) supports microbial activation and early-stage biological processes through higher surface reactivity and porosity, while higher-temperature biochar (~750–800 °C) contributes long-term structural stability and buffering capacity due to its chemical persistence [9]. Together, these components enable the transition from a mineral-dominated substrate to a biologically active protopedon.

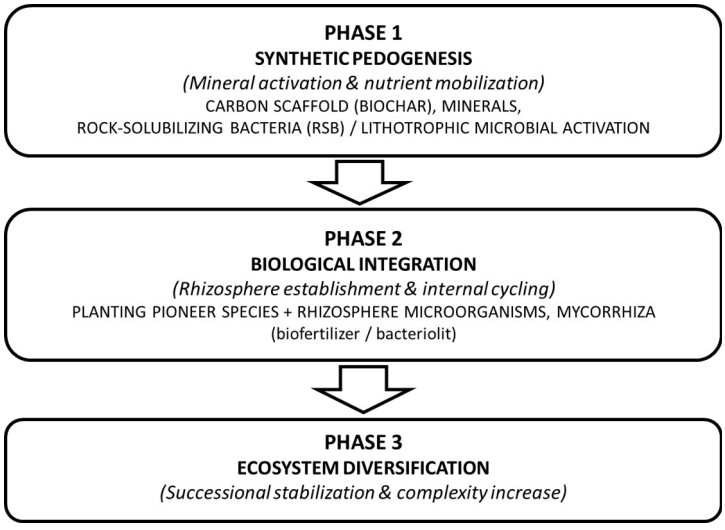

Figure 1. Graphical abstract illustrating synthetic succession in the Biorestorer concept.

Although biochar is used here as a reference implementation, the Biorestorer framework is not intrinsically dependent on biochar as a specific material. From a systems perspective, biochar functions as a carbonaceous structural scaffold, whose role may be fulfilled by alternative carbon-based or carbon-rich substrates providing comparable porosity, surface reactivity, chemical stability, and microbial hosting capacity. Functional analogues may include engineered porous carbons, pyrolyzed organic residues, charred polymer-derived materials, or carbonized waste streams produced under controlled thermal or chemical conditions. Provided that such materials offer a stable porous architecture, suitable surface chemistry for microbial attachment, and resistance to rapid degradation, they can serve as effective microbial–mineral interfaces within the Biorestorer system, thereby extending its applicability to resource-constrained and ISRU-oriented bioregenerative life support architectures.

The objective of this paper is to describe the Biorestorer system architecture, outline its conceptual pedogenetic framework, and present an illustrative assessment of early soil-like development and plant establishment on a predominantly mineral substrate. By framing soil as an emergent functional interface rather than a prerequisite material, this work contributes to scalable strategies for environmental restoration and bioregenerative life-support systems operating under resource-constrained conditions.

II. Materials and Methods

The processes described in the conceptual framework, including microbially induced weathering and nutrient mobilization, are not directly evaluated in this study and are presented as theoretical components of the system design.

A. Theoretical Framework of the Biorestorer System

The Biorestorer system is based on the premise that essential plant nutrients are inherently present within mineral parent materials and that a key limitation in soil-absent or severely degraded environments is nutrient inaccessibility rather than absolute scarcity. In natural systems, nutrient availability emerges through long-term mineral weathering mediated by physical, chemical, and biological processes [4,5]. Where functional soil is absent, these processes are limited, resulting in mineral substrates that may be chemically rich but biologically inaccessible.

Rather than compensating for this limitation through external fertilizers or organic amendments, the Biorestorer approach aims to create conditions consistent with access to nutrients associated with mineral substrates by promoting conditions consistent with early pedogenetic development. This approach is conceptually aligned with natural primary succession, in which nutrient cycling emerges through microbially influenced mineral transformations prior to significant organic matter accumulation [4,10]. Accordingly, mineral components are treated as potential nutrient reservoirs rather than inert fillers.

The Biorestorer soil initiator (a soilless substrate), integrates interdependent components:

1) mineral parent material,
2) rock-solubilizing and lithotrophic microorganisms,
3) dual-temperature biochar serving as a structural and biochemical scaffold,
4) a controlled water regime,
5) Staged System Design and Operational Phases.

Together, these components establish a framework for synthetic pedogenesis in which mineral composition, microbial activity, porosity, moisture dynamics, and pH buffering are treated as controllable design variables.

An illustrative assessment of system behavior under a defined framework, including parallel system pathways, is presented in the following sections.

B. Mineral Components as Synthetic Parent Material

The mineral fraction of the Biorestorer substrate functions as a synthetic parent material analogous to bedrock or unconsolidated deposits in natural soil formation [5]. A range of silicate and carbonate rocks may be used, including basalt, andesite, dolomite, granodiorite, limestone-derived materials, regolith analogues, and other locally available mineral resources, depending on terrestrial or extraterrestrial application context.

These substrates contain essential macro- and micronutrients, including calcium, magnesium, potassium, phosphorus, iron, and trace elements bound within their crystal lattices [5].

