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REVIEW

Impacts on Soil Health of Soil Improvers Derived from Agri-Food Processing Residues: a Systematic Review with a Focus on European Field Studies

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Abstract

The circular bioeconomy, centred on the principles of "Reduce, Reuse, and Recycle", is central to achieving the goals of the European Green Deal and the "Farm to Fork" strategy. The key approach, within this framework, is the valorisation of food processing side-streams through various processing technologies to produce fertilisers that, when applied to the soil, act as potential "soil improvers". When applied to soil, these materials affect not only the physical, chemical, and biological properties of soil but also impact greenhouse gas emissions, nutrient leaching, and the levels of contaminants or pathogens. A systematic review of field studies conducted in European soils between 2014 and 2024 was performed with stringent inclusion and exclusion criteria, which allowed the identification of suitable articles in three independent steps. The main soil improvers derived from various agri-food side-streams were biochar, compost, and digestate. Their effects, along with the potential risks associated with their use in agricultural fields, were carefully evaluated and discussed. This review forms part of the DeliSoil project "Delivering safe, sustainable, tailored & societally accepted soil improvers from circular food production for boosting soil health" funded under the European Union "A Soil Deal for Europe". This systematic review showed that soil improvers enhance soil health by improving microbial diversity, organic matter, and water retention, and by boosting plant growth. However, potential risks require careful management, and long-term studies are needed to fully assess their environmental and agronomic impacts.

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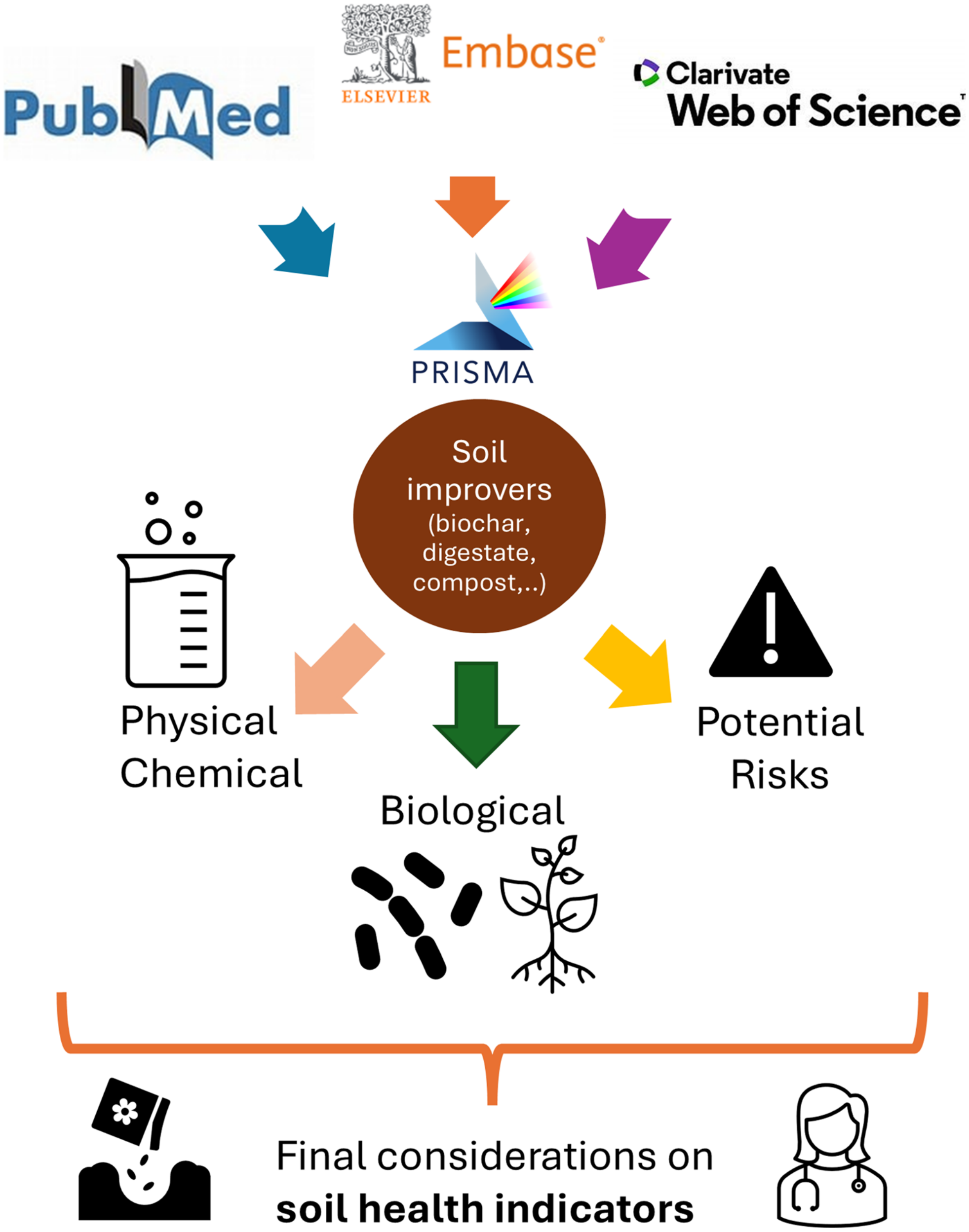
Graphical Abstract



Highlights

- A systematic review found 74 relevant works on the effect of improvers on EU soils.
- Key soil improvers are compost, biochar, and digestate.
- The improvers impact positively soil fertility, microbial activity, nutrient cycling.
- Each improver has potential environmental risks such as increase in GHGs emissions.

Keywords Biochar · Digestate · Compost · Nutrient leaching · GHG emissions · Soil health

1 Introduction

Agriculture, along with food production, is one of the most traditional sectors of the European Union's economy. Increased market competition due to global food chains, industrialized processes, and the pursuit of higher productivity have turned modern agriculture into a sizeable economic sector, but this development is challenging the environment (Khatri et al. 2023). For instance, agriculture accounts for approximately 11% of all greenhouse gas (GHG) emissions in the European Union (EU), and remains a significant source of emissions of harmful pollutants (Shabir et al. 2023). Furthermore, agriculture, fisheries, and the broader food production system are key drivers of biodiversity, which can be compromised by land conversion, soil degradation, overfishing, water abstraction, and the spreading of chemicals and nutrients. Indeed, overexploitation of soil can reduce its ability to retain water, allow pesticides to contaminate groundwater, and diminish the overall diversity of the agricultural landscape (Di Vaio et al. 2024; Sharma et al. 2021). Furthermore, at the core of the 2030 United Nations Sustainable Development Goals (SDGs) agenda for sustainable development, there are 17 goals which, if implemented, should drive us to a more egalitarian and salubrious world to live in (Swan et al. 2024). Soil plays an important role, either directly or indirectly, in achieving at least 12 of these goals (Sharma et al. 2025). In response to these challenges, the European Union has adopted a "Soil Strategy" to achieve healthy soils by 2050. This strategy is supported by a comprehensive framework that defines concrete measures to protect and restore soils, to reinstate their sustainable use (Arias-Navarro et al. 2023).

Soil is a non-renewable resource with basic and fundamental environmental functions, including supporting biodiversity and providing ecosystem services. Soil health constitutes the bedrock of agriculture, offering a vital medium for plant growth and, consequently, food production (Telo Da Gama 2023). When soils are healthy, they yield higher productivity of nutritious crops that provide nourishment for both humans and animals (Timmis and Ramos 2021). Indeed, it is recognized that the quality and quantity of our food are directly connected to the quality of our soils (Montgomery and Biklé 2021). Soil and climate changes are also intricately linked (Gurmessa et al. 2024). This relationship encompasses many factors, such as carbon (C) sequestration, water cycle regulation, temperature modulation, and support for biodiversity, all of which warrant a more in-depth exploration (Lal 2004). Climate change also affects soil microbial populations and their enzymatic activities, which are critical to soil function (Singh et al. 2022). Thus, implementing sustainable soil management practices can help preserve and enhance soil biodiversity, maintain ecosystem resilience, and the soil's multifunctionality (Creamer et al. 2022; Li and Qi 2025). Soil can adapt to climate change and demonstrate resilience. This capacity is rooted in soil biodiversity, where a diverse range of organisms contributes to greater robustness and ability to recover (Mahnken et al. 2022; Marín-Sanleandro et al. 2023). The European Commission's Soil Mission wants to improve the health and resilience of European soils by 2030 (European Commission 2021). More specifically, the mission aims to regenerate Europe's agricultural soils and make them more climate resilient, and to improve the health and resilience of at least 75% of all soils through sustainable soil management practices. Building on this, the recent *Soil Monitoring Law* has been proposed to address the urgent issue of soil degradation in Europe (European Union 2023). With regular monitoring and harmonized assessment methods, the directive aims to provide actionable data to combat degradation and enhance soil resilience. Its implementation is crucial for aligning policy actions and enabling the protection and restoration of soil health. This highlights how urgent is to improve soil health using new sustainable soil management practices, such as the transformation of residues from the agri-food industry into soil improvers (Andrunik and Smol 2025; De Corato et al. 2024; Kochanek et al. 2022; Palansooriya et al. 2022).

