

Agronomic use of *biol* and its effects on soil quality and plant growth: A narrative synthesis with bibliometric analysis

Uso agronómico del *biol* y sus efectos en la calidad del suelo y el crecimiento vegetal: una síntesis narrativa con análisis bibliométrico

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ABSTRACT

Biol is a liquid organic fertilizer derived from the anaerobic digestion of agricultural and plant residues, and it has gained attention as a sustainable alternative to chemical-intensive fertilizers. In this article, we synthesize the available evidence on *biol* composition and its effects on soil quality and plant responses. A narrative review approach was adopted, supported by a systematized literature search in Scopus, SpringerLink, PubMed and SciELO, covering 2000 to 2025, complemented by targeted manual searches and citation chasing. In addition, a bibliometric keyword co-occurrence analysis was conducted in VOSviewer, using an expanded corpus of 64 related articles. The database search retrieved 5278 records. After database-specific filtering, de-duplication and the sequential screening of titles, abstracts and full texts, 15 articles from the automated, script-based pathway and 22 manually identified key studies were retained, yielding 37 studies through a PRISMA-inspired selection process. Through bibliometric mapping, we identified three dominant thematic clusters: (i) organic amendments and waste management; (ii) soil quality and biogeochemical processes; and (iii) crop response and productivity. Overall, the evidence gathered indicates that *biol* may improve soil physicochemical and microbiological properties and support seed germination and root and shoot development across several crops—particularly *Zea mays*—when applied at appropriate dilutions. However, given its highly variable composition, prior characterization and appropriate dosing is required in order to minimize agronomic and/or environmental risks. Our findings support the potential of *biol* for sustainable agriculture and circular waste management, while underscoring the need for more standardized reporting of composition and field performance.

Keywords: digestate, liquid organic fertilizers, anaerobic digestion, sustainable agriculture, circular economy

RESUMEN

El *biol* es un fertilizante orgánico líquido derivado de la digestión anaerobia de residuos agrícolas y vegetales, y se ha consolidado como una alternativa sostenible frente a la fertilización química intensiva. Esta revisión sintetiza la evidencia disponible sobre su composición y sus efectos en la calidad del suelo y la respuesta de los cultivos. Se empleó un enfoque de revisión narrativa, respaldado por una búsqueda sistematizada en Scopus, SpringerLink, PubMed y SciELO para el periodo 2000-2025, complementada con búsquedas manuales dirigidas y rastreo de citas. Asimismo, se realizó un análisis bibliométrico de coocurrencia de palabras clave en VOSviewer utilizando un corpus ampliado de 64 artículos relacionados. La búsqueda inicial recuperó 5278 registros; tras aplicar filtros específicos por base de datos, eliminar duplicados y efectuar un cribado secuencial de títulos, resúmenes y textos completos, se recuperaron 15 estudios provenientes de la ruta automatizada y 22 estudios clave identificados manualmente. Se obtuvo así un conjunto final de 37 estudios, conforme a un proceso de selección inspirado en PRISMA. El mapeo bibliométrico identificó tres clústeres temáticos dominantes: (i) enmiendas orgánicas y gestión de residuos, (ii) calidad del suelo y procesos biogeoquímicos y (iii) respuesta del cultivo y productividad. En conjunto, la evidencia indica que el *biol* puede mejorar propiedades fisicoquímicas y microbiológicas del suelo y favorecer la germinación y el desarrollo radicular y aéreo en diversos cultivos —especialmente *Zea mays*— cuando se aplica en diluciones adecuadas. No obstante, su composición altamente variable exige caracterización previa y una dosificación apropiada para minimizar riesgos agronómicos o ambientales. Los hallazgos respaldan el potencial del *biol* para una agricultura sostenible y una gestión circular de residuos, y subrayan la necesidad de una mayor estandarización en el reporte de su composición y desempeño en campo.

Palabras clave: digestato, fertilizantes orgánicos líquidos, digestión anaerobia, agricultura sostenible, economía circular



1. Introduction

As a strategic natural resource, soil serves as a dynamic reservoir for the water, nutrients and essential microorganisms required for crop growth and development. Soil preservation is essential for ensuring global food security, particularly given increasing demand for food (Kahandage *et al.*, 2023); however, intensive chemical fertilizer use is recognized as a key factor in the deterioration of soil quality. While such compounds have significantly increased agricultural productivity, they have also led to adverse impacts upon the environment and human health (Reyes and Cano, 2022; Lin *et al.*, 2019).

Excessive application of chemical fertilizers at inappropriate rates has negatively affected soil microbiota and has altered both soil structure and pH. This practice has also promoted groundwater degradation and caused major disruption to aquatic ecosystems. Furthermore, it has reduced the water-holding capacity of soils (Bardales, 2023). Such alterations result in delayed plant growth and undermine the sustainability of agricultural systems (Pahalvi *et al.*, 2021). In response to these adverse effects, there has been growing interest in more sustainable approaches, including organic agriculture, with the aim of reducing or eliminating chemical input, and encouraging the adoption of alternative, more responsible and balanced production methods (Baweja *et al.*, 2020; Bardales, 2023).

In the context of such challenges and the search for sustainable alternatives to chemical fertilizers (Waqas *et al.*, 2023), *biol* has emerged as a promising option for sustainable agriculture. This liquid organic by-product is obtained through the anaerobic digestion of organic waste from both animals and plants (Milivojevic, 2018). Once decomposition is complete, *biol* can be used to amend soil, enhancing nutrient availability and promoting healthier, more effective plant development (Figure 1).