Although often considered inert on operational timescales, mineral-bound nutrients become bioavailable through microbially mediated weathering, particularly within acidic or chelating microenvironments [4,10]. The Biorestorer system is explicitly designed to promote such microenvironments, enabling mineral dissolution and nutrient release without external fertilization. While mineral composition influences pH dynamics and weathering rates, it does not

alter the fundamental role of the mineral fraction as a long-term nutrient source, allowing adaptation to local geological conditions through material substitution.

C. Rock-Solubilizing and Lithotrophic Microorganisms

Rock-solubilizing bacteria (RSB) and functionally similar lithotrophic microorganisms form the core biological component of the Biorestorer system. These organisms mobilize nutrients directly from mineral substrates through the production of organic acids, chelating compounds, and redox-active metabolites, facilitating the release of phosphorus, calcium, magnesium, iron, and trace elements [4,11].

In natural primary succession, such microorganisms establish the first biologically accessible nutrient pools under low-carbon conditions [4,10]. Biorestorer deliberately integrates this function into the engineered substrate, treating microbial mineral weathering as a conceptual system component rather than an emergent byproduct. The system does not depend on high organic inputs, enabling pedogenetic processes to proceed under low-carbon conditions characteristic of arid, degraded, or extraterrestrial analogue environments.

D. Dual-Temperature Biochar as Structural and Biochemical Scaffold

Within the Biorestorer system, biochar functions primarily as a structural and biochemical scaffold rather than as a deliberately added nutrient source. Biochars produced at different pyrolysis temperatures exhibit distinct and complementary properties. Lower-temperature biochar (~500–600 °C) provides higher surface functionality and cation exchange capacity, supporting microbial colonization, nutrient retention, and early rhizosphere development [6]. Higher-temperature biochar (~750–800 °C) offers greater chemical stability and long residence times, contributing to long-term structural integrity and buffering capacity [9].

The combined use of these biochar fractions balances early biological activation with long-term system stability. In addition, biochar provides microhabitats that buffer moisture, pH fluctuations, and temperature extremes, enhancing microbial survival and activity during early synthetic pedogenesis [7,8,12].

Importantly, these roles are defined functionally rather than materially. While biochar represents a convenient and well-characterized carbon scaffold, its structural and biochemical functions within the Biorestorer framework are in principle substitutable by alternative carbon-based or carbon-rich scaffolds that provide comparable porosity, surface reactivity, and environmental buffering.

E. Water Regime and Process Activation

Water availability is a critical control variable within the Biorestorer system, as microbial mineral weathering and nutrient mobilization are strongly water-dependent [4]. The system is designed to operate under intermittent wetting regimes, reflecting hydrological conditions typical of arid and semi-arid environments. Episodic water inputs activate microbial metabolism, promote localized mineral dissolution, and support aggregation while limiting nutrient leaching and system destabilization [13].

Within synthetic pedogenesis, the water regime functions as an engineered process parameter regulating microbial activity, reaction kinetics, and system progression toward a biologically active protopedon. As plants are introduced, they become integral system components, contributing to nutrient and carbon cycling through root exudation and rhizosphere structuring. Early vegetation thus reinforces synthetic pedogenesis and supports the transition from an externally activated system toward a partially self-sustaining bioregenerative loop.

F. Staged System Design and Operational Phases

The Biorestorer framework is structured as a staged system design in which synthetic pedogenesis is approached as a sequence of functionally distinct but interconnected phases. Rather than representing discrete experimental treatments, these phases define operational states of the system characterized by evolving interactions between mineral, microbial, and plant components, conceptually aligned with processes described in natural soil development and ecological succession [4,5,10].

In the initial phase, mineral components, carbon scaffolds, and microbial inoculants are combined to establish a baseline substrate with controlled physical and geochemical properties, including porosity, moisture retention, and pH buffering. This phase focuses on enabling microbial colonization and early system activation under low-organic conditions, consistent with early-stage mineral–microbe interactions observed in primary succession environments [4,10].

Subsequent phases involve the introduction of vegetation and the emergence of plant–microbe–substrate interactions. Root development and biomass turnover contribute to internal carbon inputs and localized modification

of substrate conditions. Microbial inputs may be maintained or supplemented across phases as part of the integrated system design, without isolating their individual effects.

The transition between phases is guided by operational indicators rather than predefined thresholds. These indicators may include stabilization of substrate conditions and the emergence of observable biological activity, without implying specific causal mechanisms.

This staged approach provides a structured framework for examining system behavior across configurations while maintaining flexibility in implementation.

III. Illustrative Study Methodology

A. Scope and Study Design

The study was designed as a minimal feasibility assessment of the Biorestorer framework under a defined set of conditions. Its objective was not to test specific mechanisms or comparative performance, but to examine whether the system can maintain functional continuity across staged transitions and support observed plant establishment in a mineral-dominated substrate.

The experiment was not intended as an optimization study, comparative agronomic trial, or quantitative performance evaluation. Instead, it was designed as an illustrative, system-level assessment of the framework under a defined configuration. Observed plant growth was interpreted as an indication that the system configuration may be compatible with the transition from synthetic pedogenesis (Phase I) to biological integration (Phase II), but not as evidence of underlying mechanisms or their relative contributions. Quantitative observations were collected as contextual indicators of system stability and were not used as primary success criteria.