One of the major advantages of utilizing soil improvers from the agri-food industry residues is their contribution to the principles of a circular bioeconomy (Lehmann et al. 2020). Circular bioeconomy is a theory that advocates the better and complete utilization of biomass resources in a closed-loop manner, promoting the key principles of reduce, reuse, and recycle (Mak et al. 2020). Transitioning towards a circular bioeconomy can offer significant benefits, including reduced GHG emissions, sustainable resource management, and improved environmental protection (Srivastav et al. 2024). Therefore, by repurposing waste streams from agri-food production, amendments can be obtained and later used to improve soil quality while reducing the environmental impact of waste disposal (Rashwan et al. 2023; Xu et al. 2023). Healthy fertile soils are the foundation of sustainable agriculture, providing essential nutrients, water holding capacity (WHC), aggregate stability, and habitat for the organisms that contribute to overall soil function, which plays a vital role in nutrient cycling, C sequestration, and disease suppression (Lehmann et al. 2020). The application of soil improvers derived from the agri-food industry can have profound impacts on the physical, chemical, and biological characteristics of soil, ultimately enhancing its overall health and productivity (Al-Shammary et al. 2024; Mondaca et al. 2025). The soil health can be improved through managed utilization of organic residues coupled with an advanced biotechnological approach, which, in turn, will increase crop productivity, thereby promoting food security at a global level and resulting in an improved economy (Gupta et al. 2021). Despite the growing use of soil improvers derived from agri-food industry residues, there is a lack of comprehensive studies that analyse their impacts on the physical, chemical, and biological properties of soil, as well as their potential effects on soil biodiversity and plant health.

To address this, a systematic review (SR) was conducted within the framework of the DeliSoil project (Delivering safe, sustainable, tailored, and societally accepted soil improvers from circular agri-food production processes for boosting soil health, https://delisoil.eu/). The SR also cons idered broader aspects, such as GHG emissions and nutrient leaching, to evaluate the environmental footprint of soil improvers and potential risks to ensure that these materials do not adversely affect soil health or environmental stability. Additionally, this approach aimed at identifying those soil health parameters more sensitive to the use of new soil improvers and the key factors influencing soil health.

2 Data Collection & Methods

2.1 Search strategy, Selection of Suitable Papers and Data Extraction

In the SR, three different databases were interrogated: PubMed, EMBASE, and Web of Science (WOS). To retrieve the relevant articles, inclusion and exclusion criteria were carefully defined. Briefly, the works needed to be based on soil improvers derived from the agri-food industry and tested in field studies carried out in an EU country where the soil was not contaminated.

To perform the SR, the PRISMA 2020 guidelines were followed (Page et al. 2021). The literature search covered the period 1st January 2014 to 25th September 2024, which allowed the inclusion of the most recent and relevant papers, and focusing on the current state of knowledge, avoiding possibly outdated information. The 2014–2024 timeframe was specifically selected to reflect the decade most relevant to current European policy frameworks, including the European Green Deal, Farm to Fork Strategy, and Circular Economy Action Plan. The following months were dedicated to the analysis of the retrieved manuscripts: screening of records with ASReview (October-November 2024), assessment of eligibility (December 2024-January 2025), primary description of selected entries (February and March 2025), and writing/reviewing of the manuscript (April-June 2025).

The articles were selected through three-step filtering processes.

2.1.1 First Filtering Process

Initially, keywords that could define or describe a soil improver were compiled. These included terms related to materials derived from food processing residues and their applications in soil management, along with their general impact, physical-chemical-microbiological-plant effects, and possible risks related to their use. This initial selection was centralized and conducted by a single researcher, during which only duplicated articles were removed.

Firstly, the words that could define/describe a SOIL IMPROVER(s), or the technologies employed to produce them, were collected using the following keywords (searched in singular and plural forms):

soil improver, *organic fertilizer*, *food processing*, *food processing residue*, *food processing stream*, *soil amendment*, *food industry by-product*, *raw material*, *alternative processing stream*, *food supply chain waste*, *food processing waste stream*, *HTC*, *biostimulant*, *meat processing waste*, *recycled fertilizer*, *horn meal*, *spent mushroom substrate*, *tea waste*, *compost*, *digestate*, *biochar*, *processing industry*, *insect frass*, *vegetable waste*, *fruit waste*, *pomace*, *wine production waste*, *tomato waste*, *olive oil waste*, *hydrothermal carbonization*, *rendering of animal product*, *thermal conversion*, *pelletizing*, *thermal drying*, *olive mill pomace*, *tomato pomace*, *aerated compost*, *tea extracts*, *anaerobic digestion*, *recycled waste*, *biofertilizer*, *biobased fertilizing product*, *pyrolysis*, *biobased fertilizer*, *animal waste*, *potato industry waste*, *sugar industry waste*, *animal feed industry*, *alcohol production waste*, *slaughterhouse waste*, *animal by-products*, *meat and bone meal*, *feather meal*, *blood meal*, *pyrogasification*, *vinasse*, *molasses*. Words were searched in their singular or plural form.

The impact of soil improvers was evaluated considering three different aspects:

(1) The first search was named "GEN" as in GENERAL because attention was given to widespread soil improver effects, search words were:

soil health, *sustainability*, *regenerative agriculture*, *soil indicators*, *circular economy*, *carbon footprint*, *environmental health*, *human health*, *emissions*, *carbon sources*, *GHG emissions*, *ecosystem services*, *fertilizer*, *eutrophication*, *cover cropping*, *perennial systems.*

The two lists were combined in the search with *"AND"* considering title, abstract, and key words.

Other inclusion criteria were:

- The study was conducted in the European Union; this was ensured by filtering for author affiliations within EU member states.

- The work was based on field experiments or field trials or plot experiments (pot or greenhouse studies were excluded) on EU territory-soil.
- Articles were written in English.

(2) Physical-chemical-microbiological-plant effects (PCMP).

In parallel, keywords defining possible physical-chemical-microbiological and biological effects of soil improvers were defined:

Physical and Chemical Effects *chemical parameters*, *chemical properties*, *physical characteristic*, *soil organic matter*, *carbon stock*, *carbon concentration*, *macronutrients*, *micronutrients*, *pH*, *CEC*, *electric conductivity*, *acidification*, *texture*, *porosity*, *bulk density*, *water holding capacity*, *soil water content*, *soil structure*, *erosion*, *salinity*, *chemical degradation*, *contaminants*, *contamination*, *toxic elements*, *OCP*, *PAH*, *PCB*, *pollution*, *pollutants*, *nitrification*, *bioaccumulation*, *ammonia content*, *nitrates content*, *nitrogen fluxes*, *denitrification*, *carbon fluxes*, *soil organic matter*, *soil organic carbon*.

Possible Microbiological Effects *microbial biomass*, *biological properties*, *biodiversity*, *N-fixing bacteria*, *nitrogen fixing bacteria*, *P-solubilising bacteria*, *soil fertility*, *fungal biomass*, *fungal diversity*, *fungal density*, *respiration*, *microbial biomass*, *bacterial biomass*, *bacterial diversity*, *bacterial density*, *edaphon*, *worms*, *nematodes*, *enzymes*, *arthropods*, *microbiome*, *soil biodiversity*, *taxonomy diversity*, *pathogens*, *antimicrobial resistance*, *AMR*, *microbe*, *fungi*, *bacteria*, *protozoa*, *fungal to bacteria ratio*, *mycorrhizae*.

Possible Effects On Plants *plant nutrients*, *nutrients sources*, *roots*, *yield*, *plant growth*, *crop growth*, *plant germination*, *crop germination*, *plant maturation*, *crop maturation*, *nutrients availability*, *biomass*, *plant development*, *crop development*, *biomass quality*, *plant availability.*

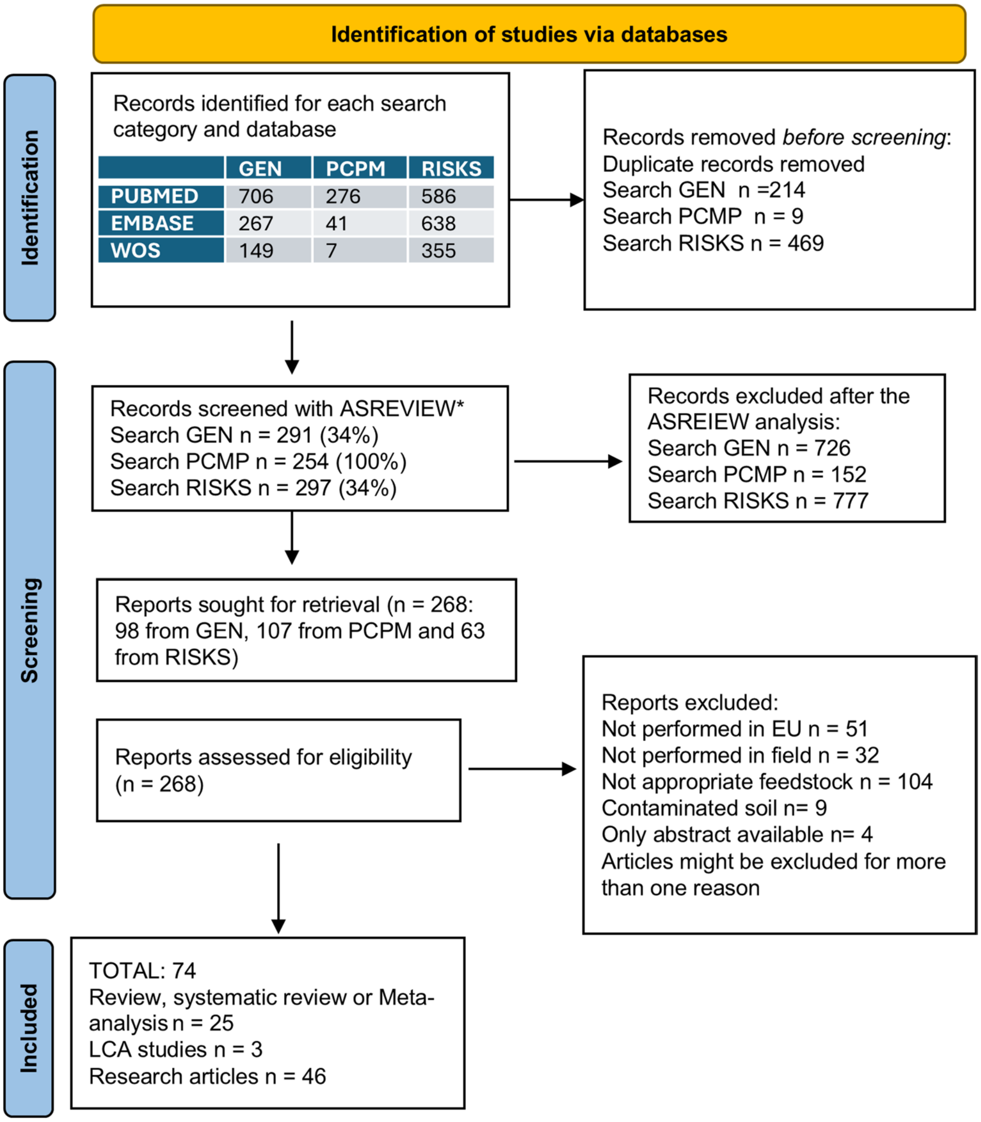
The second search string combined the list that defined the soil improvers with the lists describing the possible effects using the Boolean operator "AND". This approach ensured more precise results, requiring that each retrieved article contained at least one keyword from each of the four effect categories (physical, chemical, microbiological, and plant effects) within the title, abstract, or keywords. The same inclusion criteria were applied as described above.