Effects of NPK on plants

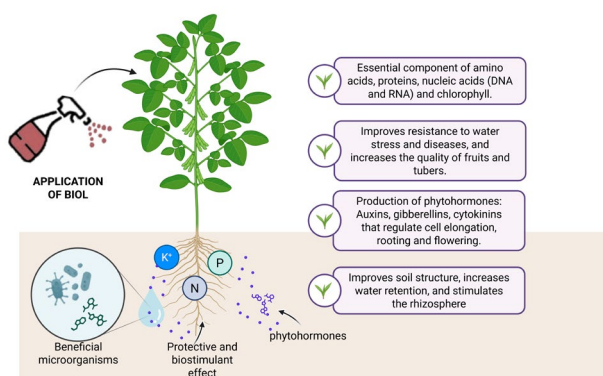


Figure 1. Effects of *biol* application and NPK ratio on crops

Note. Created using BioRender.

Key macronutrients, most notably nitrogen (N), phosphorus (P) and potassium (K), together with secondary and trace elements, underpin physiological processes and yield formation in crops. Furthermore, phytohormones such as auxins and gibberellins, as well as beneficial microorganisms, enhance soil functionality (Mwakidoshi *et al.*, 2023). Unlike chemical fertilizers, which act rapidly but are less sustainable, *biol* has a positive effect on the physical, chemical and biological properties of soil, by stimulating microbial activity, increasing moisture retention and supporting the biodiversity of soil microfauna (Baweja *et al.*, 2020).

In this context, our aim in this review was to synthesize and critically analyze research on the agronomic use of *biol* as an alternative or complement to mineral fertilizers, with emphasis on its physicochemical and microbiological composition, its effects on soil quality, and plant responses from germination to crop growth and yield. In our review, we also examined reported contrasts between *biol*-based input and mineral fertilizers, in both agronomic and environmental terms. Finally, a bibliometric approach was applied, in order to identify thematic clusters, research trends and knowledge gaps applicable to the development of more sustainable agricultural practices. Specifically, the aim of our review was to: (i) synthesize the reported physicochemical and microbiological attributes of *biol* and highlight key sources of compositional variability; (ii) summarize evidence on the effects of *biol* on soil quality indicators; (iii) synthesize reported plant responses from seed germination to crop growth and yield; (iv) compare reported agronomic and environmental contrasts between *biol*-based inputs and mineral fertilizers; and (v) map thematic clusters, research trends and knowledge gaps, using keyword co-occurrence bibliometric analysis.

2. Methodology

We conducted our study using the methodology of a narrative review, supported by a systematized and transparent search and selection of the scientific literature addressing the agronomic use of *biol* and functionally equivalent biodigester-derived liquid organic amendments. In our review, we focused on evidence related to *biol* composition, soil quality responses, crop performance and comparisons with mineral fertilizers, complemented by a bibliometric analysis, in order to explore research trends and thematic structures.

In Latin American literature, the term *biol* is commonly employed to refer to liquid effluents obtained from the anaerobic digestion of organic residues, whereas in English-language studies the terms more frequently used include *liquid organic fertilizer*, and *digestate* or *biogas effluent*. In this review, we employ *biol* as an umbrella term to encompass these functionally equivalent liquid products derived from biodigesters.

2.1. Search strategy and data sources

We conducted a comprehensive literature search across four scientific databases: Scopus, SpringerLink, PubMed and SciELO. The search period was restricted to 2000-2025, in order to incorporate early experimental studies on *biol* and anaerobic digestion effluents, as well as more recent research conducted in accordance with standardized agronomic and environmental assessment frameworks. Database-specific filters were applied in order to restrict the results to original research articles within the subject areas of agronomy, soil science and environmental science. Full texts were accessed through open-access sources or institutional subscriptions, with the aim of excluding relevant studies based solely on access limitations.

The search strategy was based on Boolean operators and was consistently applied across the aforementioned scientific databases, using the following main query:

("biol" OR "liquid organic fertilizer" OR "digestate" OR "biogas effluent") AND ("soil quality" OR "soil properties" OR "soil nutrients" OR "soil fertility") AND ("crop growth" OR "plant growth" OR "agricultural sustainability")

2.2. Study selection and screening process

The identification of relevant literature was achieved by following a hybrid approach combining: (i) an automated, string-based search pathway across databases (Scopus, SpringerLink, PubMed and SciELO); and (ii) a complementary manual and targeted search

strategy. In the automated phase, database-specific filters were applied (publication type, subject area and, where available, open-access status), after which records from Scopus and SpringerLink met the basic eligibility criteria.

Subsequently, all the records were consolidated into a single corpus and duplicates were removed. Screening was conducted in two stages: (i) title and abstract screening according to predefined inclusion and exclusion criteria; and (ii) full-text assessment focusing on studies that explicitly evaluated *biol* or functionally equivalent biodigester-derived liquid amendments applied to agricultural soils or crops. This procedure was conducted under a predefined search protocol as part of the review process and the bibliometric analysis. Further quantitative details on the search outputs and selection outcomes are reported in the Results section. The complete identification, screening and selection workflow is summarized in a PRISMA-inspired flow diagram (Figure 2) and documented in detail in Supplementary File S1.

2.3. Bibliometric analyses

In order to examine research trends and the thematic structure associated with *biol* and liquid organic amendments, we conducted a bibliometric analysis in VOSviewer, restricted to bibliometric mapping. To minimize redundancy and semantic overlap, author-provided keywords were cleaned and harmonized. Based on the curated keyword set, keyword co-occurrence networks were constructed and visualized as network and density maps, in order to identify thematic clusters and association patterns.

