


Alignment between product-based regulation and soil process-based functions in biochar systems under EU policy

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ABSTRACT

As biochar transitions from a niche soil amendment to a component of carbon dioxide removal (CDR) strategies, its governance has largely developed within product-based regulatory frameworks. This article synthesises soil science evidence to assess the extent to which current regulatory approaches are aligned with soil processes, heterogeneity, and long-term soil functioning. We argue that prevailing frameworks, exemplified by the EU Fertilising Products Regulation (FPR) 2019/1009 and illustrated through its national implementation in Portugal, assess biochar as a standardised input, despite its role as a persistent and soil-dependent amendment.

This framing positions biochar primarily as a discrete material rather than as an intervention whose function emerges through interactions with soil physical, chemical, and biological processes over time. By analysing the interface between waste, product, and soil-related legislation, we highlight how regulatory pathways—particularly those related to waste classification and End-of-Waste procedures—may influence the deployment of biochar in Mediterranean contexts. We conclude by outlining elements of a soil-informed governance approach that complements existing frameworks by better integrating soil processes, hydrological function, and long-term soil resilience.

1. Introduction

The rapid expansion of biochar production, driven by climate mitigation and carbon dioxide removal strategies, has intensified the need for regulatory frameworks that ensure environmental safety while enabling soil-based climate adaptation (Woolf et al., 2010; Lehmann and Joseph, 2024). As biochar moves from a voluntary niche into a regulated component of national climate and agricultural strategies, it has become subject to the structured frameworks of product regulation. However, this highlights a broader limitation of product-based regulatory frameworks when applied to soil-dependent interventions, where material properties alone do not determine environmental outcomes (Štrubelj, 2022; Cavallin, 2025).

Within the European Union, this transition is governed by the Waste Framework Directive (2008/98/EC), under which biomass-derived materials such as biochar remain classified as waste until they achieve End-of-Waste (EoW) status. This requires demonstrating a specific market use and compliance with safety criteria designed to prevent

environmental harm. In practice, this creates a regulatory pathway where biochar is first treated as a potential waste and subsequently as a fertilising product under Regulation (EU) 2019/1009. In Member States such as Portugal, the absence of dedicated EoW criteria leads to case-by-case assessment by national authorities, introducing administrative uncertainty and reinforcing a product-based regulatory logic that does not explicitly account for soil-dependent variability.

Lawmakers and standardisation bodies primarily define biochar as a product: a discrete commodity characterised by fixed chemical and physical traits, such as carbon content, H:C_{org} ratios, and specific surface area. Current governance is bifurcated between product-quality standards, such as the European Biochar Certificate and the International Biochar Initiative standards, which focus on material safety and physicochemical consistency, and GHG-focused removal methodologies, including private carbon removal standards and the emerging EU Carbon Removals and Carbon Farming Regulation framework (European Parliament and Council of the European Union, 2024; Štrubelj and Rodway-Dyer, 2024; European Biochar Certificate (EBC), 2025;

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European Commission, 2026a,b). However, both frameworks predominantly view biochar as a stationary additive; the former treats it as a fertiliser-like input with intrinsic safety limits, while the latter treats it as a static 'removal credit' whose permanence is modelled via material-based proxies, such as H:C_{org} ratios, rather than soil-matrix interactions. Table 1 provides a synthesised comparison of these diverging frameworks, highlighting the split between material safety and climate-service valuation (Štrubelj and Rodway-Dyer, 2024).

In stark contrast, soil science defines biochar as a process-altering constituent. From a pedological perspective, biochar's climate mitigation potential, hydrological flux regulation, and agronomic efficacy are not intrinsic properties, but rather emergent properties derived from its dynamic interaction with specific soil mineralogies, hydraulic regimes, and microbial communities (Lehmann et al., 2011; Schmidt et al., 2021; Deshoux et al., 2023; Li et al., 2026). Here, the pedosphere is understood as the integrated soil system formed through interactions among minerals, organic matter, water, air, and living organisms (Bünemann et al., 2018).

By examining the divergence between product-based regulatory frameworks and soil process-based understanding, this paper highlights a growing bottleneck in climate-adaptation strategies. This mismatch is particularly evident in regions like Portugal, where the lack of a dedicated soil framework leaves biochar caught in a waste-management bureaucratic process that does not fully account for the demonstrated need for long-term pedological carbon stabilisation. This paper contributes a soil-process perspective to biochar governance, bridging soil physics, soil biology, and regulatory design. Importantly, this limitation is not unique to biochar but is most relevant for persistent or structurally active soil amendments, including compost, digestate-derived products, and pyrogenic carbon materials, whose environmental effects depend not only on chemical composition but also on longer-term interactions with soil physical structure, hydrology, mineral surfaces, and biological processes. In this context, biochar is used here as an illustrative case to examine how regulatory systems that focus on material characteristics may insufficiently capture the soil-dependent nature of environmental outcomes. Accordingly, this paper shifts the focus toward the limited operationalisation of soil-use governance within existing regulatory frameworks. Recent scholarship advances EU biochar governance for CAP, organic and carbon farming, but regulatory fragmentation persists; value-chain analysis shows legal complexity, and soil uncertainties remain post-application (Cavallin, 2024).