(3) This third search, named "RISKS", combined the string with those defining the soil improvers with "AND", to define the environmental footprint of soil improvers and their potential risks. Inclusions and exclusion criteria were the same as above, with one exception, considering that the number of retrieved field experiments was few, also pot experiments were included. Possible risks related to the use of soil improvers were defined as:

nitrogen leaching, *phosphorous leaching*, *heavy metal*, *trace metal*, *pathogen*, *parasite*, *Cd*, *cadmium*, *Pb*, *lead*, *As*, *arsenic*, *Ni*, *nickel*, *Cr*, *Chromium*, *Cu*, *copper*, *Zn*, *zinc*, *organic contaminant*, *microplastic*, *prion*, *plant pest*, *drug resistance*, *antibiotic*, *anaerobic microbe*, *toxicology*, *ecotoxicology.* Words were searched in their singular or plural form.

2.1.2 Second Filtering Process

Starting from the records obtained from the "identification" step (Fig. 1), in order to screen the number of potentially relevant papers, the ASREVIEW tool was used (Van De Schoot et al. 2021). Here, at least 33% of the articles were screened, and "the stop rule was 25" meaning that the analysis could stop after 25 articles in a row were not selected. This is because these two parameters, as stated by the ASREVIEW creators, allow for the identification of 95% of the relevant papers. ASREVIEW was used with the default setup (extraction technique: TF-IDF, classifier: Naive Bayes, query strategy: Maximum, balance strategy: Dynamic resampling). To perform the screening, the same inclusion criteria listed above were considered. Moreover, papers focused on bioremediation or phytoremediation studies or polluted soils were excluded. Furthermore, the tested soil improvers had to derive from agri-food residues (for example, biochar derived from untreated wood scraps and sawdust was excluded). The full text of the articles selected with ASREVIEW was checked to see if they met the inclusion/exclusion criteria described above. At this stage, reviews, SR, and meta-analysis were considered regardless of their origin, if they were present in this list (Supplementary file 1: List of articles). The latter were evaluated independently of the locations from which the original data were sourced, but only if the soil improver used was agri-food waste-derived. This step was carried out by a team of 5 people, who, based on the title and abstract provided by the ASREVIEW interface, had to agree to insert the manuscript for the following steps. Thanks to this: 726 articles were excluded from the GEN list, 152 from the PCMP list, and 777 from the RISKS list. The Supplementary file 1 includes for each research article: climate under which the experiment took place, and soil characteristics (type of soil, bulk density, and available water capacity according to the projects: iSQAPER and LUCAS (https://www.isqaper-is.eu, accessed on 31.10.25 (Ballabio et al. 2016).



	GEN	PCPM	RISKS
PUBMED	706	276	586
EMBASE	267	41	638
WOS	149	7	355

Fig. 1 Workflow of the SR following the PRISMA statement (http://www.prisma-statement.org/). Three main steps were: (I) identification (according to the searches GEN, PCPM and RISKS in three websites: PubMed, Embase and WOS), (II) screening (based on the defined inclusion and exclusion criteria using ASREVIEW tool and manually) and the final step (III) with the final list of the included articles (divided in review/meta-analysis/SR, LCA studies and research articles)

2.1.3 Third Filtering Process

The full articles were then carefully read and once more checked against inclusion and exclusion criteria. This step was carried out by several authors: each entry was checked by at least two researchers to make sure that the inclusion and exclusion criteria were met. Research articles were excluded if they were not conducted on EU soil, or if they were not performed in a field, not done with the appropriate feedstock, performed on contaminated soil, or because only abstracts were available (some papers were excluded for more than one reason). Review articles and meta-analyses were also included when relevant; however, due to their aggregated nature, it was not always possible to isolate and exclude non-EU data within them. This limitation was acknowledged, and such reviews were retained only when their focus was consistent with the scope of this study, namely, soil improvers derived from agri-food waste. The selected articles are discussed in this manuscript. Finally, the suitable articles were fully analysed and summarized, collecting and highlighting major information (i.e., type of soil, rate of application, type of soil improver, feedstock, and effects measured).

2.2 Analysis of Key Words

2.2.1 Abstract Bibliometric Analysis

The abstracts of the selected articles were extracted and compiled into a standardized format. To conduct the bibliometric analysis, Bibliometrix package within the R Studio environment (Vers. 2023.12.1+2) was utilized (Aria and Cuccurullo 2017). The BibTeX (.bib) file containing all pertinent information about the selected articles, including bibliographic details and abstracts, was imported into R Studio for further processing and analysis. A network analysis and a word cloud were generated. The 50 most used bigrams were analysed in terms of frequency over time in a cumulative manner. For the heatmap visualization, the data matrix was imported into a Jupyter Lab (V.4.2.5) environment. Raw data are provided in the Supplementary Materials section (Supplementary file 2: bibliometrix).

2.2.2 Geospatial Analysis and Visualization of Soil Improvers Across European Countries

Data processing was conducted in Python (Ver. 3.12.7) (Jupyter et al. 2018) using pandas (Ver. 2.2.2) (McKinney 2010) for data handling and geopandas (Ver. 1.0.1) for spatial analysis. Standard data cleaning procedures were applied to ensure that each row represented a single country, with standardized lowercase names for consistent geographic matching. Country boundaries were obtained from a publicly available GeoJSON dataset and filtered to retain only European countries based on a predefined list. The resulting GeoDataFrame was reprojected to EPSG:3035 for accurate spatial analysis. A dictionary was constructed to count the occurrences of soil improvers per country, and these counts were merged with the European GeoDataFrame using standardized country names. Invalid geometries were corrected with a zero-width buffer, and a bounding box was applied to constrain the spatial extent to continental Europe. Centroids were computed as anchor points for visualization. Each country's data were represented by a centroid-based pie chart (Hunter 2007), with wedge sizes proportional to the relative frequency of soil improver categories. All steps were performed within a Python script using pandas (2.2.2), geopandas (1.0.1), matplotlib (Ver. 3.9.2) (Hunter 2007), shapely (Ver. 2.0.7), and numpy (Ver. 1.26.4) (Virtanen et al. 2020), ensuring reproducibility (Supplementary file 2: bibliometrix).

3 Results and Discussion

3.1 Selection Procedure

The workflow of the study followed the PRISMA protocol, and the main steps were summarized in Fig. 1. First, the three combinations of the keywords were searched in PubMed, Embase, and WOS. When the searches from the different databases were combined, 908 unique articles were identified for GEN, 315 for PCMP, and 1110 for RISKS. Of these, articles common to the different lists were removed, which brought the unique number of works down to 821 for GEN, 254 for PCPM, and 835 for RISKS. Next, the suitable articles were selected using the ASREVIEW tool with default settings (Van De Schoot et al. 2021). Here, the title and abstract were screened to see if, based on the text, the article fit our inclusion/exclusion criteria. At the end of the screening, 98 were considered suitable for GEN, while 63 were considered suitable for the RISKS category. The same principle was applied to the PCMP group: abstracts and titles were tested, but in this case, all of them were screened, and 107 records were considered suitable.

All selections were combined in a unique file, and, in the next step, the 268 articles were further checked for their suitability by reading the full text (Supplementary file 1: list of articles). Considering the exclusion criteria applied, 51 studies were removed for being conducted outside the European Union; 104 due to the use of non-food-derived feedstock for soil improver production; 32 for lacking field-based testing; 9 for being conducted on contaminated sites; and 4 due to the availability of the abstract only. Following this screening, 25 reviews/meta-analyses/systematic reviews, 3 life cycle assessment (LCA) studies, and 46 original research articles were selected for the final evaluation. Thus, the final selection brought up 74 relevant articles for the defined research questions (see Supplementary file 1: List of articles). Figure 2A shows the distribution of the 46 research works considering the country where the work was performed. The map represents a broad distribution of the field trials considered, allowing to generalize the different results for the entire European Union soil. Spain is the country with the most suitable articles, followed by France, Italy, and Denmark. The distribution of publications according to the year (Fig. 2B), shows that the interest in agri-food-derived soil improvers was already present at the beginning of our search period, but with a trend of increase in recent years.