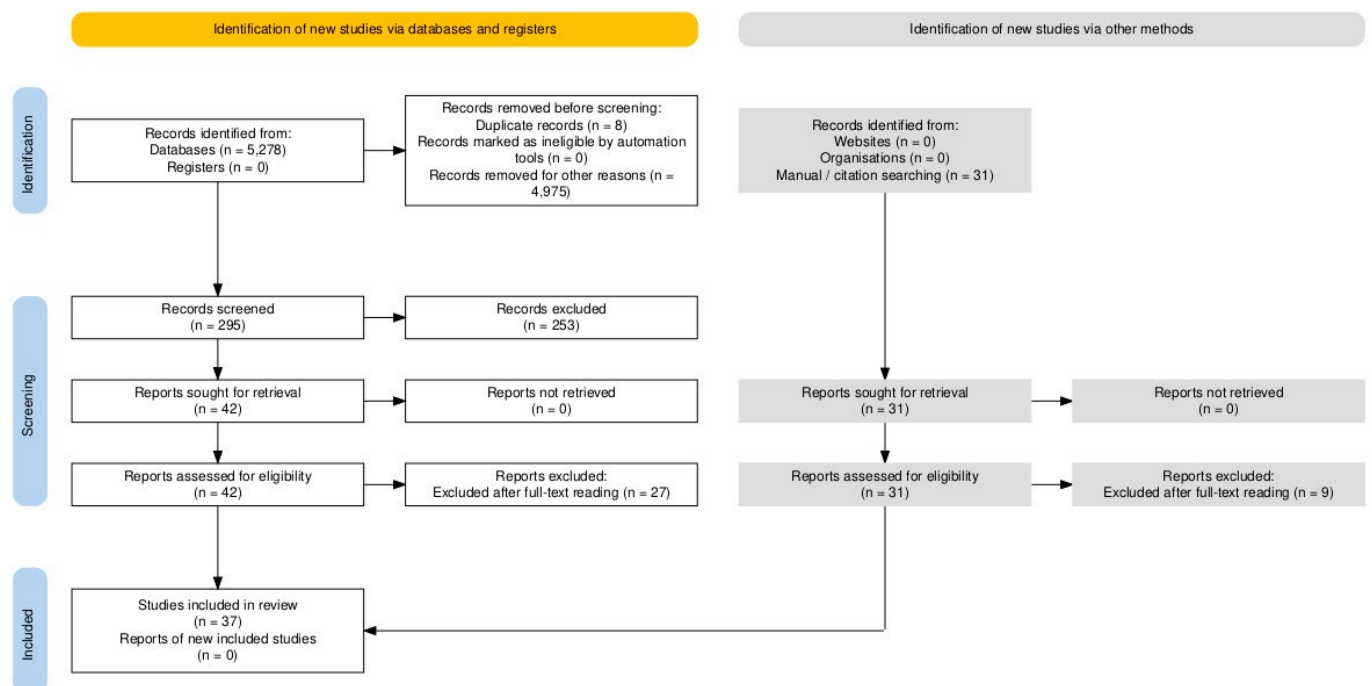


Figure 2. PRISMA 2020-inspired flow diagram summarizing the identification, screening and selection process of the studies included in this review
Note. Generated in R using PRISMA2020 (Haddaway *et al.*, 2022).

3. Results

In line with the aforementioned specific objectives, below we present our report on the bibliometric mapping outcomes and synthesize the empirical evidence on *biol* characteristics and its effects on soils, seed germination and crop growth.

3.1. Bibliometric mapping of biol research

Bibliometric mapping was performed on an expanded corpus of 64 articles (37 included in the evidence synthesis, plus 27 thematically related articles incorporated exclusively for bibliometric analysis). Following keyword cleaning and harmonization, 58 author keywords met the inclusion threshold and were used to construct the keyword co-occurrence network.

Network visualization (Figure 3.a) revealed three dominant thematic clusters: (i) organic amendments and waste management; (ii) soil quality and biogeochemical processes; and (iii) crop response and agricultural productivity. The network connected recurrent terms related to organic fertilization and digestate/*biol*, soil properties and nutrient dynamics, microbial activity, crop yield and sustainable agriculture, thereby delineating the main research axes and their interconnections.

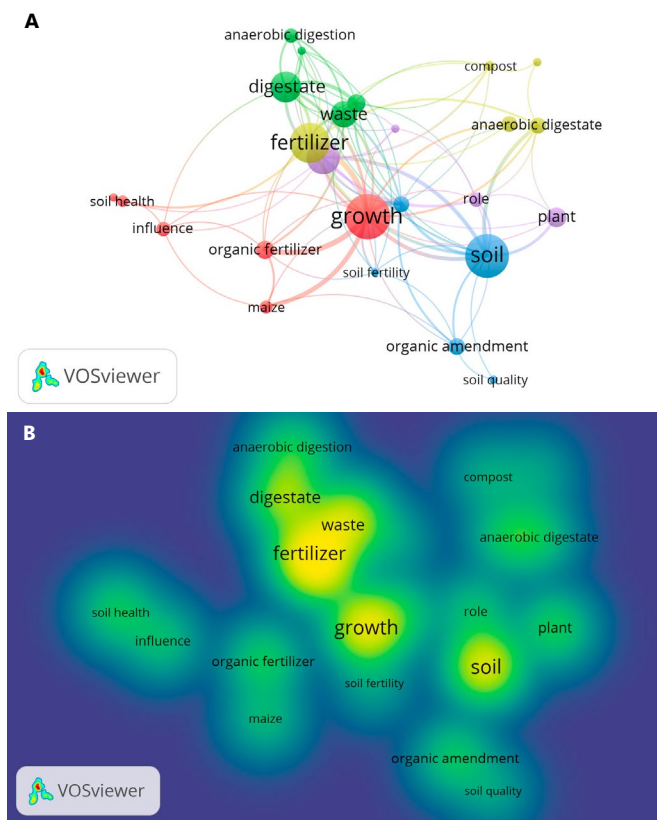


Figure 3. Keyword co-occurrence maps in VOSviewer based on the expanded corpus (n = 64): (a) network visualization; (b) density visualization

Using the same 64-article corpus, the density visualization (Figure 3.b) adds an intensity dimension by highlighting areas with the highest concentration of keyword occurrence and co-occurrence around these axes. Consistent with the specific aims of our review, the resulting thematic structure provides the organizing framework for the subsequent narrative evidence synthesis (Sections 3.2-3.6).