Current EU rules, including the EU Fertilising Products Regulation (FPR) 2019/1009, as amended by Commission Delegated Regulation (EU) 2021/2088 introducing CMC 14 for pyrolysis and gasification

materials (European Parliament and Council of the European Union, 2019; European Commission, 2021), establish important product-level safeguards through feedstock eligibility, process requirements, H:C_{org} thresholds, and contaminant limits. Yet these safeguards do not fully operationalise the soil-contextual conditions under which biochar becomes beneficial, neutral, or potentially problematic. Therefore, the regulatory challenge is not only to define safe biochar products, but also to develop soil-informed guidance for their application across heterogeneous soil systems.

This article adopts a conceptual review methodology, integrating soil science, hydrology, product, climate, and environmental law to critically examine biochar governance frameworks. Rather than presenting new experimental data, the paper synthesises established empirical evidence and regulatory analysis to identify structural mismatches between soil processes and product-based regulation (Bouma and McBratney, 2013).

2. Chemical dimension: product regulation and soil-dependent behaviour

From a regulatory perspective, chemical thresholds form the primary basis for assessing biochar safety and compliance. Current biochar governance is anchored in product-based regulatory frameworks that define materials through intrinsic characteristics such as feedstock origin, production conditions, and chemical composition. This approach is consistent with broader fertilising product legislation, where safety and market harmonisation are ensured through standardised thresholds. However, when applied to soil-dependent amendments such as biochar, this regulatory logic assumes that material properties alone determine environmental outcomes, without fully accounting for soil-specific interactions.

2.1. Fixed chemical thresholds and soil-dependent hazard

Current regulatory frameworks, most notably the EU Fertilising Products Regulation (FPR) 2019/1009 via CMC 14, and voluntary standards like the European Biochar Certificate (EBC), rely on absolute concentration limits for heavy metals and Polycyclic Aromatic Hydrocarbons (PAHs) (Štrubelj, 2022). While UK low-risk waste positions (LRWPs) establish clear thresholds for annual application and production quantities, a lack of clarification persists regarding specific contaminant limit values, for which no clear definitions are currently provided (Ghaleigh and Štrubelj, 2025). These thresholds are designed to ensure product safety before the material enters the market (European

Table 1

Characteristics of the formal scope (territory, sphere) and substantive scope (feedstock, production, toxicants, quantifying emissions, permanence, soil-application MRV). A characteristic receives a ✓ if it is within the substantive scope of the standard, and an × if it is outside the scope. The table concludes with each standard's overarching focus, deduced from its substantive characteristics (GHG-focused or product-focused). GHG = Greenhouse Gas. MRV = Monitoring, Reporting, and Verification.

Scope	Puro.earth	Verra	C-Sink	Artisan C-Sink	EBC	WBC	BQM	IBI	FPR (EU 2019/1009)	CRCF (EU 2024/3012)
Territory	International	International	Regional	International	Regional	International	National	Regional	Regional	Regional
Sphere	Private	Private	Private	Private	Private	Private	Private	Private	Public	Public
Feedstock	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Production	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Toxicants	×	×	×	×	✓	✓	✓	✓	✓	✓
Quantifying emissions	✓	✓	✓	✓	×	×	(✓) ¹	×	×	✓
Permanence	✓	✓	✓	✓	×	×	(✓) ¹	×	×	✓
Soil application	✓	✓	✓	✓	(×) ²	×	✓	×	×	(×) ²
MRV	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Focus	GHG	GHG	GHG	GHG	Product	Product	Product	Product	Product	GHG

Notes:

¹ Partially covered, conditional or indirectly addressed.

² Soil application not fully integrated or only partially within scope.

Adapted from Štrubelj and Rodway-Dyer (2024).

Chemicals Agency, 2022). However, soil chemistry demonstrates that the environmental issue of a constituent is not defined by its total concentration (C_{total}), but by its bioavailable fraction within a specific soil solution (Sauvé et al., 2000; Smolders et al., 2009; Petruzzelli et al., 2020).

Biochar exceeding established contaminant thresholds, such as limits for PAHs, may be legally restricted from certification under product-based regulation. These thresholds are grounded in environmental protection principles and play a critical role in preventing the introduction of potentially harmful substances into soils. (Gruss et al., 2019). At the same time, soil-specific characteristics—such as high sorption capacity in clay-rich systems—may influence the environmental behaviour of these compounds, highlighting the relevance of soil context when considering application outcomes. Product-based regulation of biochar relies on fixed thresholds to ensure material safety before application. While soil-specific processes such as sorption, pH buffering, and mineral interactions are recognised within soil science and are increasingly considered within soil-related policy frameworks, their integration into product regulation remains limited. As discussed in later sections, instruments such as the Soil Monitoring Law and the Common Agricultural Policy provide entry points for addressing soil variability at the land-management stage, whereas product regulation primarily governs material quality and market placement before application.