Among the more common feedstock used to make soil improvers, we found municipal/urban or domestic waste (defined as food scraps, leftovers, or kitchen waste from plant or animal sources, potentially mixed with yard waste as leaves, branches, grass clippings), followed by those produced from plant residues (i.e. wheat bran, rice or maize straw, rice husk, peanut envelopes, coconut shells, corn cobs, rapeseed, sunflower husks, tomato stalks, or fruit crop waste). Digestate and silages (i.e., from corn or triticale) were also among the feedstocks retrieved. Less common substrates were winery wastes, olive mill waste or olive leaves, meat flour, spent mushroom substrate, and coffee grounds. In some cases, these materials have been combined

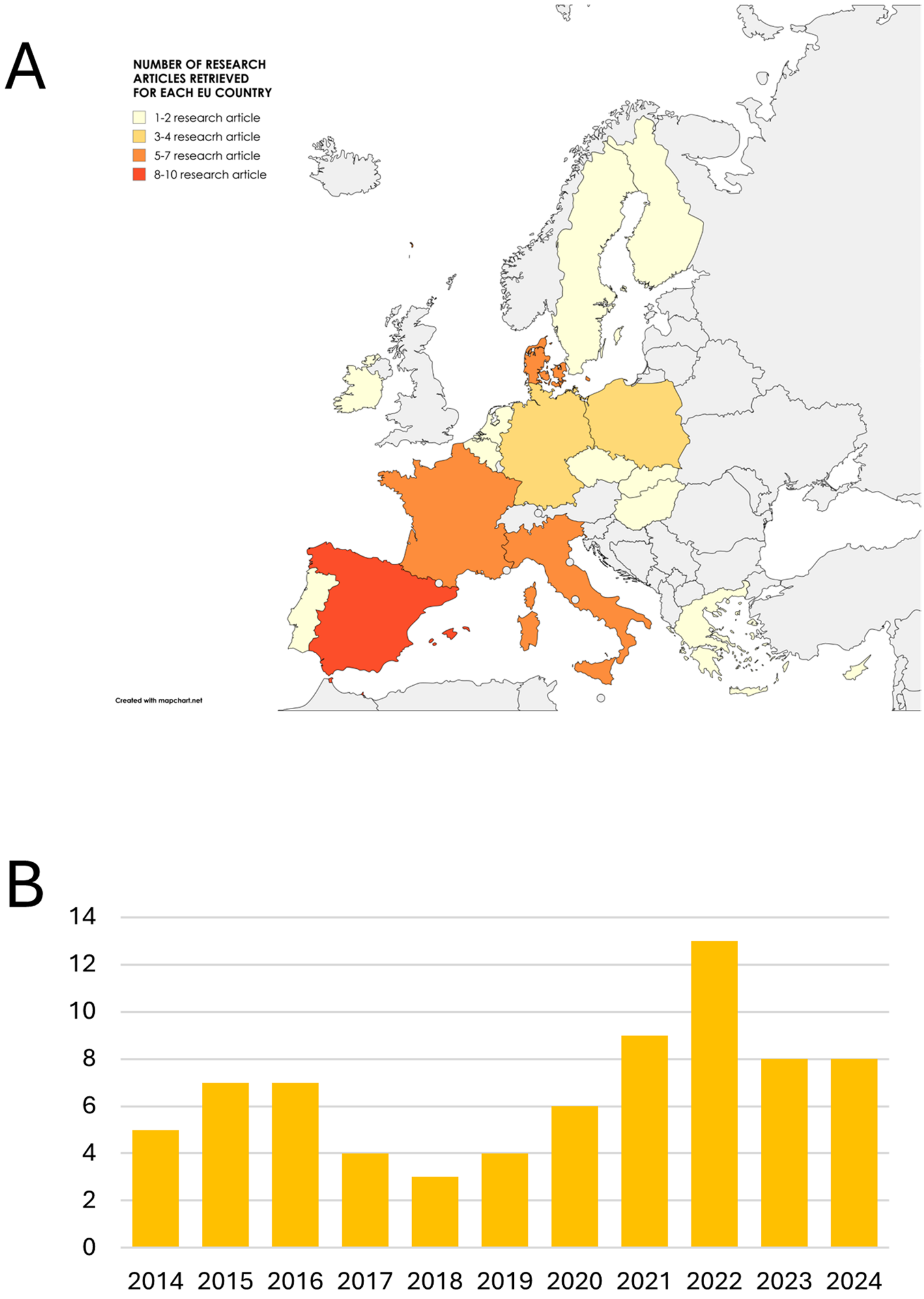


Fig. 2 Distribution of articles per country and for each year. **A**: heat-map of the distribution of the research papers performed in Europe, the legend on the left correlates colour with the number of articles retrieved, countries in grey were the one for which no research article was retrieved. The online tool mapchart.net was used; **B**: distribution of the published works (review/meta-analysis/SR, LCA studies and research articles) for each year

with paper fibre sludge or, more often, with manure (i.e., sheep, pig, or chicken) or, in a few cases, sewage sludge to improve local waste management. From these materials, the main derived products were biochar and compost, followed by digestate. The rate of application for the three products was: 3–30 Mg ha^{-1} for biochar, 50–160 Kg N ha^{-1} and/or 4.5–80 Mg ha^{-1} for compost, and 59–200 Kg N ha^{-1} and/or 8–150 Mg ha^{-1} for digestate. To improve the overview of the results, data have been organized according to the type of soil improver produced.

In summary, using the PRISMA guidelines, over 2300 articles were carefully screened, this allowed the identification of 74 relevant articles on agri-food-derived soil improvers, showing increasing research interest particularly on the use of biochar, compost, and digestate applied at varying agronomic rates.

3.2 Analysis of Key Words

The bibliometric analysis provided a detailed overview of the thematic structure of the systematic search, mapping out the current research priorities and interconnections among themes. The word cloud showed that "organic matter or OM" was the most frequently mentioned term (32 occurrences), followed by "organic amendments" (25) and "GHG emissions" (22). This high frequency of core terms suggested the focus on the fundamental components of soil health as well as the environmental impacts associated with soil management practices (Fig. 3A). The temporal trends, illustrated by the heat map data, revealed a steady increase in the use of these key terms over the 2014–2024 period, suggesting a growing emphasis on both enhancing soil quality and monitoring environmental factors (Fig. 3B). Complementing this, the co-occurrence network analysis showed the interrelationships among the various research themes. The network is organized into distinct clusters: one cluster grouped terms like "OM", "agricultural soils", and "soil organic", which likely reflected the core agronomic and soil quality aspects; another cluster was characterized by terms such as "GHG emissions" and "greenhouse gas", emphasizing environmental impact and climate-related concerns; while a third cluster combined process-oriented terms including "biochar application", "nitrous oxide", and "pyrolysis temperature", implying at studies that relate processing parameters to agronomic outcomes like "crop yield". Another important cluster, comprising terms such as "soil amendment", "soil properties", and "soil pH", highlighted parameters crucial for monitoring soil health, essential for evaluating the short- and long-term impacts of soil improvers on nutrient availability, microbial activity, and overall soil stability (Fig. 3C). The importance of these terms is confirmed by a meta-analysis showing that pH and "soil organic carbon" are among the terms most frequently identified, while cation exchange capacity and microbial biomass carbon are terms that strongly correlated with the size of the effect on agricultural soil quality (Bedolla-Rivera et al. 2023).

The distribution of soil improver studies across Europe revealed regional trends in the adoption and utilization of various organic amendments. Compost, biochar, and digestate were the main soil improvers in use, and their geographic distribution reflected both local agricultural practices and the availability of organic waste resources (Fig. 4). In southern European countries, such as Spain, Italy, and Portugal, the use of compost and digestate, with a range of organic feedstocks being utilized, was found. In Spain, compost was produced from urban waste, olive processing residues, and agri-food by-products, highlighting the efforts to integrate organic waste management with agricultural sustainability, particularly in

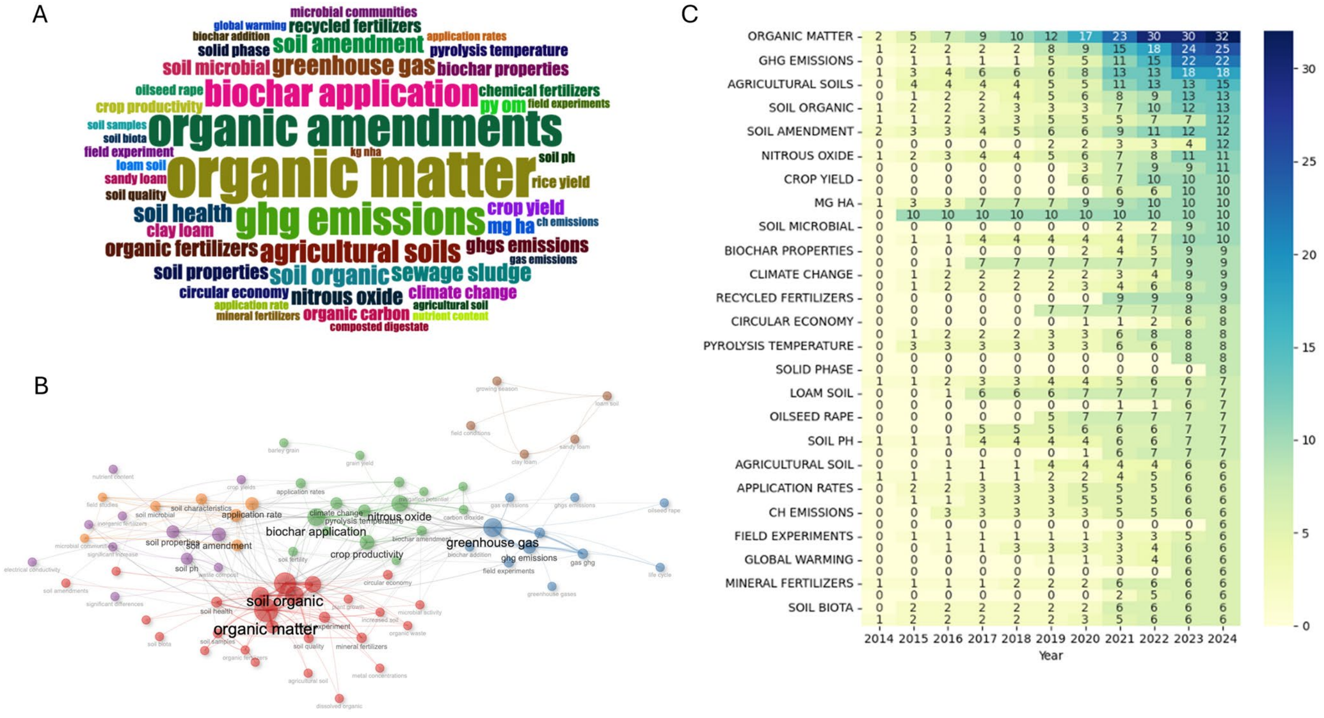


Fig. 3 Bibliometric analysis. (**A**) Word cloud of the most frequent keywords; word size is proportional to their occurrence frequency. (**B**) Keyword co-occurrence network; node size represents keyword frequency, colours indicate thematic clusters, and edges co-occurrence strength. (**C**) Heatmap showing the temporal evolution (2014–2024) of the most relevant keywords; colour scale represents frequency of occurrence, with darker shades corresponding to higher values