3.2 Organic amendments (OAs)

Across the reviewed literature, we found that organic amendments (OAs) are consistently framed as core inputs in sustainable agriculture, as they enable the recycling of organic residues through aerobic and anaerobic processes, generating products such as compost, biosol, *biol*, bokashi and other liquid organic fertilizers (Figure 4). Collectively, this evidence base links OAs primarily to improvements in soil fertility, waste valorization, and environmental co-benefits, and emphasizes an integrated nutrient management approach in which OAs complement inorganic fertilization by enhancing soil biochemical functioning and symbiotic activity, ultimately improving crop performance across agricultural systems (Álvarez-Solís *et al.*, 2010). Convergent findings also report synergistic effects when amendments such as biochar are combined with mineral fertilizers and/or digestate/compost, showing higher yields and altered nutrient uptake patterns relative to single-input applications. This suggests improved nutrient-use efficiency and a potential pathway to reduce reliance on mineral fertilizers (Glaser *et al.*, 2015).



Figure 4. Types of organic fertilizers. Manure, worm casting, compost (aerobic fertilizers) and *biol*, biosol, bokashi (anaerobic fertilizer)
Note. Created using BioRender.

In agro-industrial systems, several studies describe the anaerobic digestion of crop residues (e.g., banana, papaya and mango) as a pathway that simultaneously produces energy carriers (biogas and methane) and organic fertilizers, thereby linking waste management with renewable energy generation (Bello *et al.*, 2015).

Together, the studies reviewed report that OA application can improve the physical, chemical and biological properties of soils, enhance nutrient availability and serve as a partial substitute for chemical fertilizers. At the same time, the literature highlights persistent limitations associated with the absence of a standardized characterization of nutrient composition and microbiological load, restricting comparability across different studies and management contexts (Ramos and Terry, 2014; Bonanomi *et al.*, 2020).

3.3 Biol

Across the studies included in this review, *biol* is described frequently as a liquid organic input with agronomic potential, particularly when applied via foliar or soil-based strategies. The synthesized evidence reports benefits primarily related to: (i) improved soil structure and water retention; (ii) increased cation exchange capacity; (iii) enhanced microbiological activity; and (iv) nutrient supply and availability. In specific contexts, yield gains and cost reductions are also reported (Table 1). Furthermore, several of the studies reviewed frame *biol* as an alternative or complement to mineral fertilizers, highlighting its contribution to nutrient supply, stimulation of soil biological activity and the mitigation of environmental impacts linked to intensive chemical fertilization (Bardales *et al.*, 2023).

In the evidence reviewed, the benefits attributed to *biol* align with broader findings on organic amendments, particularly improvements in soil structure, nutrient availability and microbial activity, which collectively support plant development and more efficient nutrient cycling (Chang *et al.*, 2010; Bonanomi *et al.*, 2020; Ramos and Terry, 2014). Across the synthesized studies, *biol* application is associated with enhanced cation exchange capacity, increased availability of essential nutrients (N, P and K), and positive effects on soil enzymatic activity, which may contribute to improved crop performance and the partial substitution of synthetic fertilizers (Pahalvi *et al.*, 2021; Thonar *et al.*, 2017; Nghia *et al.*, 2022; Romanowska-Duda *et al.*, 2024).

From a systems perspective, the literature describes anaerobic digestion as generating a liquid fraction (*biol*) and a solid fraction (*biosol*), both of which can be reintegrated into agricultural systems; it further reports that *biol* production typically involves selecting organic substrates, mixing and homogenizing them with water, and maintaining controlled fermentation until maturity (Bardales *et al.*, 2023). Within this framework, the combined reuse of *biol* and *biosol* is discussed as a strategy to mitigate negative effects associated with intensive agriculture, promote organic-waste recycling, and strengthen circular-economy approaches in agroecosystems (Thangarajan *et al.*, 2013; Bardales *et al.*, 2023; Figure 5).

Table 1. Reported benefits of *biol* application as a liquid organic fertilizer.

Benefit	Description	References
Improves soil structure	Enhances water retention, facilitating root development. Increased biomass and carbon in the soil.	Chang <i>et al.</i> (2010); Nabel <i>et al.</i> (2017)
Cation exchange capacity	Increases the ability of soil to absorb and release nutrients (potassium, magnesium, calcium, etc.) to crops.	Bonanomi <i>et al.</i> (2020)
Stimulates microbiological activity	Promotes the growth of beneficial microorganisms that facilitate the decomposition of organic matter and contribute to nutrient cycling. Depending on the soil, organic fertilizer and beneficial microorganisms improve growth, nutrient uptake and phosphorus utilization.	Pahalvi <i>et al.</i> (2021); Thonar <i>et al.</i> (2017)
Nutrient supply	Improves soil moisture retention. The contribution of nitrogen from cattle urine and the complementary effect of molasses and noni as soil improvers and bioactivators. Provides a base of essential nutrients such as NPK, benefiting agricultural soil quality. The activities of acid phosphatase, alkaline phosphatase, RNase and total dehydrogenase are associated with greater efficiency in the nutrient cycle (P, C and N). Furthermore, these effects contribute to increased CO ₂ sequestration through greater accumulation of energy-rich biomass and facilitate the partial replacement of synthetic fertilizers. The combined application of biofertilizer and biochar increases corn yield by 30-42%. Furthermore, it improves the availability of potassium, magnesium and zinc, and reduces the accumulation of sodium, copper, nickel and cadmium in crop tissues.	Pahalvi <i>et al.</i> (2021); Musrab <i>et al.</i> (2024) Nghia <i>et al.</i> (2022); Romanowska-Duda <i>et al.</i> (2024); Nurcahyanti <i>et al.</i> (2024); Ramezani <i>et al.</i> (2015); Mekki <i>et al.</i> (2013)
Cost reduction	The use of organic fertilizers represents a sustainable, economically viable and environmentally friendly alternative for improving corn productivity, costs reductions, and more resilient farming systems.	Jjagwe <i>et al.</i> (2020)