This reflects the study design, which was not intended as a comparative or hypothesis-testing experiment, but as an illustrative assessment of system behavior under a defined configuration. The results should therefore be interpreted as preliminary qualitative observations within the scope of the framework.

B. Experimental Setup

The experiment was conducted under controlled indoor conditions using a total substrate volume of 32 L. Moisture levels were maintained at values sufficient to support microbial activity, within a range reported in the literature to be associated with mineral weathering processes [4]. No external fertilization or organic amendments were applied at any stage.

The substrate consisted predominantly of mineral components with minimal organic matter inputs. Organic material was not intentionally introduced and was present only in negligible amounts associated with mineral fractions, consistent with experimental approaches focusing on early pedogenetic processes under low-carbon conditions [14].

Substrate (soil initiator), composition (v/v):

1) 70 % basalt aggregate (1–3 mm fraction), commercially available construction-grade jointing gravel,
2) 20 % dolomite rubble of natural origin, included as a mineral component with buffering capacity,
3) 10 % biochar (KBRO-600-ZZ Biograda, produced from digestate derived from kitchen waste, high ash content).

The initial microbial population was not assumed to originate from the biochar component. Instead, dolomite of natural origin was included as part of the substrate, which may contain naturally occurring microbial communities. In addition, a commercial microbial inoculant was applied during experimental phase 2.

Waste-derived biochar was selected to reflect circular resource use under constrained biomass conditions. While such materials are sometimes regarded as lower-grade in conventional agronomy due to elevated ash content, this mineral fraction represents an inherent component of biochar rather than an externally added amendment. In the present system, it may represent a potential source of buffering capacity and mineral-associated nutrients; however, its functional contribution under the tested conditions cannot be resolved. The feedstock choice also supports scalability through high-volume waste streams.

Parameter	Unit	Value
Production temperature	°C	~500
pH (H_2O)	–	8.9
Ash content	% (dry basis)	42.5
Total organic carbon (TOC)	% (dry basis)	34.2
Total nitrogen (N)	% (dry basis)	2.5
Phosphorus (as P_2O_5)	% (dry basis)	2.44
Potassium (as K_2O)	% (dry basis)	1.83
Calcium (Ca)	% (dry basis)	10.3
Iron (Fe)	mg/kg	5310

Table 1. Physicochemical Properties of the Biochar Sample (KBRO-500-ZZ)

The biochar component was characterized by an accredited laboratory (ALS Czech Republic). The analyzed sample (KBRO-500-ZZ), produced at ~500 °C, provides an indicative characterization of the mineral ash fraction and associated nutrient content of a biochar derived from the same feedstock as that used in the system (KBRO-600-ZZ). While differences in pyrolysis temperature (500 °C vs 600 °C) may influence specific physicochemical properties, this analysis provides contextual insight into the mineral characteristics of the biochar component. The complete laboratory report is provided in Supplementary Material S1.

The resulting substrate was mineral-dominated in composition and function, incorporating biochar as a stable carbon scaffold, with only negligible incidental organic material associated with the dolomite fraction and no added humus, compost, or externally supplied NPK fertilizers.

Substrate pH was monitored during Phase I at weeks 2, 3, and 4 using semi-quantitative colorimetric drop tests (1:5 w/w substrate-to-distilled-water suspension; 30 min equilibration) as operational system indicators of substrate condition rather than quantitative analytical measurements. Iron was assessed using colorimetric drop tests in week 4 of Phase I as a qualitative indicator of system state under the tested conditions. During Phase II, both pH and iron presence were re-evaluated prior to green manuring to monitor system conditions as part of phase-transition assessment under plant growth.

C. Pre-treatment and System Activation

To initiate synthetic pedogenesis, the basalt and biochar fractions were mixed at a 1:1 ratio, and the biochar component was pre-activated within the mixture by soaking for 24 hours in 2 L of activation solution consisting of 20 mL household vinegar diluted in tap water (corresponding to approximately 1 % vinegar solution, ~0.08 % acetic acid). The mixture was not rinsed, allowing all soluble compounds to remain within the system. This pre-treatment was intended to activate the biochar surface and provide a transient stimulus for microbial activation and mineral surface reactivity without inducing sustained acidification, consistent with approaches used to trigger early-stage microbial activity in mineral substrates [4].

D. Phase I: Synthetic Pedogenesis

Following substrate preparation, the system was incubated for five weeks without vegetation to allow for initial biological colonization and early substrate transformation processes. Comparable timescales for the onset of microbially mediated mineral transformations under controlled conditions have been reported in the literature [4,14].

The system was monitored qualitatively for physical stability and visually observable structural changes. These observations describe visible structural changes but do not allow inference about pedogenetic processes or underlying mechanisms.

E. Phase II: Biological Integration, Test Groups, and Replication Structure

After completion of Phase I, and following confirmation of stable substrate pH and a positive qualitative iron response as operational indicators compatible with Phase II, the experiment was divided into two parallel test groups using *Sinapis alba* (white mustard) as a fast-growing, non-pioneer test species. The aim was to qualitatively observe plant establishment under mineral-dominated conditions without direct mechanistic inference [3].