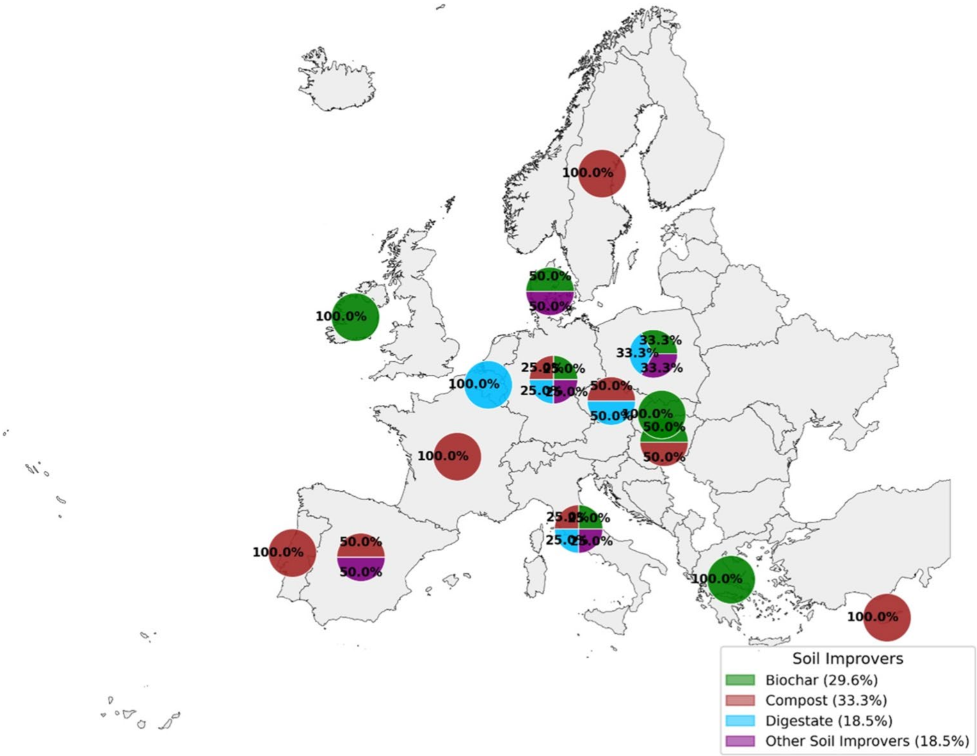


Fig. 4 The distribution of studies on the use of organic soil improvers in Europe. The study reflects local agricultural practices and resource availability, with compost, biochar, and digestate in prevalent use in several regions

the context of vineyard and olive cultivation, which are key agricultural sectors in the region. Similarly, Italy and Portugal have been prominent in utilizing composted organic materials, including municipal solid waste and agricultural residues, for enhancing soil fertility. In Denmark and Germany, the studies focused on biochar from agricultural residues such as wheat straw, maize silage, and even waste from livestock farming. Also, digestate from biogas plants was widely used in countries such as Germany, Italy, and Belgium, where biogas production was an established practice. As for Eastern Europe, the screening identified 15 potentially relevant studies, but only 7 were selected according to the inclusion criteria, highlighting a research gap in this area. These studies from Hungary and Poland used biochar from feedstocks such as grain husks and kitchen waste. Scandinavian countries, such as Sweden, also featured prominently in the use of compost derived from domestic waste. This reflected their advanced waste management systems, which were designed to recycle organic materials efficiently. The geographic patterns in the data suggested that the use of soil improvers was closely tied to the local availability of organic waste resources and the specific needs of regional agricultural sectors. This regional diversity underscores the importance of localized and tailored strategies for sustainable agriculture, where the selection of soil improvers is influenced by both available waste streams and the specific soil management needs of each region.

Overall, the bibliometric analysis showed that research on agri-food-derived soil improvers increasingly focuses on soil OM, organic amendments, and GHGs emissions, with interconnected themes linking soil health, processing parameters, and environmental impacts. while the geographical analysis showed regional patterns in the use of the amendments driven by local waste availability.

3.3 Description of the Main Classes of Soil Improvers Identified

Most of the field research studies discussed here have been carried out under Atlantic and Mediterranean (temperate and suboceanic) climates, and on soil mostly with a bulk density above 1.27 T m^{-3} and an available water capacity between 0.07 and 0.1 (volume fraction). Biochar, compost, and digestate can be considered as the most cited soil improvers derived from food industry by-products.

3.3.1 Biochar as Soil Improver

The characteristics of biochar depend on the biomass used and the conditions of the pyrolysis process. Each type of pyrolysis (slow, fast, flash, microwave, vacuum, and hydro) has a specific processing time, a temperature of operation, and pressure, which all need to be monitored (as summarized in Table 1). Biochar yield is highly dependent on the pyrolysis process employed, ranging between 10 and 90 wt% (Table 1). To improve the yield and the basic characteristics of the biochar produced characteristics of the feedstock

Table 1 Description of the main parameters defining the production of biochar, compost or digestate.For each of them, feedstocks and processing parameters, such as processing time, temperature, and pressure together with yields are considered. The table reports important parameters to monitor, starting from the characteristics of the feedstock, the monitoring of the key features of the processes and finally analyses to be performed on the product to define its quality

	Feedstock	Processing time	Temperature of the process	Pressure of the process	Yield	Feedstock parameters	Monitoring parameters during process	Parameters to determine the quality of the final product	References
BIOCHAR	woody biomass, food and agricultural waste, green and food waste, municipal waste§,…	300–7200 s Slow pyrolysis 0.5–10 s Fast pyrolysis < 1s Flash pyrolysis < 30s Microwave pyrolysis < 1s Vacuum pyrolysis 60–120 s Hydro pyrolysis	300–600 °C Slow pyrolysis (heating rate < 0.5 °C/s) 700–1000 °C Fast pyrolysis (heating rate > 100 °C/s) 900–1200 °C Flash pyrolysis (heating rate 1000 °C/s) 300–700 °C Microwave pyrolysis (heating rate 0.5–2 °C/s) 300–700 °C Vacuum pyrolysis (heating rate 0.1–1 °C/s) 350–600 °C Hydro pyrolysis (heating rate 10–300 °C/s)	0.1 Mpa Slow, fast and flash pyrolysis 5–20 Mpa Microwave pyrolysis 0.01–0.2 Mpa Vacuum pyrolysis 10–17 Mpa Hydro pyrolysis	27–40 wt% Slow pyrolysis 40 wt% Fast pyrolysis 20 wt% Flash pyrolysis 30–50 wt% Microwave pyrolysis 80–90 wt% Vacuum pyrolysis 10–50 wt% Hydro pyrolysis	Moisture content Volatiles (wt%) Fixed carbon (wt%) Ash (wt%) Total C, H, N, O, S	Temperature Time of operation Feeding rate Analysis of fuel gas and gas from oxidizer/engine	*Physical Parameters* Dry matter* Particle size distribution Surface area Bulk density Pore size *Chemical parameters* pH* Electrical conductivity* (EC)* Total organic C* (%) Content of K*, P*, Ca Mg, Na, Fe, Cl, S Heavy metals* Polycyclic aromatic hydrocarbons PAHs* PCDD/Fs* Polychlorinated biphenyls PCBs O, H and N, molar H/C_{org} and O/C Ash content *Surface characteristics* SEM, FTIR, SEM-EDX *Structural characteristics* TGA, TEM and XRD and NMR *Ecotoxicological toxicity testing* (e.g. seed germination)	(Dutta et al. 2021; European Union 2019; Li et al. 2023; Mei et al. 2024; Supraja et al. 2023; Uday et al. 2022), https://biochar-international.org/ https://www.european-biochar.org/en

Table 1 (continued)