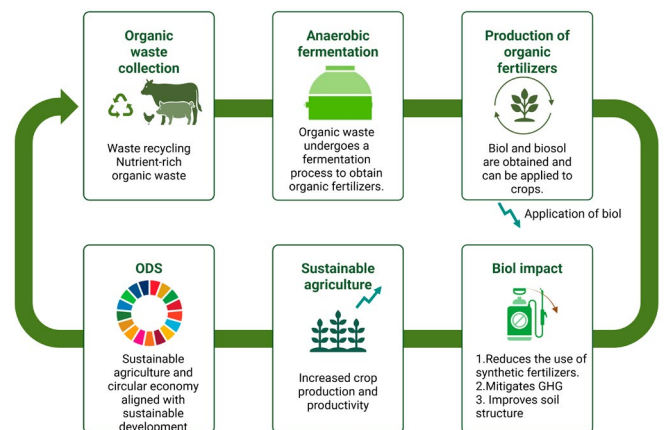


Figure 5. Circular economy in agriculture

Note. Created using BioRender.



3.4 Physicochemical and microbiological properties of biol as influenced by feedstock composition

Biol exhibits a wide range of physicochemical and microbiological properties, largely influenced by the type and proportion of organic residues used as feedstock and by digestion and management conditions. Accordingly, parameters such as pH, electrical conductivity (EC) and nutrient concentrations should be interpreted as context-dependent indicators, rather than as fixed reference values for «*biol*» as a uniform product.

For example, Bardales *et al.* (2023) reported a *biol* with a slightly acidic pH (6.90) and an EC of 1.63 dS/m, indicating a moderate concentration of soluble salts. Nutrient concentrations of nitrogen (290 mg/L), phosphorus (17.78 mg/L) and potassium (111.7 mg/L) were also reported, supporting its agronomic potential as a liquid organic input. In contrast, Phibunwatthanawong and Riddech (2019) documented substantial variability in *biol* properties, with pH ranging from 4.5 to 7.8 and markedly higher EC values (25-33 dS/m), reflecting much greater soluble salt content. This variability underscores that *biol* composition should not be generalized, and that the origin and processing of the organic residues should be considered.

Beyond nutrient composition, microbiological quality may represent a critical constraint for safe use. Nghia *et al.* (2022) evaluated biogas effluents enriched with fish emulsion and beneficial bacteria for their potential use as liquid organic fertilizers (*biol*), reporting a nearly neutral pH (7.37), biochemical oxygen demand (BOD) of 224 mg/L and chemical oxygen demand (COD) of 860 mg/L, indicating substantial bioavailable organic matter. Nutrient analysis also showed relevant concentrations of nitrogen (220 mg/L), phosphorus (41.9 mg/L) and

potassium (110 mg/L). However, microbiological assessments revealed high levels of potential pathogens, with *Escherichia coli* reaching 42,200 MPN/100 mL and total coliforms 198,100 MPN/100 mL, while *Salmonella* was not detected (i.e., absent or below the detection threshold). These findings highlight the possibility that physicochemical «fertilizer value» and microbiological safety may not align and should be evaluated jointly.

Given this variability, recent work has recommended technological tools (e.g., optical spectroscopy), in order to improve the precision of physicochemical characterization in liquid organic fertilizers such as *biol*. Accurate quantification is important for avoiding nutrient misestimation and preventing adverse effects associated with inappropriate nutrient loading. In biogas systems, the composition of manures and digestates may vary widely depending on animal species, feeding practices and management conditions, limiting the reliability of standardized reference tables. While laboratory analyses provide precise measurements, cost considerations and access constraints may hinder routine use; nevertheless, detailed nutrient information remains important for efficient plant nutrition and for mitigating environmental impacts associated with nutrient excess (Horf *et al.*, 2022).

Therefore, prior characterization of *biol*, including physicochemical and microbiological parameters, should be considered before field application. Although this section of our review focuses on composition and quality indicators, crop-specific application rates, dilution levels and agronomic responses are addressed separately in the synthesis on plant performance (Section 3.6). In this framework, Table 2 summarizes reported ranges and values for key parameters across studies, addressing both agronomic potential and considerations for responsible use (Albuquerque *et al.*, 2011).