The two groups represent distinct operational scenarios rather than comparative experimental variants. In both groups, independent pots served as biological replicates, with the pot constituting the experimental unit.

1) Test Group 1 – Phenological Growth:

5 independent pots (n = 5), each containing 1 mustard plant, were cultivated through a full phenological cycle

without biomass removal.

2) Test Group 2 – Green Manuring:

5 independent pots (n = 5), containing 13 mustard plants in total, were cultivated for biomass production. After harvest, above-ground biomass was reincorporated into the substrate as green manure. A subsequent bean generation was then grown in the amended substrate: first sowing in 3 pots (n = 3), followed by repeated sowing in 5 pots (n = 5) containing 8 bean plants in total.

In both groups, Bacteriolit (Marcel Mézy) microbial inoculant was applied at 1 g per 3.2 L pot to support early rhizosphere microbial activity and initiate internal nutrient cycling [4].

Although replicated cultivation units were used within each phase, no uninoculated negative control was included; replication therefore supports internal consistency assessment only, not comparative causal inference.

F. Observations and Interpretation Criteria

The primary outcome of the study was the visual observation of sustained plant growth on a mineral-dominated substrate lacking conventional organic soil inputs.

Supporting observations included:

1) substrate pH (measured after two weeks and monitored thereafter),
2) qualitative colorimetric indication of iron presence (drop-based spot test),
3) visual evidence of structural changes,
4) above-ground green biomass at harvest.

Substrate pH and qualitative iron presence were monitored primarily as operational indicators guiding the transition from Phase I (synthetic pedogenesis) to Phase II (biological integration), rather than as measurements of nutrient dynamics or evidence of underlying mechanisms.

Biomass data were recorded exclusively for contextual comparison and were not interpreted as indicators of system performance or optimization.

The study was interpreted as consistent with early soil-like system behavior if the following conditions were observed:

1) structural stability of the mineral substrate,
2) absence of system collapse or extreme pH drift,
3) sustained growth of *Sinapis alba* in both test groups.

These criteria are intended as qualitative reference points for interpreting system behavior within the scope of an illustrative study.

IV. Observations

A. Phase I: Synthetic Pedogenesis Outcomes

During the five-week incubation period without vegetation, the mineral-dominated substrate remained structurally stable, showing no collapse, excessive compaction, or component segregation. Visual inspection revealed localized structural changes, particularly in regions with higher biochar content.

Substrate pH stabilized at approximately 7.5 following the incubation period and remained stable throughout Phase I and subsequent plant growth. No progressive acidification or alkalization was observed, indicating physicochemical conditions compatible with plant establishment under the tested conditions.

Qualitative iron spot tests produced a positive colorimetric response, indicating the presence of iron under the tested conditions. This observation is descriptive only and does not provide quantitative or mechanistic information.

Taken together, these observations indicate observable structural changes in the substrate during the incubation period, consistent with early-stage soil-like structural features (in a descriptive sense).

However, in the absence of control treatments and quantitative chemical or microbiological analyses, these results should be interpreted as qualitative indicators rather than evidence of defined mechanisms.

Figure 2. Substrate structure at different stages of the experiment: *(left) freshly prepared substrate; (center) after Phase I (synthetic pedogenesis); (right) after Phase II (2 weeks of green manuring). Visual differences in substrate structure are observable across stages.*

B. Phase II: Plant Establishment and System Response

Following transition to Phase II, *Sinapis alba* successfully germinated and exhibited sustained growth in both test groups under mineral-dominated conditions, without the addition of external fertilizers or organic amendments.

In the phenological growth group, plants completed their growth cycle without biomass removal. Continuous development without visible signs of severe nutrient limitation or system instability provided a qualitative indication of sustained plant–substrate interaction under the given conditions.

In the green manuring group, harvested *Sinapis alba* biomass was incorporated into the substrate. The system remained structurally stable following biomass incorporation, with no visible signs of anaerobic collapse or excessive compaction.

A second plant generation (*Phaseolus vulgaris*, bush bean cultivar ‘Sonesta’) successfully germinated and exhibited sustained early growth in the green manuring group without additional substrate modification or nutrient inputs. This observation is consistent with the possibility of internal system reinforcement following biomass incorporation.

Figure 3. Test groups. *(left) Test group 2 (green-manuring); (right) Test group 1 (phenology). Representative plant height of approximately 127 cm observed at 63 days after sowing (28 Sep 2025).*

C. Supporting Observations

In Test Group 2 (green manuring), above-ground green biomass was recorded at harvest to enable contextual comparison with existing studies. Mean biomass yield reached approximately 14 g/L of substrate volume (46 g per pot). These values were used exclusively as supporting indicators of sustained plant growth under mineral substrate conditions and were not interpreted as measures of system performance, productivity, or optimization.

Throughout Phase II, no signs of system collapse, severe nutrient limitation, or pathological plant responses were observed. Root systems visibly penetrated and structured the substrate, further indicating functional plant–substrate integration.