2.2. Carbon stability: from intrinsic ratios to soil protection mechanisms

The $H:C_{\text{org}}$ ratio serves as the primary regulatory proxy for carbon stability across European governance. While the EU FPR mandates a ratio of < 0.7 to qualify the material as a 'stable' constituent of a fertilising product, the legal certification of 'permanence' for carbon dioxide removal (CDR) is more specifically addressed within the Carbon Removal Certification Framework (CRCF) (European Commission, 2026a,b). Both frameworks rely on intrinsic material properties, such as chemical stability indicators, to assess long-term sequestration potential. This reflects the upstream nature of product-based regulation and the current classification of biochar under the permanent carbon removal category within the CRCF. While this approach provides standardisation and comparability, it only partially captures the role of site-specific soil processes in determining long-term carbon stabilisation outcomes. Alternative approaches, such as those associated with carbon farming pathways, could provide a more soil-contextualised framework by linking biochar application to land management practices and soil-specific conditions. (Gholamahmadi and Kammann, 2026).

Soil science research indicates that the long-term persistence of pyrogenic carbon (PyC) is significantly influenced by its interaction with the soil mineral phase (Amelung et al., 2020; Li and Tasnady, 2023). In many Mediterranean soils, particularly those under pressure from intensive agriculture in Portugal and Spain, the physical protection offered by iron and aluminium oxides can stabilise biochars that might otherwise fall outside high-quality and stability thresholds (Fernández-Ugalde et al., 2017). By ignoring these pedogenic interactions, current regulations incentivise a narrow range of "high-carbon" biochars, potentially overlooking locally produced, "low-carbon" soil conditioners that offer superior functional resilience in specific mineral contexts (Joseph et al., 2021). This bias may limit regional circular biochar systems that are well adapted to local soil mineralogy but poorly aligned with uniform product criteria (FAO, 2021).

2.3. National implementation: Portugal as an illustrative regulatory case

Waste regulation constitutes a particularly problematic and structurally ill-fitting regime for biochar governance, often constraining its recognition as a beneficial soil amendment rather than a residual material. In Portugal, the governance of biochar is primarily administered by the Agência Portuguesa do Ambiente (APA), acting as the national

waste authority under the General Waste Management Regime. In the absence of specific national End-of-Waste (EoW) criteria for biochar, the APA assesses EoW status on a case-by-case basis. In practice, this requires producers to demonstrate compliance with 'proxy' standards, primarily the safety and contaminant limit values defined in the EU Fertilising Products Regulation (FPR) 2019/1009 (CMC 14) or the General Waste Management Regime (Decree-Law no. 102-D/2020). This administrative logic implicitly treats biochar as a uniform industrial substance rather than a soil-dependent amendment, creating practical barriers for producers operating with heterogeneous Mediterranean feedstocks (Garcia et al., 2022; Gholamahmadi, 2026a). This administrative inertia creates a bottleneck due to several factors. In the Portuguese context, the practical constraint is less the EU Fertilising Products Regulation itself than the national waste-law pathway through which biomass residues are classified and assessed before they can be used for biochar production or soil application. Mediterranean biomass streams such as olive pomace or shrubland clearance residues may therefore face administrative uncertainty where their status as waste, by-product, or input material requires case-by-case interpretation under national procedures and precautionary considerations related to potential contaminants. Furthermore, the current regulatory framework introduces administrative and compliance requirements that may act as entry barriers, particularly where conformity must be demonstrated under optional harmonisation frameworks or where End-of-Waste (EoW) status must be obtained at the national level (Gholamahmadi, 2026a). While these procedures are essential to ensure material safety and prevent improper classification of waste, they can create practical constraints for scaling biochar systems, especially across different production contexts.

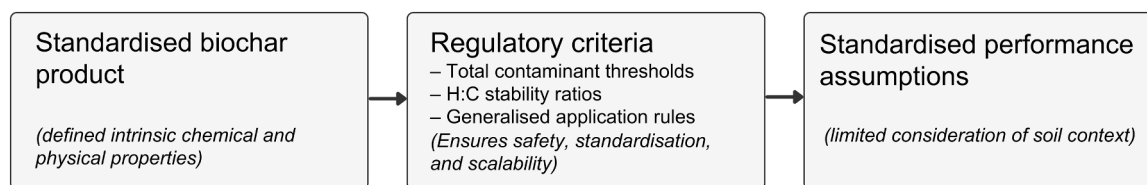
The structure of these frameworks reflects their primary focus on material classification and standardisation before market placement. This upstream orientation provides important safeguards, ensuring that only materials meeting defined criteria are placed on the market. At the same time, it does not fully capture the variability of soil-dependent processes that influence biochar behaviour after application, including interactions with soil structure, mineralogy, and biological activity. This distinction is illustrated in Fig. 1.