Table 2. Reported physicochemical and nutritional parameters of *biol* across different studies

Physicochemical Parameter	Bardales <i>et al.</i> (2023)	Nghia <i>et al.</i> (2022)	Phibunwatthanawong and Riddech (2019) (<i>biol</i>)	Phibunwatthanawong and Riddech (2019) – Commercial Solution A and B
Type of organic residues	Animal manure and plant residues	Fish emulsion and beneficial bacteria	Molasses, distillery slops, and sugarcane leaves	Molasses, distillery slops, and sugarcane leaves
pH	6.90	7.37	4.5-7.8	6.20-6.41
EC (dS/m)	1.63	-	25-33	3.01-3.25
Nitrogen (mg/L or %)	290.00	220.00	0.14-0.33%	0.139-0.198%
Phosphorus (mg/L or %)	17.78	41.90	0.002-0.017%	0.005-0.310%
Potassium (mg/L or %)	111.7	110.00	0.81-11.8%	0.002-2.530%
COD	-	860	-	-
BOD	-	224	-	-

3.5 Impact of chemical fertilizers (CFs) and liquid biofertilizers

As summarized in Table 3, the literature reviewed consistently demonstrates that the type of fertilizer applied exerts a direct influence on soil quality, biological activity and crop performance. Urra *et al.* (2020) reported that continuous use of liquid organic fertilizers leads to improvements in soil physicochemical properties and increases nitrogen availability in maize (*Zea mays*). In contrast, Zhang *et al.* (2023) showed that the application of chemical fertilizers tends to increase soil pH and promote salt accumulation, which can result in the long-term deterioration of soil structure. Unlike mineral fertilizers, organic amendments such as *biol* enhance soil NO_3^- -N availability and improve water retention, thereby reducing nutrient leaching and contributing to improved soil functioning.

Furthermore, evidence synthesized across different studies indicates that chemical fertilizers, while effective in supplying inorganic nutrients rapidly, generally fail to improve soil physical properties or organic matter content and may exacerbate compaction and structural degradation under prolonged use (Dincă *et al.*, 2022; Zhai *et al.*, 2023).

Conversely, organic amendments contribute to improved soil aggregation and stability through the stimulation of microbial communities and the formation of stable macroaggregates (Tang *et al.*, 2024; Brtnický *et al.*, 2024). Enzymatic activity, including dehydrogenase and urease, is typically enhanced when organic fertilizers are applied alone or in combination with mineral fertilizers, supporting more active nutrient cycling processes (Zhang *et al.*, 2023; Villarino *et al.*, 2025).

Table 3. Comparison of chemical fertilizers and *biol* (liquid organic fertilizer) regarding soil quality, biodiversity and soil physical properties

Parameter	Chemical Fertilizer	Organic Amendment	Reference(s)
Impact on soil	<ol style="list-style-type: none"> 1. Raises pH and leads to salt accumulation, affecting long-term soil structure. 2. Does not improve physical properties such as structure or organic matter content, promoting compaction and soil quality loss. 3. Enzymatic activity (dehydrogenase and urease) is present in all forms of microbial respiration evaluated, except for L-arginine-induced respiration. 	<ol style="list-style-type: none"> 1. Increases NO_3^--N and water retention, reducing nitrate leaching. 2. Improves soil structure and stability, fostering microbial communities and stable macroaggregates. 3. Organic fertilizer + chemical fertilizer increased enzyme activity (dehydrogenase, arylsulfatase, N-acetyl-β-D-glucosaminidase and urease) and all forms of microbial respiration, except that induced by L-arginine. 4. In the long term, it helps reverse soil degradation and improve sustainability; however, phosphorus must be monitored, in order to prevent potential environmental impacts. 	Zhang <i>et al.</i> (2023); Dincă <i>et al.</i> (2022); Zhai <i>et al.</i> (2023); Tang <i>et al.</i> (2024); Brtnický <i>et al.</i> (2024); Villarino <i>et al.</i> (2025)
Effect on biodiversity	<ol style="list-style-type: none"> 1. Reduces soil quality and microbial diversity, adversely affecting long-term structure. 2. Prolonged use may inhibit enzymatic activity and reduce biodiversity. 	<ol style="list-style-type: none"> 1. Enhances microbial activity and improves physicochemical properties, benefiting water retention. 2. Promotes microbial activity and diversity, both of which are essential for soil health. 3. The increase in organic carbon is attributed to the rise in pH, which enhances its solubilization and, consequently, its availability to soil microorganisms. 	Dincă <i>et al.</i> (2022); Zhai <i>et al.</i> (2023); Zhang <i>et al.</i> (2023); Tang <i>et al.</i> (2024); Galamini <i>et al.</i> (2024).
Application requirements	<ol style="list-style-type: none"> 1. Requires frequent applications, due to rapid nutrient release, which may lead to imbalances. 2. Use without <i>biol</i> is less effective for improving long-term properties. 	<ol style="list-style-type: none"> 1. Requires fewer applications, due to gradual nutrient release, maintaining balance and reducing frequency. 2. At 15-30% ratio with chemicals, improves short-term properties in medium soils. 3. The use of organic and synthetic fertilizers increases soil organic carbon by 1-5%. Furthermore, the combined application of synthetic and organic fertilizers increases mobile phosphorus by 38%. 	Zhang <i>et al.</i> (2023); Dincă <i>et al.</i> (2022); Zhai <i>et al.</i> (2023); Baksinskaite <i>et al.</i> (2025)
Effect on crop yield	<ol style="list-style-type: none"> 1. Increases maize yield in the short term, with no significant correlation to root system or enzymatic activity. 	<ol style="list-style-type: none"> 1. Contributes to sustained yield by increasing soil fertility when combined with chemicals. 2. Improves grain yield by 15-30%, with a positive correlation to root system and enzymatic activity. 	Dincă <i>et al.</i> (2022); Zhai <i>et al.</i> (2023)
Effect on NPK nutrients	Significant improvements in maize grain yield, but not matched by improvements in soil quality.	<ol style="list-style-type: none"> 1. Optimal doses of organic amendments resulted in significant improvements in soil microbial activity and biomass. 2. Increase in microbial production of extracellular enzymes linked to the acquisition of N, C and P. 3. The application of organic fertilizer reduced the soil pH and generally improved its properties, with the potential to increase nutrient availability and improve soil structure in horticultural crops. 4. The digestate (28% manure, 15% hay, 57% silage) applied at doses of 0 to 150 mg N kg⁻¹ of soil linearly increased biomass and nitrogen uptake, with a recovery of 37%. 	Urra <i>et al.</i> (2022); Galamini <i>et al.</i> (2024); Djebali <i>et al.</i> (2025); Kizito <i>et al.</i> (2019)



With regard to biodiversity, several studies report that exclusive reliance on chemical fertilizers may reduce microbial diversity and inhibit enzymatic activity, thereby negatively affecting long-term soil quality (Dincă *et al.*, 2022; Zhai *et al.*, 2023). In contrast, organic amendments such as *biol* promote microbial activity and diversity, largely due to increases in organic carbon availability and improved soil physicochemical conditions that favor microbial proliferation (Galamini *et al.*, 2024). These effects are considered critical for sustaining soil resilience and ecosystem function.