D. Summary of Observations

The study indicates that the Biorestorer system, under the tested configuration, maintained structural integrity and supported plant establishment in a mineral-dominated substrate without the addition of compost, humus, or conventional fertilizers.

Specifically, the system exhibited the following observable outcomes:

1) structural stability of the mineral-dominated substrate throughout both experimental phases, without collapse, excessive compaction, or component segregation,
2) stable substrate pH (~7.5) under both incubation and plant growth conditions,
3) qualitative colorimetric responses consistent with iron presence,
4) sustained plant growth of *Sinapis alba* under mineral-dominated conditions,
5) successful establishment of a second plant generation (*Phaseolus vulgaris*) following biomass incorporation,
6) absence of visible system instability, severe nutrient limitation, or pathological plant responses during the observation period.

These observations are consistent with observable system-level properties such as structural stability and sustained plant growth under the given conditions.

The observed system behavior is consistent with the qualitative interpretation criteria defined for this study and supports further investigation of the Biorestorer framework under controlled and comparative experimental conditions.

V. Discussion

The conceptual framework is defined independently of material-specific nutrient inputs, whereas the implemented system included mineral-associated nutrient sources as part of the substrate configuration.

Plant establishment and sustained growth were observed in a mineral-dominated substrate under the tested system configuration. These observations describe system behavior under the tested conditions but do not constitute evidence for the framework or its underlying assumptions.

The mineral ash fraction, as an inherent component of biochar resulting from the pyrolysis process, is structurally associated with the carbon matrix rather than present as a freely available amendment [15,16]. Elemental analysis of the biochar indicated the presence of mineral-associated nutrients (e.g., K_2O 1.83 %, P_2O_5 2.44 %), although these forms are not directly equivalent to readily available fertilizer inputs and do not imply immediate nutrient accessibility under the tested conditions [15,16].

Accordingly, this work does not determine the origin of nutrients supporting plant growth or distinguish between mineral-associated availability and microbially mediated mobilization. Any apparent consistency with processes described in the conceptual framework is therefore non-mechanistic and does not imply validation of underlying assumptions.

A. Nutrient Accessibility Versus Nutrient Addition

A key implication of these observations is the distinction between nutrient accessibility and external nutrient addition. The absence of compost, humus, or conventional fertilizers indicates that plant growth occurred without external organic inputs. However, the substrate was not chemically inert and included mineral-associated nutrient sources, particularly within the biochar component, which contained an ash fraction.

Plant establishment therefore indicates that conditions compatible with plant growth were present within the system in the absence of external inputs; however, their specific sources and relative contributions cannot be resolved without control treatments and quantitative analysis. Observed stabilization of substrate pH (~7.5) and qualitative colorimetric detection of iron are consistent with the presence of mineral-associated components under the given conditions, but do not allow determination of nutrient availability or underlying processes.

An initial *Phaseolus vulgaris* sowing (3 plants) was affected by external operational factors (pest infestation and subsequent phytotoxicity from treatment), leading to premature loss despite prior establishment. These effects were treated as external constraints unrelated to substrate performance, and the system was re-sown (8 plants) to allow continued qualitative observation.

Mechanical support structures in plants, including stem base thickening and anchoring root development, represent adaptive responses influenced by environmental conditions such as mechanical stress, water availability, light regime, and resource availability [17–19]. Under conditions of low mechanical loading and stable water availability, plants may preferentially allocate biomass to vertical growth and photosynthetic tissues.

Plant morphology was not used as a standalone diagnostic indicator of nutrient status, as similar structural traits may arise from multiple interacting environmental drivers, including light availability and mechanical loading [20–22]. Under the tested conditions, morphology cannot be unambiguously attributed to nutrient-related limitations.