	Feedstock	Processing time	Temperature of the process	Pressure of the process	Yield	Feedstock parameters	Monitoring parameters during process	Parameters to determine the quality of the final product	References
COMPOST	Food, vegetables, garden green waste, tomato plant waste, bread waste, cocoa husk, potato peels, dairy waste,…	From 21 to 189 days depending on the type of feedstock	Peak temperature: >50˚C for 3–4 d >60 ˚C after 48 h Mesophilic phase: 10–46 °C Thermophilic phase 46–70 °C Maturation at 20–35 °C	Atmospheric pressure	40–60 wt%	C/N ratio Bulk density Porosity Moisture content Ash (%) Total C, N. H, O, S	Pile temperature, O_2 consumption, Enzymatic activity, Gas emissions (CO_2; CH_4; N_2O), Organic carbon, Temperature, Aeration	Dry matter* Stability* Presence of pathogens* Impurity content* Heavy metals* PAHs*, PCBs, Content of K*, P* Microbial biodiversity Odor emissions C/N ratio Humic substances CEC Salinity index Cress Test pH	(Ansari et al. 2024; Azim et al. 2018; European Union 2019; Lim et al. 2016; Manea et al. 2024; Noor et al. 2024; Pal et al. 2024)
DIGESTATE	Food waste, sugar beet pulp, fruit marc and maize silage, agricultural feedstock, herbaceous biomass silage, straw or stalk from corn,…	21 days to 6 weeks			30–50 wt%	Biomethane potential BMP pH Volatile matter (%) Fixed C (%) Ash (%) Total solids (%) Total C (%) H (%) NH4 + N (g/kg) N (%) O, S, K, P (%) Chemical oxygen demand		Presence of pathogens* Heavy metals* PAHs* Impurities* Content of K*, P* Phytotoxicity Stability and odor	(Dutta et al. 2021; European Union 2019; Le Pera et al. 2022; Peng and Pivato 2019)

§: defined as food scraps, leftovers, or kitchen waste from plant or animal sources, potentially mixed with yard waste as leaves, branches, grass clippings

*: parameters that are obligatory following the European Union, "Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003."

can be monitored (such as moisture and ash content). The final product can be characterized according to its physical, chemical, surface, or structural parameters along with its potential ecotoxicity (Table 1) following international standards (for an updated view of the methodologies, the following websites are recommended: https://www.european-biochar.org/en and https://biochar-international.org/). In a review published in the Journal of Hazardous Material (He et al. 2021) focusing on the identification of soil indicators when using biochar, it is mentioned that pH, soil aggregate stability, and soil OM are measurements that should be prioritized. Other articles showed that biochar can positively impact several physical-chemical characteristics of the soil. Indeed, biochar can increase soil moisture by water retention, therefore improving the WHC (Almeida et al. 2024; Ayaz et al. 2021; Castracani et al. 2015; Enaime et al. 2023; Farkas et al. 2020; Siedt et al. 2021). Cation exchange capacity (CEC) rises (Enaime et al. 2023), while soil bulk density diminishes upon the addition of biochar (Enaime et al. 2023). Biochar can increase soil pH (Ayaz et al. 2021; Castracani et al. 2015; Farkas et al. 2020; He et al. 2021; Horák et al. 2017; Ye et al. 2020) and this effect is particularly clear in soils with a pH lower than 6.5 (Ye et al. 2020). Considering the articles retrieved in our SR, biochar was found to increase soil nutrient availability to plants. This has been reported for potassium (K), phosphorus (P), and nitrogen (N) (Ayaz et al. 2021; Deng et al. 2025; Enaime et al. 2023; Jindo et al. 2020; Ye et al. 2020). However, this is dependent on biochar and soil properties, as biochars low in P may decrease P availability in soil (Jindo et al. 2020). For example, biochar derived from wheat and miscanthus straw pyrolyzed at high temperatures decreased P uptake in potatoes (Yang et al. 2022). In general, carbonization concentrates P into the biochar in a more stable form that could be more available for plants in acidic soil (Zhang et al. 2024). Moreover, adding biochar to acidic sandy soil decreases ammonia and nitrate concentrations, but in calcareous soil, neither of the two changed (Farkas et al. 2020). Total and organic C increase upon the addition of biochar, providing substrates for microbes, which can ultimately give an increase in C fluxes (Enaime et al. 2023; Saarnio 2016; Sagrilo et al. 2015), especially when food waste-derived biochar has been studied (Sagrilo et al. 2015). All these improvements can promote plant yield (Ye et al. 2020). This has been positively correlated with biochar produced at temperatures (T) lower than 400 °C and used at application rates between 5 and 10 Mg ha^{-1} (Ye et al. 2020). Most of the articles described the effects on the chemical and physical characteristics of the soil, but only a few defined the microbiological and biological effects. The porous structure of biochar can create a positive niche promoting microbial growth, and it was reported that microbial biomass and activity were higher upon the application of biochar derived from plant residues (Castracani et al. 2015; Deshoux et al. 2023; Jindo et al. 2020), but the results are not conclusive. Biochar affects soil microbial species, although not always (Farkas et al. 2020), and their diversification (Castracani et al. 2015), but the possible consequences of those changes are not clear. Moreover, biochar can also increase ants' abundance, particularly of *Tetramorium caespitum*, while soil microfauna did not show any effects at least in a short time frame (Castracani et al. 2015). The possibility of using nano-biochar, having dimensions lower than a micrometre as well as up to nanometres, can increase soil pore tensile strength and increase *Actinobacteria*, *Bacteroidetes* presence, and decrease *Proteobacteria* (Rajput et al. 2022). Overall, many of these positive changes are connected to a homogeneous distribution of the solid material within the soil. Indeed, spatial heterogeneity strongly hinders agronomic observations (Olmo et al. 2016). Biochar products do not have a sufficient sorption capacity for N and cannot be defined as biofertilizers, but studies have reported ways to fortify this product (Rasse et al. 2022). For instance, the combination of nano-biochar with compost has been reported to reduce disease incidence, promote plant growth, increase plant height, enhance the fungal diversity index, and improve nitrogen and potassium content (Rombel et al. 2022). Recently, the advantages and limitations of waste-derived nano-biochar have been systematically reviewed, overall supporting its potential application in sustainable agriculture (Sani et al. 2023).

The articles identified by the SR have shown that biochar, when added to soil, can provide multiple positive effects (WHC, CEC, pH, and nutrient availability) although there is variability according to feedstock and pyrolysis parameters. Less clear are the results on the microbial population present in the soil, and specific studies and reviews should provide these data.

3.3.2 Compost as soil improver

Compost is regarded as a vital source of OM and nutrients for agriculture, playing a crucial role in sustaining soil biodiversity (Kovačić et al. 2022). Several articles have investigated the effects of compost application on soil properties and plant growth. Compost can be derived from a multitude of feedstock (Table 1) by a natural and relatively long process. Composting occurs at atmospheric pressure and has different stages, each with a specific temperature. To be considered as a soil improver, it is important to evaluate its qualitative properties, which depend both on the feedstock and on the composting process. Production of humic-like substances, C/N ratio, pH, microbial biodiversity, and odor emission are some of the different parameters monitored in the newly produced compost, as summarized in Table 1. Compost had significant beneficial effects on certain soil properties and crops, including soil extractable P, and K, as well as on plant yield, chlorophyll content, and foliar area (Alvarenga et al. 2017). Compost application also influenced the quantity of dissolved organic carbon (DOC) in the luvic cambisol soil after 7 years (Cambier et al. 2014; Musadji et al. 2020). These studies have shown that the low spring DOC values are close to the rainfall. DOC value was thus attributed to the rainy spring event. Furthermore, DOC concentrations decreased with increasing soil depth. The higher DOC levels observed in amended plots were associated with the abundance of plant residues and their degradation products present in the compost. Increased DOC levels in soil can improve soil health as well as increase microbial enzyme activity (Cambier et al. 2014; Musadji et al. 2020). In addition, a study conducted in 2024 in Italy found that applying composted digestate to sandy loam and medium loam soils significantly increased sunflower yields (Gurmessa et al. 2024). Moreover, it was observed that compost positively influenced the quality of and the quantity of DOC (Cambier et al. 2014; Musadji et al. 2020). When examining the impact of compost on soil, it was found that compost application led to an increase in soil OM (Alvarenga et al. 2017; Cicatelli et al. 2014; Martínez-Sabater et al. 2022; Musadji et al. 2020; Soria et al. 2022; Viketoft et al. 2021; Warrinnier et al. 2020), and that this amendment helped mobilize macro- and micronutrients. This increase positively influenced bacterial activity (Musadji et al. 2020), soil microbial abundance (Viketoft et al. 2021), and soil respiration rates (Soria et al. 2022). Additionally, compost application was associated with an increase in soil pH (Cicatelli et al. 2014; Martínez-Sabater et al. 2022), electrical conductivity (EC) (Cicatelli et al. 2014; Martínez-Sabater et al. 2022), WHC (Soria et al. 2022), and extractable P (Martínez-Sabater et al. 2022), a phenomenon observed especially in soils previously used for agricultural activities. Composting was reported to allow the breakdown of labile organic compounds and the production of material rich in OM, macro-, and micronutrients, and free of phytotoxic elements, which benefits plant growth and facilitates the integration of compost as an organic amendment into the soil (Enaime et al. 2023). Regarding plant growth, compost application resulted in increased plant biomass and yield compared to the control treatment (no amendment or mineral fertilizers), as well as improvements in plant nutritional status (Alvarenga et al. 2017; Chen et al. 2024). However, the effects of compost on plant biomass varied depending on the specific plant species and the duration of compost application. For example, in barley, N management strategies significantly affected nutrient content in terms of total N, Ca, and Mg present in grain (Omirou et al. 2023). The effects of compost on microbial communities were mixed. While compost application did not significantly influence the abundance of fungi (Viketoft et al. 2021), changes in the bacterial community were observed (Sanz et al. 2022), mostly in silty clay soils on *Lactuca sativa* and *Raphanus sativus*. The observed increase in OM positively influenced bacterial activity (Musadji et al. 2020), soil microbial abundance (Viketoft et al. 2021), and soil respiration rates (Soria et al. 2022). Moreover, compost made from agro-industrial residues (coffee ground, defatted olive marc) combined with plant waste (artichoke, fennel, or tomato) helped horticulture to defend itself from soil-borne pathogens (De Corato et al. 2016).