Differences are also evident in application requirements and nutrient dynamics. Chemical fertilizers typically require frequent applications due to rapid nutrient release, increasing the risk of nutrient imbalances and losses. Organic amendments release nutrients more gradually, reducing application frequency and improving nutrient-use efficiency (Zhang *et al.*, 2023; Baksinskaite *et al.*, 2025). Several studies have indicated that combined applications of organic and mineral fertilizers, particularly at ratios of 15-30%, can enhance soil organic carbon (by 1-5%) and increase mobile phosphorus availability (by up to 38%), while maintaining short-term productivity in medium-textured soils (Dincă *et al.*, 2022; Zhai *et al.*, 2023).

With regard to crop yield, chemical fertilizers generally increase yields in the short term; however, these gains are often not accompanied by improvements in soil biological activity or root system development (Dincă *et al.*, 2022). In contrast, organic amendments contribute to more sustained yield responses by improving soil fertility and biological functioning, particularly when applied in combination with mineral fertilizers (Zhai *et al.*, 2023). For example, optimal doses of organic amendments have been associated with increased microbial biomass, enhanced extracellular enzyme production linked to nitrogen, carbon and phosphorus acquisition, and improved nutrient uptake efficiency (Urta *et al.*, 2022; Galamini *et al.*, 2024). Digestate-based fertilizers applied at rates between 0 and 150 mg N kg⁻¹ soil have been shown to linearly increase plant biomass and nitrogen uptake, with recovery efficiencies of up to 37% (Kizito *et al.*, 2019; Djebali *et al.*, 2025).

Overall, the evidence reviewed indicates that while chemical fertilizers remain effective for short-term nutrient supply, their exclusive use may compromise soil structure, biodiversity and long-term sustainability. Therefore, integrating organic amendments such as *biol*, either as substitutes or complements to mineral fertilizers, constitutes a more balanced strategy, capable of enhancing crop productivity while maintaining soil health and nutrient stability over time (Tang *et al.*, 2024).

3.6 Effects of *biol* on seed germination and crop growth

As shown in Table 4, the literature reviewed indicates marked benefits of *biol* application in terms of seed germination and early crop development across multiple crop species, including maize (*Zea mays* L.), provided that appropriate dilution levels are used in order to avoid phytotoxic effects. Collectively, these studies indicate that effectiveness is dependent upon controlled application rates. For example, Aguado *et al.* (2023) evaluated tomato seeds (*Solanum lycopersicum* L.) as bioindicators and reported that *biol* dilutions between 1% and 3% did not induce phytotoxicity, whereas a 5% concentration significantly reduced both germination and root growth (not reported in Table 4).

Beyond its nutritional contribution, the studies reviewed note that *biol* may contain naturally occurring phytohormones (e.g., auxins, gibberellins and cytokinins) involved in plant growth regulation. In this context, Kusuma *et al.* (2021) applied fish-waste-derived *biol* to rice seeds (*Oryza sativa* L.) at a 2.5% dilution, reporting an 88.18% germination rate and a 20.74 cm increase in root elongation. These responses were described as being influenced by environmental factors, including water availability, nutrient uptake and light intensity; additionally, pre-sowing seed soaking in organic solutions has been associated with enhanced seed viability, likely through activation of endogenous growth regulators.

Phibunwatthanawong and Riddech (2019) evaluated liquid organic fertilizer formulations derived from residual molasses, distillery slops and sugarcane leaves for hydroponic Green Cos lettuce (*Lactuca sativa* var. *longifolia*). The formulations showed high physicochemical variability (pH 4.5-7.8; EC 25-33 dS/m), reflecting differences in substrate composition. Fertilizer maturity and phytotoxicity were assessed using the germination index (GI). All the formulations fermented for 30 days and diluted 1:100 exhibited GI values above 100%, indicating the absence of phytotoxic effects. The highest GI was observed for Formula 3 (F3) (147.9%). Under the same dilution, plant growth was comparable to that obtained with liquid chemical fertilizers. In this experiment, treatments T4 and T6 corresponded to Formulas 3 and 5, respectively (Formula 3: distillery slop:sugarcane leaves:filtrate water = 1:0.1:0.25, v: w: v; Formula 5: distillery slop:sugarcane leaves:filtrate water = 1:0.25:0.25, v: w: v). Specifically, treatment T6 enhanced root elongation after 14 days (24.03 cm), whereas treatment T4 showed the highest overall development at 21 days (root length 37.66 cm, plant height 17.33 cm and shoot fresh weight 21.65 g). By day 28, T4 also produced a higher number of leaves and greater root length than the chemical fertilizer control, indicating the agronomic potential of *biol*-based formulations in hydroponic systems. In a related study conducted in wheat (*Triticum aestivum* L.), Mironenko *et al.* (2022) reported that a trout-

waste-derived protein hydrolysate enhanced germination (88.0%) and root growth (11.69 cm), indicating the effectiveness of fish-derived bio-based inputs for early plant development.