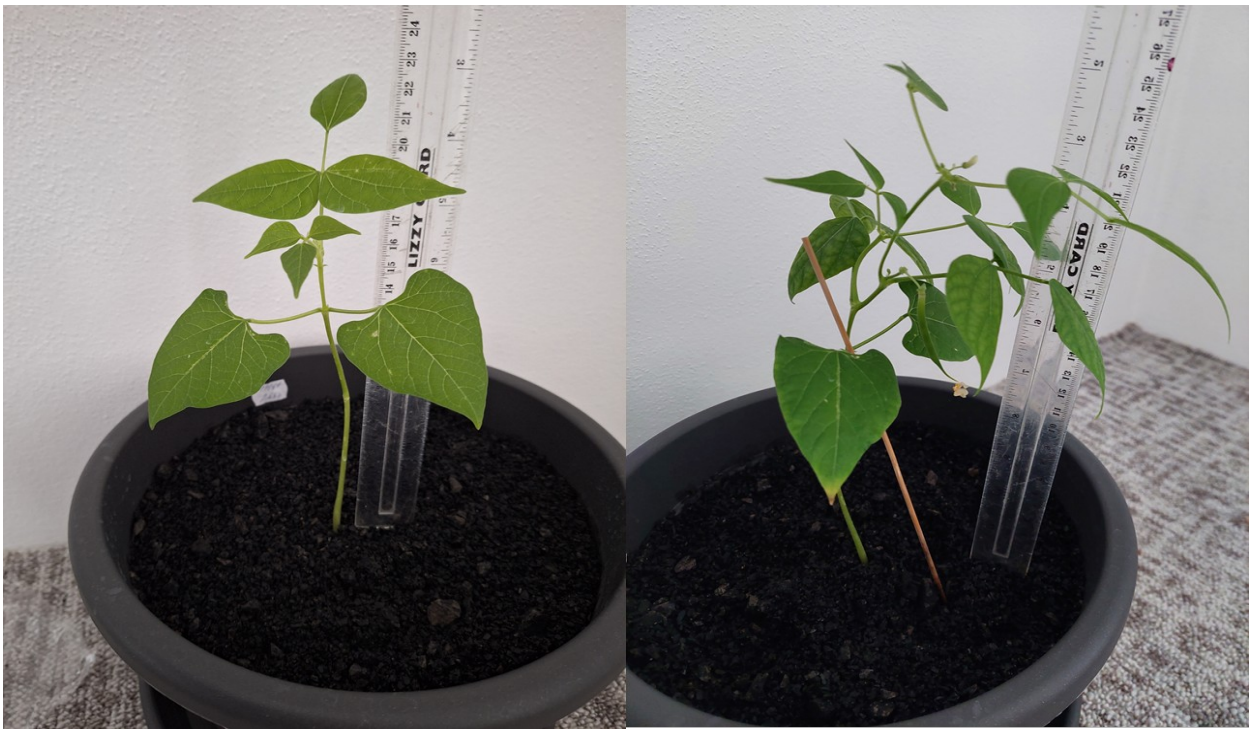

Figure 4. Phaseolus vulgaris during Phase II. *Limited mechanical anchoring observed under substrate conditions (same plant, winter window-light conditions; 16 November and 6 December 2025).*

Figure 5. Phaseolus vulgaris during Phase II. *Following re-sowing after loss of the initial sowing, images show the same plants on 10 January and 30 January 2026, from vegetative growth to flowering and early pod formation under substrate conditions. Plant architecture and shoot development are consistent with low mechanical loading and winter window-light conditions.*

B. Role of Plants in Synthetic Pedogenesis and Cycle Closure

Root penetration and rhizosphere development were observed alongside structural changes in the substrate. These observations coincide with localized variation in substrate conditions. Green manuring provided an internal, plant-derived organic input within the system.

Following plant establishment, root exudation and biomass turnover can act as internal carbon inputs for microbial processes, supporting system-level carbon cycling without reliance on external organic amendments. The successful establishment of a second plant generation following green manuring indicates system continuity beyond a single growth cycle under the tested conditions [23].

Importantly, these processes did not result in a conventional amendment-based system. Organic inputs remained internally generated and limited in scale, preserving the mineral-dominated character of the substrate within the system-level framework.

C. System Stability and Engineered Control

The absence of system collapse, extreme pH drift, or structural failure highlights the importance of engineered control variables within the Biorestorer framework. Controlled water availability, mineral composition, and biochar scaffolding created a bounded operational space in which biological processes could proceed without destabilizing feedbacks. This controlled yet biologically active state differentiates synthetic pedogenesis from both uncontrolled natural succession and conventionally managed growth substrates lacking dynamic biological feedbacks [14].

While only a single biochar fraction (~600 °C) was used in the illustrative study, a laboratory characterization was performed on a comparable biochar produced at ~500 °C, indicating the presence of a substantial mineral ash fraction and associated nutrient content. While not identical to the material used in the experiment, this analysis provides contextual information on the potential nutrient pool of biochar-associated mineral fractions.

The complementary functions of low- and high-temperature biochars in balancing early activation and long-term structural stability are therefore proposed at the conceptual system level rather than resolved experimentally in this study [9].

The observed system stability should be interpreted as a qualitative outcome under the tested configuration rather than as evidence of specific controlling mechanisms. However, Phase I conditions (pre-vegetation incubation) provide an internal temporal reference for subsequent observations in Phase II, allowing limited qualitative assessment of system stability across experimental phases. No substantial qualitative changes in pH or semi-quantitative colorimetric iron response were observed between these phases, consistent with stable physicochemical conditions over time, without implying specific underlying processes.

Literature reports indicate that untreated mineral substrates or early-stage systems lacking developed organic matter typically exhibit limited nutrient accessibility and constrained plant establishment without external inputs [4,5,10].

D. Scope and Limitations

The study was intentionally limited in scope and designed as an exploratory, system-level assessment of the Biorestorer framework under a defined configuration. The framework is inherently defined at the system level, integrating multiple interacting components and sequential developmental phases, and is therefore not readily reducible to single-variable experimental validation. Accordingly, the objective of this study was not to isolate individual mechanisms or quantify performance, but to examine whether the integrated system can sustain functional continuity under defined conditions.

Within this scope, the absence of control treatments, statistical hypothesis testing, and comparative experimental design reflects the exploratory nature of the study rather than an omission in experimental design. Consequently, the results should not be interpreted as indicators of agronomic productivity, system efficiency, or validated functional relationships. No uninoculated control treatment was included, and therefore causal attribution of observed outcomes to specific system components is not possible.