3. Physical dimension: soil structure and hydrological processes

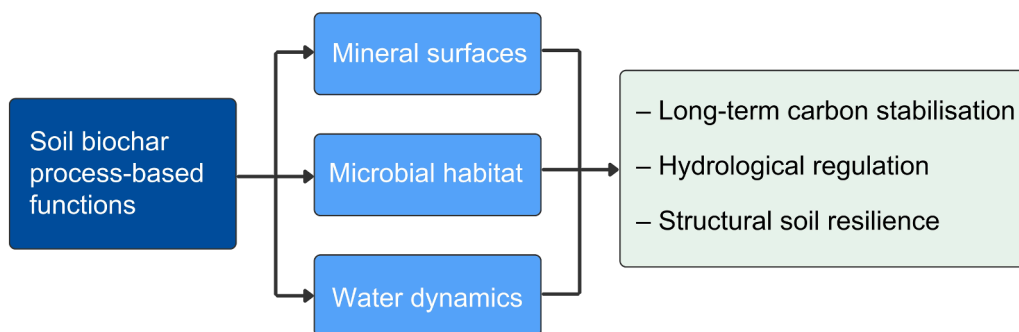
This issue is particularly relevant for structurally active soil amendments such as biochar, where effects depend not only on chemical composition but also on changes in soil pore structure, aggregation, infiltration, and water retention. Product legislation can define the quality and safety of biochar before market placement, but it does not directly regulate how biochar affects soil structure, water flow, infiltration, or erosion resistance after application. These physical outcomes are strongly soil-dependent and are therefore more closely connected to soil-use governance instruments than to product regulation alone.

3.1. The hydrological blind spot

Current governance frameworks, including the EU Fertilising Products Regulation (FPR), primarily assess fertilising products through material composition, safety thresholds, and agronomic functions. At the same time, product-based regulatory approaches perform an essential function by ensuring material safety, limiting contaminant inputs, and enabling standardisation across markets. However, soil physics identifies one of biochar's most relevant roles as a modifier of pore-size distribution, hydraulic conductivity (K_{sat}), and water retention dynamics (Jarvis, 2020). By creating a "dual-porosity" system, biochar has been shown to support soil water retention and flow regulation under certain conditions, for example, increasing matric suction in coarse-textured soils (Blanco-Canqui, 2017; Razzaghi et al., 2020). These changes can be quantified through measurable indicators such as saturated hydraulic conductivity (K_{sat}), runoff coefficients, soil moisture



Limited alignment between product-based regulation and soil processes



Standardised regulatory frameworks ensure safety and scalability, while soil responses emerge through context-dependent physical, biological, and hydrological processes.

Fig. 1. The upper panel illustrates product-based regulatory logic, where biochar is assessed as a standardised input defined by intrinsic properties such as contaminant thresholds and stability indicators. The lower panel represents a soil process-based perspective, in which biochar interacts with soil physical, chemical, and biological components over time, generating context-dependent outcomes including carbon stabilisation, hydrological regulation, and structural resilience. The figure highlights the partial alignment between standardised regulatory approaches and soil-dependent processes.

retention curves, and aggregate stability indices. These effects are supported by quantitative evidence. Meta-analyses have reported increases in water retention ranging from 20% to 50%, infiltration rates on the order of 10–30% and reductions in runoff and soil erosion ranging from approximately 10–50%, depending on soil type, application rate, and climatic conditions (Blanco-Canqui, 2017; Razzaghi et al., 2020; Gholamahmadi et al., 2023). However, evidence remains inconsistent, with Rabbi et al. (2021) reporting in an experiment that plant available water, permanent wilting point, and saturated hydraulic conductivity did not significantly improve overall, and that hydraulic responses depended strongly on soil texture, application rate, and experimental conditions.

This hydrological role is only indirectly addressed within current EU soil and agricultural governance. The Soil Monitoring Law (Directive (EU) 2024/1760) establishes a framework for assessing soil health through descriptors that include soil structure and water retention capacity. Its purpose is not to create incentives for specific soil amendments such as biochar, but to harmonise soil monitoring, assessment, and management across Member States. The Directive nevertheless creates potential opportunities for biochar where national implementation links soil water retention, structure, or erosion-related descriptors to management responses. Because Member States retain discretion in monitoring systems and implementation pathways, the relevance of biochar will depend on how these descriptors are operationalised in practice (Ginzky and Pieper, 2026; European Parliament and Council of the European Union, 2025).

The Common Agricultural Policy (CAP) operates differently. Rather than operating as a soil monitoring framework, the CAP primarily structures agricultural support, while also incorporating environmental conditionality through eco-schemes, GAECs (Good Agricultural and Environmental Conditions) and SMRs (Statutory Management Requirements). Within the CAP, eco-schemes provide a mechanism for incentivising soil-related practices, while GAECs and SMRs impose only limited baseline requirements; collectively, these instruments do not provide a coordinated or explicit pathway for recognising biochar as a hydrological regulator.

This is particularly relevant in Mediterranean regions such as Portugal, where intense rainfall events, including Atmospheric River (AR)-linked storms, alternate with prolonged droughts. In such contexts, biochar may contribute to landscape-scale adaptation by improving infiltration, water retention, and erosion resistance (Gholamahmadi et al., 2025a; Gholamahmadi et al., 2025b). Yet these benefits are not directly captured by product-based regulation, and their recognition under soil and agricultural policy remains dependent on future national implementation choices. This does not indicate an absence of soil governance, but rather a gap in how existing frameworks operationalise soil-process-based interventions such as biochar. For example, contaminant thresholds based on total concentrations may be appropriate for ensuring safety at market entry but may not fully reflect differences in bioavailability across soil types, where high clay or organic matter content can reduce mobility, while coarser-textured soils may exhibit greater transport potential under similar concentrations. Overall, the effects of biochar on hydrological and structural properties are context-dependent, with both positive and neutral responses reported across the literature.