In summary, findings from multiple studies indicate that compost, whose quality depends on feedstock and composting conditions, has significant positive implications for soil properties (SOM, pH, nutrient availability, DOC and nutrient availability), plant growth, and microbial communities.

3.3.3 Digestate as soil improver

Digestate refers to an organic matrix primarily valued for its fertilizing properties, including its high N and P content and low C/N ratio. The production of digestate can start from a multitude of feedstock (Table 1) and its production can last between 21 days and up to 6 weeks, with a yield up to 30–50% wt. High-quality digestate suitable for soil fertilization is distinguished by key characteristics (Table 1), including the declared nutrient content, pH value, dry matter (DM), OM content, and its homogeneity. Equally important are the health and safety features of digestate, which need to be monitored, such as purity, hygiene, or sanitization (ensuring it is free from pathogens and other unwanted biological content), and safety (ensuring it is safe for living organisms and the environment) (Kovačić et al. 2022). This was attributed to improved soil chemical properties, including enhanced microbial biomass and enzyme activities vital for the decomposition of OM and nutrient cycling. The application rate of 50 kg N ha^{-1} of N-equivalent liquid digestate led to these improvements, emphasizing its efficacy in nutrient-poor soils with low OM content (Eickenscheidt et al. 2014). Additionally, another study from Italy demonstrated that digestate, particularly its liquid fraction applied at 200 kg N ha^{-1}, gradually increased crop yields over time compared to conventional N fertilizers. This was particularly notable in conditions where traditional fertilizers provided limited benefits, highlighting liquid digestate's potential for sustainable nutrient management (Riva et al. 2016). Digestate from olive mill wastes (OMW) provided key nutrients like N, K, P, and OM, improving soil fertility and partially replacing chemical fertilizers. It worked best on clay-loam soils and slightly lowered soil pH, though this effect diminished over time. OMW boosts soil microbiology but can negatively impact plants if applied in high doses or too close to sowing. Some plants, like tomato roots, are more sensitive to OMW's fatty acids and phenols, which hinder nutrient absorption (Enaime et al. 2024). Additionally, solid digestate products, including bio-thermically dried organic waste, vegetables, fruits, and garden compost, have been shown to affect P dynamics in soil. Studies indicated that a significant decrease in soil P availability (0.01 M $CaCl_2$ and hot water extractable P) and P leaching can already be achieved by zero-P fertilizer application during this 4-year period without any crop yield losses and with equal P export (Vanden Nest et al. 2015). This highlights digestate's potential for improving nutrient management by reducing P leaching while maintaining productivity. Long-term field trials, such as a six-year study in the Czech Republic, have reported that the regular application of liquid digestate enhanced soil stability (such as erosion resistance, soil structure, CEC, and resistance to compaction and compression), increased the labile fractions of soil organic C, and boosted microbial diversity. These trials used rates of 150 kg N ha^{-1} for digestate and 300 kg N ha^{-1} for compost, showing how tailored application rates can optimize benefits. Such long-term applications not only improved soil structure but also contributed to the overall resilience and health of agricultural ecosystems by encouraging the growth of beneficial microbial communities (Řezáčová et al. 2021).

In summary, the strategic use of digestate can profoundly benefit agricultural productivity and soil health. Research on digestate as a soil improver has demonstrated positive impacts on soil chemistry, microbial diversity, and crop yields, particularly in nutrient-poor soils while optimized application rates enable efficient nutrient management, reduced phosphorus losses, and partial replacement of mineral fertilizers.

For future research it would be interesting to take into account also the different pedoclimatic conditions, so that possible region-specific solutions could be identified, as underlined in other studies (Bøe et al. 2024; Nolfi et al. 2025). In Table 2 it is evident that the use of soil improvers of various origins has been reported to change soil microbial structure and functional microbial diversity, enhance microbial growth, increase SOM and CEC, immobilize heavy metals, stimulate degradation and/or mineralization, and improve soil structure and WHC. However, in order to observe these positive effects, feedstock material and the overall fabrication process needs to be carefully monitored, as recently stated (Amery et al. 2026; Zapata-Morales and Moreno-Andrade 2025). Specifically, biochar improves soil moisture retention, but its biological effects are often inconsistent and unclear and needs to be further investigated. Indeed, in a recent SR it was stated that the effects of amendments, and their management, on soil microorganisms, GHG emissions, and SOC should be simultaneously established (Latini et al. 2025) to better determine the overall outcome. Compost enhances organic matter and pH, while digestate boosts enzyme activity and erosion resistance. Additionally, compost and digestate show strong benefits for plant growth, increasing biomass, yield, and nutrient availability. Biochar can also enhance plant performance, but its effects are more variable.

3.4 Non-Conventional Soil Improvers

Fermented plant-based residues, animal and diary by-products, are other soil improvers used and identified in the SR. These biobased fertilizers were tested at four different European locations. Their use as an amendment gave yields similar to mineral references at the same total N rate, and no consequences on soil, crop, and climate were registered (Müller et al. 2024). Moreover, from winery waste, two products have been produced specifically from the wine clarification process, such as bentonite or the must-filtration, such as perlite. The effects of these two winery residues were assessed by applying both 21–24 Mg ha^{-1} and 71–81 Mg ha^{-1}, but only the bentonite waste gave an effect when applied at the highest concentration (71 Mg ha^{-1}). In this case, an increase in soil pH, EC, exchangeable K, water-soluble K, and the P content was observed while the activity of the enzyme phosphomonoesterase decreased (Rodríguez-Salgado et al. 2017). The application of spent mushroom substrate could stimulate soil respiration and dehydrogenase activity, while reducing acid phosphatase and arylsulfatase activity (Kwiatkowska and Joniec 2022). The biosorption, an eco-friendly process that employs microorganisms to eliminate heavy metal ions from polluted environments, of spent mushroom substrates created a fertilizer rich in micronutrients (Zn, Mn, and Cu) easily bioavailable to maize cultures (Tuhy et al. 2015). Moreover, studies on wheat showed that adding 10 Mg ha^{-1} of spent mushroom substrate to 120 kg ha^{-1} of N allowed an increase in plant height, grain yield, soil organic matter, total N, exchangeable K, soil microbial respiration, and microbial biomass (Ahmed et al. 2025). N uptake was reported to be positively stimulated by the soil application of residues derived from a complex mix containing liquid and solid bovine manure, crop residues (silage maize and grass), and organic wastes from the agri-food industry (Tsachidou et al. 2019). Another alternative involves the use of whey, a dairy-processing waste, which has plant, soil chemical, and fungicidal activities (Ntalli et al. 2019). This product helped combat root-knot nematodes and enhanced soil biotic components, as it acted as a food web enhancer and a nematocidal,

Table 2 Summary of the effects given by biochar, compost and digestate. The chemical physical and biological changes in soil or on plants connected to the use of soil improvers, the table reports the risks related to their application. Additional considerations are present in the last column

	SOIL EFFECTS	BIOLOGICAL EFFECTS	EFFECTS ON PLANTS	ISSUES AND RISKS IDENTIFIED	ADDITIONAL CONSIDERATIONS
BIOCHAR	*INCREASE*: -Soil moisture & WHC - CEC and pH (especially if<6.5) - Availability of K, P, N (depending on biochar composition) -Total and organic C *DECREASE*: - Bulk density	*INCREASE*: - Creates niches for microbes - Microbial biomass/activity - Altered species diversity	*INCREASE*: -Plant yield (esp. T<400 °C, 5–10 Mg ha^{-1}) -nutrient uptake	-Variable GHG effects- Potential for CO$_2$ increase - Heavy metals-PAHs, PCDD/Fs, VOCs	-Biological effects are often inconsistent and unclear - Limited N sorption (not a biofertilizer) -Reduces CH$_4$ and N$_2$O (esp. in acidic soils) - Effect depends on pyrolysis temperature, C/N ratio, and feedstock - Biochar stabilizes metals
COMPOST	*INCREASE*: -OM, pH, EC, WHC, extractable P, K -DOC (surface layers) -Improved nutrient mobilization	*INCREASE*: -Bacterial abundance and activity *DECREASE*: -soil pathogens	*INCREASE*: -Plant biomass, yield, chlorophyll, foliar area	-GHG emissions (CO$_2$, CH$_4$, N$_2$O) - Metal mobility/accumulation -Organic contaminants leaching	-The effects on fungi are mixed - Effects depend on compost maturity & source material -Reduces heavy metal uptake in some cases - Can increase metal solubility, Zn and Cu accumulation, and leaching potential due to increased soluble OM
DIGESTATE	*INCREASE*: -Soil fertility, CEC, and structure -Microbial biomass & enzyme activity -Soil stability & erosion resistance (long term) *DECREASE*: -P leaching (better nutrient cycling)	*INCREASE*: -Microbial diversity and enzyme activity - Supports nutrient cycling and decomposition	*INCREASE*: Crop yields (esp. in nutrient-poor soils) - Effective N and P supply	-CO$_2$, CH$_4$, N$_2$O, NH$_3$ emissions - Nutrient leaching - Limited removal of ARGs and antibiotics	- Overapplication (esp. OMW-based) can harm sensitive plants -N$_2$O emissions reduced when combined with biochar

inhibiting the agricultural pest *Meloidogyne javanica* (Ntalli et al. 2019). Shrimp waste chitin supplemented at 20 Mg ha^{-1} to soil changed soil microbial communities and, at the same time, plant pathogens and plant-pathogenic nematodes diminished (Cretoiu et al. 2013). Several works also reported the possibility of using microbial inoculants for the bioconversion of waste into “bio-organic” fertilizers (Kiruba and Saeid 2022) to improve their effectiveness.

Studies on non-conventional soil improvers show that amendments derived from fermentation, winery waste, pelletized meat/bone meal, blood/feather, pig bristles, hydrolysed horn meal, spent mushroom substrate, dairy by-products, shrimp waste, and mixed organic residues can maintain crop yields comparable to mineral fertilizers and, at the same time, improve soil characteristics.