The study provides an initial feasibility-oriented reference point for the Biorestorer framework rather than a component-resolved or mechanistic evaluation. A rigorous evaluation of individual components or phase-specific contributions would require a structured experimental design with multiple control and comparison treatments across different stages of system development, which was beyond the scope of the present work.

Key aspects not addressed in this study—including microbial community composition, nutrient fluxes, and long-term dynamics—represent priorities for future work aimed at evaluating system performance, robustness, and applicability across different mineral substrates and operational contexts.

E. Implications for Restoration and Bioregenerative Systems

Within the limited scope of this study, the observations indicate a possible conceptual pathway for initiating soil-like functionality in environments where restoration approaches based on secondary succession may be ineffective. By framing soil formation as a staged and partially controllable process, the Biorestorer concept provides a conceptual link between ecological succession theory and engineered bioregenerative systems [3].

VI. Conclusions

This work presents Biorestorer as a systems-based framework for synthetic pedogenesis, offering a novel perspective on soil formation as an engineered process. The framework is based on mineral components forming a soilless substrate combined with a carbon scaffold and targeted microbial activation within a structured, staged system design, representing a configuration with potential applicability in terrestrial restoration and in situ resource utilization (ISRU) contexts. By reframing soil not as a material input but as an emergent functional interface guided through staged system design, the framework integrates interacting biological and mineral components within a structured succession-based approach. Within this context, pedogenetic processes are treated as contributing elements of system development rather than primary objects of validation, aligning the framework with established concepts of ecological succession while extending them into engineered environments.

The illustrative study was designed to examine whether the integrated system can sustain observable plant growth under a defined configuration. Within this scope, plant establishment and continued growth were observed under mineral-dominated conditions without external organic inputs. Substrate stability, sustained growth without compost or fertilizers, and the emergence of a second plant generation are consistent with continued plant–substrate interaction under the tested conditions.

The use of waste-derived, ash-rich biochar in the illustrative study further highlights the adaptability of the Biorestorer framework to suboptimal and heterogeneous material inputs. Rather than relying on idealized or highly processed substrates, the framework is compatible with circular resource use, where locally available minerals and waste-derived carbon materials can be integrated as functional system components. This flexibility suggests conceptual relevance for resource-constrained environments and indicates possible future applicability in degraded terrestrial systems as well as extraterrestrial settings, where ISRU principles may be relevant.

Notably, the successful establishment of a second plant generation (*Phaseolus vulgaris*), a cultivated species rather than a classical pioneer plant, indicates that plant establishment was not limited to a single species within the tested configuration. This observation should be interpreted cautiously and does not imply agronomic performance or nutrient sufficiency under field conditions.

In the absence of control treatments and quantitative analyses, these findings remain qualitative and do not allow attribution to specific processes or mechanisms. The study therefore does not aim to validate underlying mechanisms, but to assess whether the framework is operationally feasible at the system level. As such, it is not structured as a comparative or hypothesis-testing experiment.

Taken together, the observations provide an initial system-level reference point for the Biorestorer framework and are consistent with its conceptual viability under the tested conditions, while identifying clear priorities for further controlled investigation. Future work will focus on quantitative characterization, inclusion of control treatments, and evaluation of longer-term system dynamics to assess performance, scalability, and applicability in both terrestrial restoration and bioregenerative life-support contexts.

Declaration on the Use of Generative AI and AI-Assisted Technologies

During the preparation of this manuscript, the author used generative AI tools for language editing, stylistic refinement, structural organization, and clarification of terminology. AI-assisted tools were not used to generate original scientific concepts, experimental data, analyses, interpretations, or conclusions. All scientific content, methodological decisions, data, interpretations, and final conclusions were developed, reviewed, and approved by the author, who takes full responsibility for the integrity and accuracy of the manuscript.

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Supplementary Material S1: Full laboratory analysis of biochar sample

Dátum vystavenia : 9.12.2024
Stránka : 2 z 4
Zákazka : PR24D1475 Oprava 2
Zákazník : Zdroje Zeme a. s.