3.2. Structural permanence

A further limitation concerns the temporal mismatch between soil physical processes and administrative reporting cycles. Under the CAP framework, conditionality rules link direct income support to compliance with environmental and land management standards. These rules are important for protecting soils, but they are generally assessed through relatively short administrative cycles compared with the time-scales over which biochar affects soil structure.

Soil physics demonstrates that biochar can initiate longer-term processes of aggregate stabilisation, pore reorganisation, and improved resistance to structural collapse (Six et al., 2000). Through interactions with organic matter, minerals, roots, and microbial activity, biochar may enhance resistance to slaking—the collapse of soil aggregates under the kinetic energy of rainfall—and reduce sediment-laden runoff during extreme weather events (Shi et al., 2021; Gholamahmadi et al., 2023).

These effects are not necessarily immediate or uniform. They may strengthen over time as biochar weathers, becomes colonised by microorganisms, and integrates into the soil matrix (Gholamahmadi et al., 2023; Lehmann and Joseph, 2024).

The governance limitation is therefore not that existing frameworks do not explicitly consider soil structure entirely, but that they are poorly equipped to recognise long-term, process-based improvements generated by soil amendments. Product regulation evaluates biochar before application, while agricultural and soil policies evaluate land management outcomes through descriptors, standards, or compliance rules. The challenge is to create better coherence between these phases so that long-term changes in soil structure, infiltration, and erosion resistance can be recognised without treating biochar as a special regulatory exception. Within the Carbon Removals and Carbon Farming Regulation (CRCF), alternative regulatory pathways may offer closer alignment with these temporal dynamics. While biochar is currently addressed under permanent carbon removal methodologies, carbon farming approaches provide a different framework based on land management practices and extended activity and monitoring periods. For example, CRCF provisions define minimum activity periods of at least five years (Art. 2(10)), with draft methodologies for land-based interventions extending over multiple decades. Applying a similar approach to biochar could improve the recognition of gradual soil processes, including long-term changes in structure, hydrology, and carbon stabilisation.

3.3. Catchment-scale considerations

The physical effects of biochar at larger spatial scales extend beyond individual fields and introduce considerations at the catchment level. Where biochar is applied extensively, changes in soil hydraulic conductivity (K_{sat}), infiltration capacity, and pore connectivity may influence water movement across landscapes. These effects are highly context-dependent, varying with soil type, land use, climate, and application rate, and therefore require careful interpretation (Garcia et al., 2022; Gholamahmadi et al., 2025a).

From a governance perspective, such considerations are only partially addressed within existing frameworks, which primarily assess material properties before application. While soil and water-related policies, including the Water Framework Directive and CAP-linked instruments, address hydrological outcomes at broader scales, they do not explicitly account for how soil amendments such as biochar may influence catchment-scale processes. This highlights the importance of considering soil hydrological dynamics when evaluating biochar deployment in heterogeneous environments. A structured comparison between product-centred regulatory criteria and soil process-based functional outcomes is synthesised in Table 2. In general, these findings indicate that biochar effects are governed primarily by soil-dependent processes, which vary across environmental conditions and may not be fully inferred from material properties alone.

4. Biological dimension: microbial processes and temporal dynamics

This issue also arises for persistent or biologically active soil amendments such as biochar, where environmental outcomes depend not only on material composition but also on microbial colonisation, enzyme activity, priming effects, and longer-term biological adjustment within the soil matrix.

4.1. Beyond the carbon storage mechanism: Biochar as a microbial catalyst

Current governance, particularly within the Carbon Removal Certification Framework (CRCF) and voluntary carbon markets, often treats biochar as a static "carbon vault." The primary regulatory assumption is that the climate benefit is locked within the recalcitrant aromatic rings

Table 2

Synthesis of conceptual contrast between product-centred biochar regulation and soil process-based perspectives, and their governance implications.

Feature	Product-centred regulation	Soil process-based perspective	Governance implication
Material identity	Standardised input product defined by intrinsic properties (e.g. CMC 14)	Persistent soil amendment interacting with minerals, microbes, and water	Regulated as a commodity rather than a soil intervention
Toxicity assessment	Assessed using total concentrations (e.g. PAHs, heavy metals)	Determined by bioavailability and soil buffering capacity	May not fully capture site-specific soil responses
Carbon value	Based on intrinsic chemical stability (e.g. H:C _{org} ratios, PyC mass)	Emerges through microbial mediation and organo-mineral protection	Partial accounting of soil carbon stabilisation pathways
Hydraulic role	Not explicitly recognised in product regulation	Alters pore-size distribution and hydraulic conductivity	Hydrological regulation is not explicitly addressed in governance frameworks
Temporal scale	Evaluated over short administrative cycles (1–3 years)	Develops over decadal soil formation and weathering timescales	Limited alignment between assessment timelines and soil processes
Administrative logic	Linear waste-to-product transition and standardisation	Integration into circular soil management systems	Limited coordination between product regulation and soil-use frameworks

of the material itself. However, soil biology demonstrates that biochar acts as a catalytic habitat, fundamentally reorganising the soil microbiome (Deshoux et al., 2023; Enebe et al., 2025). This regulatory framing has been further formalised by the European Commission's adoption of the first voluntary certification methodologies for permanent carbon removals, explicitly recognising biochar carbon removal as a certified pathway under the EU Carbon Removals and Carbon Farming Regulation (European Commission, 2026a,b). However, the CRCF liability structures primarily focus on biochar as a process that concludes at the point of soil application; by placing the boundary of liability at the point of incorporation, the framework reinforces the 'product-centric' view and neglects the decadal-scale, dynamic interactions between the biochar and the soil matrix.