In addition to germination assays, field-scale studies highlight the relevance of *biol* application during later phenological stages. In this regard, Aguirre *et al.* (2020) assessed the foliar application of cattle-manure-based *biol* in maize under field conditions and reported that intermediate concentrations (20-60%) resulted in the greatest increases in plant height, with values ranging from 176.5 to 192.5 cm, compared with the control. These findings indicate that, while high *biol* concentrations may inhibit germination if improperly diluted, moderate foliar applications under field conditions can effectively promote vegetative growth, underscoring the importance of distinguishing between germination-based bioassays and agronomic evaluations at larger spatial and temporal scales.

Additionally, Zhu *et al.* (2019) investigated the use of corn steep liquor (CSL), an organic by-product of wet milling used as a liquid organic fertilizer, on soybean (*Glycine max*) growth. At a 1% concentration, CSL significantly enhanced germination, reaching 95% after 84 h compared with 83% in the control. The treatment also contributed to soil pH optimization, increased nutrient availability in the rhizosphere, and promoted earlier flowering. Moreover, increased expression of genes associated with root nutrient uptake was reported, indicating the potential of CSL as an agricultural biostimulant.

Taken together, the evidence summarized in Table 4 indicates that liquid organic amendments such as *biol* and related by-products can positively influence seed germination, root development and early plant growth through combined effects on nutrient availability, soil physicochemical conditions and microbial activity. These responses support their role as functional inputs within sustainable agricultural systems, capable of enhancing crop performance while preserving ecological balance (Du Jardin, 2015). Furthermore, multiple studies concur that *biol* derived from organic residues, when applied at

appropriate concentrations and according to crop stage and application method, promotes plant development across diverse species. In this context, the valorization of organic waste streams into liquid organic fertilizers constitutes an effective strategy for the improvement of crop productivity, while simultaneously contributing to agro-environmental sustainability (Alcántara *et al.*, 2019).

4. Conclusions

Supported by bibliometric analysis, this narrative synthesis confirms that *biol* constitutes a relevant liquid organic input within sustainable nutrient management strategies when its physicochemical and microbiological properties are adequately characterized prior to application. Analysis of the 37 selected studies published between 2000 and 2025 demonstrates that the agronomic performance of *biol* is strongly conditioned by its composition, which in turn is dependent upon feedstock type, residue proportions and digestion conditions.

In line with the principal aim of our review, the evidence indicates substantial variability in the physicochemical and microbiological attributes of *biol*, including pH, electrical conductivity, nutrient concentrations and microbial loads. This variability precludes the use of generalized reference values and underscores the need for prior characterization, in order to ensure both agronomic effectiveness and microbiological safety. In this regard, future work should prioritize the standardizing of physicochemical and microbiological characterization and the validating of sanitary treatments that ensure microbiological safety without compromising nutrient availability. The elevated electrical conductivity and high microbiological loads reported in some studies indicate potential risks in the event that *biol* is applied without adequate assessment or dilution.

With regard to soil quality, the synthesis shows that *biol* application is associated consistently with improvements in soil structure, water-holding capacity, organic matter dynamics and microbial activity, particularly when compared with the exclusive use of mineral fertilizers. These effects support the role of *biol* as a soil-conditioning agent rather than solely as a nutrient source, contributing

Table 4. Effects of *biol* on seed germination and early crop growth

Study	Biol Concentration	Germination Rate (%)	Root Growth (cm)	Crop Type
Aguirre <i>et al.</i> (2020)	60%	-	-	<i>Zea mays</i>
Aguado <i>et al.</i> (2023)	1%-3%	100	48.40	<i>Solanum Lycopersicum</i> L.
Kusuma <i>et al.</i> (2021)	2.5%	88.18	20.74	<i>oryza sativa</i> L.
Phibunwatthanawong and Riddech (2019)	1%	-	24.03-37.66	<i>Lactuca sativa</i> (Green Cos)
Zhu <i>et al.</i> (2019)	1%	69 (at 36 h) / 95 (at 84 h)	-	<i>Glycine max</i>



to enhanced nutrient retention and more stable soil functioning.

With regard to plant responses, positive effects on seed germination, early growth and crop development were reported across several studies, although responses varied according to soil texture, initial fertility status and application conditions. The evidence indicates that *biol* is most effective when integrated with mineral fertilizers, typically contributing a partial proportion of total nutrient inputs, and thereby improving nutrient-use efficiency and supporting crop performance, without compromising soil health.

Furthermore, comparative analysis of *biol*-based inputs and mineral fertilizers indicates that while chemical fertilizers remain effective for short-term nutrient supply, their prolonged exclusive use may adversely affect soil structure and biological properties. In contrast, integrated fertilization strategies that combine organic amendments such as *biol* with mineral fertilizers constitute a more balanced approach, capable of sustaining productivity while mitigating long-term soil degradation.

Finally, bibliometric analysis identified clear thematic clusters centered around organic amendments, soil quality processes and crop responses, while also revealing persisting knowledge gaps constraining broader extrapolation and adoption, specifically: (i) limited standardization of *biol* characterization; (ii) a scarcity

of multi-year and multi-site dose-response studies, and; (iii) insufficient evaluation of sanitary treatments. It is essential that these knowledge gaps be addressed, through standardized characterization protocols, long-term field trials and validated sanitary measures aimed at microbiological safety, in order to consolidate the role of *biol* within integrated fertilization strategies that balance agricultural productivity with environmental stewardship.

Authors' contributions

LMLM: conceptualization, data curation, data analysis, research, methodology, project management, software, supervision, validation, visualization, original drafting, writing, revising and editing.

BJHG: Fundraising, research, resources, writing, revising and editing.

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The authors declare no conflict of interest.

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