Výsledok

Matrica: PEVNÁ VZORKA

			Názov vzorky	BIOCHAR-KBRO-ZZ-500		----		----	
			Číslo vzorky	PR24D1475001		----		----	
			Dátum odberu/čas odberu	22.10.2024		----		----	
Parameter	Kód metódy	LOQ	Jednotka	Výsledok	NM	Výsledok	NM	Výsledok	NM
Ostatné									
Neštandardný	I-ANNEX-WET	-	-	výsledky v prílohe	----	----	---	----	---
Fyzikálne parametre									
Merná hmotnosť	S-SGRAV-GR	0.01	g/cm3	2.01	± 10.0%	----	---	----	---
pH (H2O)	S-PHH2O-ELE	1.0	-	8.9	± 1.7%	----	---	----	---
Popol bezvodý A(d) pri 815 °C	I-ASH815GRS	0.10	% suš.	42.5	± 5.0%	----	---	----	---
Popol pôvodný A(ar) pri 815 °C	I-ASH815GRS	0.10	%	40.8	± 5.0%	----	---	----	---
Voda analytická M(ad)	I-WA-GR	0.50	%	2.32	± 24.6%	----	---	----	---
Voda celková M(ar)	I-WT-CC	0.50	%	3.88	----	----	---	----	---
Voda hrubá M(ex)	I-WG-GR	0.50	%	1.61	± 28.8%	----	---	----	---
Sušina pri 105 °C	S-DRY-GRCI	0.10	%	97.0	± 5.0%	----	---	----	---
Anorganické parametre									
Celkový organický uhlík (TOC)	S-TOC-TC-IR	0.10	% suš.	34.2	± 20.0%	----	---	----	---
Celkový uhlík	S-TOC-TC-IR	0.010	% suš.	36.0	± 16.2%	----	---	----	---
Dusík pôvodný N(ar)	I-ELEM-TCDS	0.10	%	2.41	± 15.2%	----	---	----	---
Dusíkaté látky v sušine	I-ELEM-TCDS	0.10	% suš.	2.50	± 15.2%	----	---	----	---
Kyslík bezvodý O(d)	I-ELEM-TCDS	5.0	% suš.	16.2	----	----	---	----	---
Kyslík pôvodný O(ar)	I-ELEM-TCDS	5.0	%	15.6	----	----	---	----	---
Síra spaliteľná bezvodá S(d)	I-ELEM-TCDS	0.10	% suš.	0.24	± 31.5%	----	---	----	---
Síra spaliteľná pôvodná S(ar)	I-ELEM-TCDS	0.10	%	0.23	± 32.5%	----	---	----	---
Celkový anorganický uhlík (TIC)	S-TOC-TC-IR	0.010	% suš.	1.80	± 15.0%	----	---	----	---
Uhličitany	S-TOC-TC-IR	0.050	% suš.	8.98	± 15.0%	----	---	----	---
Celkové kovy / Hlavné katióny									
Ca	I-CA-ICPS	0.000010	% suš.	10.3	± 20.0%	----	---	----	---
Mg	I-MG-ICPS	0.0000050	% suš.	0.464	± 20.0%	----	---	----	---
S	I-S-ICPS	5.0	mg/kg suš.	1430	± 20.0%	----	---	----	---
K ako K2O	I-K-ICPS	0.00060	% suš.	1.83	± 20.0%	----	---	----	---
P ako P2O5	I-P-ICPS	0.0023	% suš.	2.44	± 20.0%	----	---	----	---
extrahovateľné kovy / hlavné katióny									
Ag	S-METAXHB1	0.50	mg/kg	<0.50	----	----	---	----	---
As	S-METAXHB1	0.50	mg/kg	0.76	± 20.0%	----	---	----	---
Ba	S-METAXHB1	0.20	mg/kg	90.3	± 20.0%	----	---	----	---
Be	S-METAXHB1	0.010	mg/kg	0.143	± 20.0%	----	---	----	---
Cd	S-METAXHB1	0.40	mg/kg	<0.40	----	----	---	----	---
Celkový fosfor	S-METAXHB1	5.0	mg/kg	15100	± 20.0%	----	---	----	---
Co	S-METAXHB1	0.20	mg/kg	3.81	± 20.0%	----	---	----	---
Cr	S-METAXHB1	0.50	mg/kg	33.7	± 20.0%	----	---	----	---
Cu	S-METAXHB1	1.0	mg/kg	62.4	± 20.0%	----	---	----	---
Fe	S-METAXHB1	10	mg/kg	5310	± 20.0%	----	---	----	---
Hg	S-METAXHB1	0.20	mg/kg	<0.20	----	----	---	----	---
Li	S-METAXHB1	1.0	mg/kg	9.9	± 20.0%	----	---	----	---
Mn	S-METAXHB1	0.50	mg/kg	209	± 20.0%	----	---	----	---
Mo	S-METAXHB1	0.40	mg/kg	1.14	± 20.0%	----	---	----	---
Ni	S-METAXHB1	1.0	mg/kg	15.2	± 20.0%	----	---	----	---
Pb	S-METAXHB1	1.0	mg/kg	9.2	± 20.0%	----	---	----	---
Sb	S-METAXHB1	0.50	mg/kg	<0.50	----	----	---	----	---
Sn	S-METAXHB1	1.0	mg/kg	3.1	± 20.0%	----	---	----	---
Sr	S-METAXHB1	0.10	mg/kg	104	± 20.0%	----	---	----	---
Tl	S-METAXHB1	0.50	mg/kg	<0.50	----	----	---	----	---
V	S-METAXHB1	0.10	mg/kg	5.71	± 20.0%	----	---	----	---
Zn	S-METAXHB1	3.0	mg/kg	173	± 20.0%	----	---	----	---
Polycyklické aromatické uhľovodíky (PAU)									
Naftalén	S-PAHGMS05	0.010	mg/kg suš.	1.12	± 30.0%	----	---	----	---
Acenaftylén	S-PAHGMS05	0.010	mg/kg suš.	<0.130	----	----	---	----	---