Regulations currently do not fully account for the Microbial Carbon Use Efficiency (CUE). Emerging evidence suggests that biochar can increase CUE by reducing the metabolic stress of soil microbes, thereby ensuring that a higher proportion of plant-derived carbon is incorporated into microbial biomass and residues (necromass) rather than being respired as CO₂ (Giagnoni and Renella, 2022). By focusing solely on the 'Product' (the pyrogenic carbon mass), current governance does not explicitly consider the 'Process' (the microbial stabilisation of non-pyrogenic carbon). While these indirect sequestration effects could theoretically be captured under separate Carbon Farming methodologies within the CRCF, the existing regulatory silos prevent an integrated accounting of the total climate mitigation potential emerging from biochar-soil systems (Lehmann et al., 2021; Gholamahmadi et al., 2025b).

4.2. Temporal mismatch between biological response and policy reporting

Biochar application commonly induces a transitional adjustment phase in soil biological communities, as microorganisms respond to

changes in habitat structure, nutrient availability, and microscale redox conditions created by the amendment (Enebe et al., 2025). This microbial recovery period can extend from several months to multiple growing seasons, depending on soil texture, organic matter status, and prevailing climatic stressors (Lehmann and Joseph, 2024). During this phase, short-term biological indicators may not immediately reflect the longer-term stabilisation processes initiated by biochar addition. Many agricultural and environmental reporting frameworks operate on annual or multi-annual assessment cycles that implicitly assume rapid and measurable responses following soil amendment. Such timelines are poorly aligned with biologically mediated soil processes, particularly those involving microbial reorganisation and the gradual formation of organo-mineral associations (Joseph et al., 2021). Mediterranean soils, including those prevalent in Portugal, are frequently exposed to chronic water limitation and repeated drought stress, which constrain microbial resilience and prolong biological recovery following disturbance (Marañón-Jiménez et al., 2022). In these contexts, delayed biological responses following biochar application reflect inherent soil–climate interactions rather than shortcomings of the amendment itself. When uniform evaluation frameworks are applied across diverse pedoclimatic regions, soil interventions designed for long-term resilience may appear ineffective in the short term. For instance, Portuguese forest-to-farm transitions using shrubland-derived biochar may show negligible biological improvements in the first biennial audit mandated by CAP conditionality, leading to the premature withdrawal of support for an intervention that requires a decadal horizon to mature (Garcia et al., 2022).

Recognising microbial recovery time as an intrinsic component of soil process-based interventions would allow governance frameworks to better align assessment timelines with biological reality, particularly for amendments intended to enhance long-term soil stability rather than immediate productivity (Lehmann and Joseph, 2024). This temporal misalignment between biological recovery and regulatory evaluation is schematically illustrated in Fig. 2.

4.3. The priming effect: a regulatory blind spot

The interaction between biochar and native soil organic carbon (SOC)—known as the "Priming Effect"—remains absent from biochar governance (Amelung et al., 2020). While biochar can induce "Negative

Priming" (stabilising existing soil carbon), it can also, in specific nutrient-poor contexts, induce "Positive Priming" (accelerating the loss of native SOC) (Lessmann et al., 2022; Gholamahmadi, 2026b). Current law, which regulates biochar as a standardised input, does not mandate Soil Biological Baseline Assessments. Without these, we may have issues when applying biochar to soils where the biological response might temporarily contradict climate mitigation goals. The omission of microbial mediation from the regulatory framework creates a "lack of process transparency" that undermines the scientific credibility of the biochar-soil intervention (Lehmann and Joseph, 2024). This does not invalidate biochar deployment but highlights the importance of baseline soil biological assessment.

5. Governance across regulatory phases: product control and soil-use frameworks

Building on the soil-process-based evidence outlined in previous sections, this section examines how existing regulatory frameworks interact with these processes in practice.

Within the European Union, biochar is governed through a combination of product-based regulation and soil-related policy instruments that operate at different stages of its lifecycle. Product legislation, particularly the EU Fertilising Products Regulation (EU) 2019/1009, regulates biochar before market placement by defining acceptable feedstocks, production conditions, and contaminant thresholds. In parallel, soil use is addressed through broader legal frameworks, including the Soil Monitoring Law, the Nitrates Directive, the Common Agricultural Policy (CAP), and the Nature Restoration Regulation; however, these instruments remain relatively limited in scope at the EU level, with substantial discretion over soil governance retained by Member States (Montanarella, Panagos, 2021).

These frameworks perform distinct but complementary roles. Product legislation ensures that biochar placed on the market meets defined safety and quality criteria, while soil-related instruments govern land management practices and environmental outcomes following application. However, the linkage between these regulatory layers remains limited. Existing frameworks do not explicitly regulate the conditions under which biochar is applied across different soil types, nor do they systematically incorporate soil-specific variability into decision-making. As a result, while both biochar and soils are regulated, the interaction



Fig. 2. Administrative procedure governing biochar application in Mediterranean contexts. Using Portugal as an illustrative case, the figure contrasts the linear administrative procedures regulating biochar as a product with the slower biological and physical processes through which biochar contributes to long-term soil restoration. This temporal mismatch may delay the recognition of the benefits of soil-based climate adaptation.

between them is only partially addressed.

A key step in biochar governance is the transition from waste to product status. Under the EU Waste Framework Directive (2008/98/EC), biomass-derived materials may be classified as waste unless they qualify as by-products or fall outside the waste definition, for example, where biomass is purposefully cultivated for biochar production or meets specific exclusion criteria under Article 2(1)(f). Where materials are considered waste, they remain subject to this classification until they achieve End-of-Waste status by demonstrating a specific use and compliance with environmental and safety criteria (Štrubelj, 2022). In practice, this creates a regulatory pathway in which biochar moves from waste classification to recognition as a fertilising product. In Member States such as Portugal, the absence of dedicated End-of-Waste criteria can result in case-by-case assessment by national authorities, introducing administrative uncertainty (Decree-Law no. 102-D/2020). In practice, these alternative classifications (e.g., by-product status or purpose-grown biomass) may reduce reliance on End-of-Waste procedures. However, they still require demonstration of compliance with regulatory criteria at the national level. However, this process primarily concerns material classification and does not extend to soil-specific application conditions.

Once biochar is classified as a fertilising product, regulation focuses on its properties as a commercial material, reflecting the upstream function of product legislation in ensuring safety and market consistency; once compliant with the EU Fertilising Products Regulation, such products benefit from free movement within the internal market, limiting Member State discretion to restrict their use irrespective of site-specific soil conditions. This approach is effective for ensuring traceability, standardisation, and market consistency. Such standardisation is also necessary to support regulatory scalability, reduce administrative burden, and enable cost-effective monitoring and compliance across large and heterogeneous agricultural systems.

However, it does not fully address the soil-dependent processes that govern biochar behaviour after application. Chemical thresholds, such as limits on contaminants or carbon content, provide important safeguards, but they do not fully capture variability in soil physical structure, biological activity, or hydrological function. Consequently, regulatory frameworks ensure that the material is compliant at the point of sale but provide limited guidance on how its interaction with soils may vary across environmental contexts (Bouma and McBratney, 2013; Garcia et al., 2022; Gholamahmadi et al., 2025b).

This does not indicate an absence of governance but rather reflects a structural imbalance in which EU-level frameworks remain only partially integrated across regulatory phases. While product legislation operates coherently to govern biochar as a marketable material, soil-related instruments at the EU level - aside from the relatively recent Soil Monitoring Law - remain limited in scope and largely defer substantive choices to Member States. Directives such as the Nitrates Directive and Water Framework Directive address specific pressures, while the CAP primarily operates through optional incentives rather than binding soil-use rules. As a result, product legislation and soil governance operate largely in parallel, with limited mechanisms to connect material properties with soil-specific outcomes. Improving this linkage, therefore, depends less on expanding EU soil regulation than on strengthening coordination across regulatory layers and national implementation. Within this context, instruments such as the Nature Restoration Regulation may only indirectly support soil-based interventions, including biochar, where Member States choose to operationalise them.

The Carbon Removal Certification Framework (CRCF) introduces additional considerations for biochar through methodologies for permanent carbon removal. These methodologies incorporate environmental safeguards aligned with EU Taxonomy criteria, including climate change adaptation, sustainable water use, and biodiversity protection. While the CRCF remains voluntary and focuses primarily on monitoring up to the point of application, it provides a partial bridge between

product-based regulation and soil-based outcomes. However, its current scope does not fully address the variability of soil processes following biochar application. In this context, alternative positioning of biochar within carbon farming pathways—rather than permanent removal categories—could strengthen alignment with soil-based processes and longer-term land management dynamics.

6. Toward soil-informed monitoring and verification frameworks

Translating soil-process-based insights into regulatory practice requires monitoring, reporting, and verification (MRV) approaches that remain compatible with existing governance frameworks while capturing soil-dependent outcomes. Rather than developing entirely new regulatory systems, a practical pathway lies in integrating soil-functional indicators into existing instruments. A structured, tiered approach can support this integration.

6.1. Tier 1: product-level compliance

Existing frameworks such as the EU Fertilising Products Regulation (FPR) and certification schemes (e.g. EBC) ensure feedstock control, production quality, and contaminant thresholds. These remain essential safeguards and form the regulatory baseline. Maintaining this level of standardisation is critical for ensuring that MRV systems remain scalable and economically feasible, particularly in large-scale deployment contexts.

6.2. Tier 2: soil functional indicators

Soil responses to biochar can be assessed using a minimal set of measurable indicators that are both scientifically robust and field-feasible. These include physical (e.g. aggregate stability, bulk density), hydrological (e.g. water retention, infiltration capacity), and biological indicators (e.g. microbial community composition, enzyme activity). Such indicators act as proxies of soil functional condition and can capture early and site-specific responses to biochar application.

A recent soil-function indicator framework proposes a minimal triad of structural stability, microbial community composition, and biochemical activity as a practical basis for assessing biochar-enhanced soil systems under real agricultural conditions (Gholamahmadi et al., 2026). This approach emphasises repeatable measurements, site-specific baselines, and conservative interpretation, aligning with emerging EU requirements for transparency and environmental integrity.

6.3. Tier 3: system-level outcomes

At broader scales, these soil-functional changes translate into measurable outcomes, including reduced runoff, improved water regulation, enhanced drought resilience, and erosion mitigation. These outcomes are already relevant to existing policy frameworks such as the Water Framework Directive, the Common Agricultural Policy, and the Nature Restoration Regulation.

This tiered structure allows regulatory systems to retain standardisation at the product level while incorporating soil-specific responses at the application level. Importantly, it does not require biochar-specific legislation, but rather improved coordination between existing frameworks. Such an approach is also compatible with the Carbon Removals and Carbon Farming Regulation (CRCF), particularly under carbon farming pathways that account for land-based processes and longer-term soil dynamics.

7. Conclusions and policy implications

The limitations identified in biochar governance reflect a broader structural constraint in current regulatory frameworks, which remain

insufficiently equipped to address soil-dependent interventions across heterogeneous soil systems. This article has demonstrated that product-centred regulatory frameworks do not fully account for: i) the chemical paradox of total vs. bioavailable contaminants, ii) the hydrological regulation of soil water fluxes, iii) the microbial mediation of carbon stabilisation, and iv) the administrative inertia in waste-to-product transitions.

Aligning biochar governance with soil science requires a clearer articulation of the complementary roles of existing regulatory frameworks. Product-based legislation governs the quality and safety of biochar before market placement, while soil-related frameworks govern its application and interaction with heterogeneous soil systems. Strengthening the linkage between these regulatory layers is therefore essential. It must be acknowledged that current standardised approaches aim to support regulatory convenience and reduce the administrative costs of Monitoring, Reporting, and Verification (MRV) frameworks; however, this standardisation may limit the representation of pedological variability and soil-specific processes. Without a shift toward process-oriented criteria, biochar applications are being regulated in ways that constrain their contribution to soil resilience, climate adaptation, and long-term carbon stabilisation.

In practical terms, this implies that biochar governance should be understood as operating across two regulatory phases. The first phase concerns production and market entry, where product legislation such as the EU Fertilising Products Regulation ensures material safety and standardisation. The second phase concerns soil application, where frameworks such as the Soil Monitoring Law, the Nitrates Directive, and the Common Agricultural Policy govern environmental performance and land management outcomes. The effectiveness of biochar governance depends not on prioritising one framework over another, but on ensuring coherence and functional integration between these phases.

The recent introduction of EU-level voluntary standards for permanent carbon removals, specifically the Carbon Removal Certification Framework (Regulation (EU) 2024/3859), highlights the increasing policy significance of soil-based sequestration yet underscores the urgent need to align certification processes with the realities of soil science. Emerging policy developments, such as the EU Roadmap towards Nature Credits, offer a potential pathway for this alignment by identifying soil fertility, water regulation, and carbon-related ecosystem services as foundational elements of nature value creation (European Commission, 2025). Within this landscape, the newly adopted Soil Monitoring Law (Directive (EU) 2024/1760) represents a vital opportunity to complement existing product thresholds with soil-based indicators and formally integrate biological and physical indicators into a unified soil health framework. By shifting from uniform material standards toward process-oriented governance, the European regulatory environment can finally reconcile the industrial logic of waste-to-product transitions with the ecological necessity of site-specific soil restoration.

Taken together, the analysis underscores that biochar governance in the EU is characterised less by a lack of regulation than by a structural imbalance: a dense and harmonised regime governing materials at the point of market entry, contrasted with a comparatively limited and fragmented set of soil-related frameworks, most of which leave substantive implementation to Member States. As a result, the core governance challenge lies not in the proliferation of instruments, but in the misalignment between strongly integrated product regulation and weakly coordinated soil-use governance. Within this constrained landscape, instruments such as the Nature Restoration Regulation may only indirectly support soil-based interventions, including biochar, where Member States choose to operationalise them. Addressing this imbalance, therefore, requires not new layers of EU soil regulation, but improved coordination across regulatory phases, alongside practical approaches - such as the proposed tiered MRV framework - that can integrate soil-process-based indicators into existing systems while remaining administratively workable.

CRedit authorship contribution statement

Behrouz Gholamahmadi: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Conceptualization. **Luka Štrubelj:** Writing – review & editing, Validation, Investigation. **Navraj Singh Ghaleigh:** Writing – review & editing, Validation, Investigation.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this manuscript, the authors used AI-assisted tools, including ChatGPT (OpenAI), to support readability improvement, language editing, and formatting of references, and Grammarly for grammar checking. After using these tools, the authors critically reviewed and edited the manuscript and take full responsibility for the content of the published article.

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No data was used for the research described in the article.

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