3.5 Risks Connected to the Use of Soil Improvers

The use of soil improvers is not without any risk, and their application needs to be carefully managed to minimize environmental impact. Indeed, biochar may increase CO_2 emissions but stabilizes metals; compost can leach organic contaminants; and digestate poses risks from overapplication. In addition, these newly developed materials may contain pathogens, heavy metal(loid)s, and organic pollutants, and, if not properly managed, excessive nutrient inputs can result in eutrophication, nutrient immobilization, groundwater contamination, an increase of greenhouse gas emissions, soil acidification, and salinization. Moreover, emerging risks, such as the presence of microplastics, antibiotic resistant bacteria, and antibiotic-resistance genes, need to be considered (Basumatary et al. 2026; Braun et al. 2023; Czatzkowska et al. 2025; Gigliucci et al. 2025; Johansen et al. 2024). Particularly, risks related to the use of agri-food industrial residues are mainly due to the possible GHG emissions (Fu et al. 2023), nutrient leaching (Rashid et al. 2025; Siedt et al. 2021; Ylivainio et al. 2023), pathogens, antibiotic-resistant bacteria, antibiotic-resistance genes (ARG), as well as inorganic and organic contaminants in the residues (Urra et al. 2019). Soils treated with organic fertilizers (compost) showed high ARG levels—up to 100 times more than untreated soil—with levels roughly correlating to antibiotic residues within the fertilizers (Sanz et al. 2022); moreover, small amounts of ARGs were also detected in the vegetables. In parallel, soil microbial communities remained stable over time, while ARG levels were variable and transient (Sanz et al. 2022). In addition, microplastics are emerging environmental pollutants that can originate from various sources. Studies confirm that compost made from municipal or urban biowaste is a significant contributor to microplastics accumulation in soil (Braun et al. 2023; Johansen et al. 2024). Long-term field experiments revealed that soils amended with compost can retain millions of microplastic particles or hundreds of kilograms of coarse microplastics per hectare even decades after application (Colombini et al. 2022). Despite the persistence of these new contaminants in soils, no immediate adverse effects on soil bio-physical-chemical properties were observed, at least not in the short time frame (Colombini et al. 2022; Johansen et al. 2024). However, the potential risks remain significant, as microplastics can carry harmful chemicals, accumulate in organisms, and affect ecosystems. However, research focused on these issues and their presence in agri-food industrial residues is scarce, as the number of found articles was limited, especially for contaminants. Pathogens can be transmitted through organic amendments, but their risk can be substantially reduced by composting and anaerobic digestion (Urra et al. 2019), whereas the high temperatures involved in pyrolysis during biochar production are likely to destroy all pathogens.

3.5.1 Risks Associated with the Use of Biochar

GHG emissions related to biochar have been studied mostly for emissions of carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4). Biochar produced at high temperatures has a high C content, aromaticity, and sorption capacity, is more stable, and should decrease GHG emissions, while biochar produced at lower temperatures degrades more easily, providing substrates for microbes and, thus, promoting GHG emissions in the short term (Saarnio 2016). Concerning CO_2, biochar in soil has been reported to increase its emissions (Fu et al. 2023; Iboko et al. 2023), particularly when the biochar feedstock was lignocellulose-derived, and applied to fine and acidic soils (Shakoor et al. 2021). When biochar C addition exceeded twice the soil organic C content, CO_2 emissions increased (Sagrilo et al. 2015). Biochar can mitigate CH_4 emissions (Shakoor et al. 2021) in flooded soil (i.e., rice cultivation), and in acidic soils, especially when the biochar is produced at a temperature lower than 600 °C (Fu et al. 2023; Jeffery et al. 2016; Shakoor et al. 2021). Biochar can absorb on its surface NH_4 and NO_3 reducing the N available to produce N_2O (Cambier et al. 2014; Cayuela et al. 2014; Fu et al. 2023; Hassan et al. 2022), and applications of 1–2% (dry weight basis) can be enough to reduce the emissions of this gas. This reduction has been linked to pH, aeration, and WHC of the biochar (Cayuela et al. 2014; Hassan et al. 2022). Soil nitrate availability was decreased in the combined treatment of biochar and inorganic N fertilizer (Horák et al. 2017), which can be caused by microbial immobilization. If biochar is combined with organic fertilizers such as compost (Dicke et al. 2015) or manure (Horel et al. 2018). This can further lower GHG emissions. Although Fu et al. (2023) stated that, when biochar was co-applied with organic amendments, soil GHG emissions were mostly influenced by initial soil total carbon, soil texture, and biochar feedstocks. Moreover, the N_2O emission reduction was more pronounced in coarse and neutral soils (Shakoor et al. 2021). A C/N ratio in biochar higher than 30 was positively related to lowering the N_2O emissions (Dicke et al. 2015), although environmental conditions like T and precipitation were the factors mainly influencing N_2O emissions (Dicke et al. 2015). There was only one research article showing no effects on N_2O emissions, in which biochar made from straw and applied at two rates of 1.5 and 15 Mg ha^{-1} did not affect cumulative N_2O emissions in three years (Thers et al. 2020). As biochar-amended soils have been found to have higher sorption of ammonium and nitrate, N leaching has been decreased in several experiments (Siedt et al. 2021). Biochar can hold P and thus prevent leaching and runoff losses (Ayaz et al. 2021). This finding is supported by rainfall simulator studies, where organic P fertilizers caused lower P losses in leachate compared to triple superphosphate (Ylivainio et al. 2023).

Contaminants in biochar originate either from the feedstock or are produced during pyrolysis. Heavy metals in the biochar originate from the used feedstock, as non-volatile heavy metals concentrate into the biochar when OM volatilizes during the pyrolysis (Domene et al. 2015; Godlewska et al. 2021). In general, total concentrations of heavy metals in biochars derived from agri-food side streams are low (Domene et al. 2015; Godlewska et al. 2021; Vamvuka et al. 2018) and under the threshold values of the EU fertilizer product regulation (European Union 2019). In addition, pyrolysis with increasing temperatures usually reduces the bioavailability of many heavy metals (Godlewska et al. 2021; Han et al. 2022). Biochar has also been reported to stabilize heavy metals in soils. For example, biochar of vineyard origin has been reported to decrease the uptake of Cr and Pb by lettuce (*Lactuca sativa* L.) compared to the control treatment (Turull et al. 2021). However, the uptake of Zn was increased at a higher biochar application rate (6% w/w), possibly because of the increased Zn concentration in biochar-amended soil compared to the lower application rate (3% w/w) (Turull et al. 2021). Polycyclic aromatic hydrocarbons (PAHs), dioxins and furans (PCDD/Fs), and volatile organic compounds (VOCs) can be formed under certain conditions of pyrolysis (Godlewska et al. 2021; Han et al. 2022). Generally, total PAH content in biochars derived from agri-food residues is low and under the threshold value (6 mg kg^{-1} 16 USEPA PAHs) of EU fertilizer product regulation (Domene et al. 2015; European Union 2019; Farkas et al. 2020; Godlewska et al. 2021). However, in addition to the used feedstock, process parameters and design of the pyrolysis unit influence the PAH contents (De La Rosa et al. 2019; Han et al. 2022), and higher total concentrations can be found (Godlewska et al. 2021). For example, it was reported a 16 USEPA PAH content of 15.8 mg kg^{-1} in DM for wheat straw biochar produced by gasification (Visioli et al. 2016), and 15.4 mg kg^{-1} DM for grapevine wood biochar produced with the traditional kiln method in uncontrolled conditions (De La Rosa et al. 2016). When applied once to the soil, biochars have been reported to increase soil total PAH content, but the content has decreased over time at the level of control soils (Godlewska et al. 2021). In addition, the bioavailability of PAHs in biochars is generally low (Godlewska et al. 2021; Han et al. 2022), and their concentrations in the soil have also been reported to decline after application. For example, a study conducted an 851-day field experiment with wheat straw-derived biochar (application rates of 30 and 45 t ha^{-1}) reported a significant decrease in the total amount of freely dissolved PAHs in the soil over 105 days (Oleszczuk et al. 2016). In fact, throughout the experiment, the concentrations were lower than in the control soil (loamy sand), with concentrations 40–42% lower by the end of the experiment. According to the study, this may be due to various factors, such as losses by migration in the soil, and the capability of biochar to bind PAHs present in the soil. The content of PCDD/Fs is usually low except for biochars that are derived from feedstock with elevated concentrations of chlorine, such as food waste (Godlewska et al. 2021; Han et al. 2022). As with PAHs, the concentrations of VOCs in biochar can be minimized by using pyrolysis units that prevent the recondensation of pyrolysis vapours during the pyrolysis (Han et al. 2022). According to Godlewska et al. (2021), VOC concentrations could be lower in highly carbonized biochars. Generally, soil-amended biochar does not have toxic effects in a one-time application rate (< 1%), but factors such as biochar type (feedstock and pyrolysis temperature), its possible contaminants, and their bioavailability, application rate, and frequency, together with soil type, influence the toxicological effects (Domene et al. 2015; Farkas et al. 2020; Godlewska et al. 2021). More research is needed for the effect of biochar aging, or weathering, on the long-term bioavailability of its possible contaminants, as well as for nano-biochars (< 100 nm) (Rajput et al. 2022; Sani et al. 2023). For nano-biochars, potential environmental risks include, among others, ecotoxicity, nutrient adsorption from soil solution, inducing nutrient deficiency and losses to surface and groundwaters, and plant uptake of nano-biochars (Sani et al. 2023).

Research indicates that biochar can mitigate GHG emissions (N_2O and CH_4) through its sorption capacity but CO_2 emissions may increase depending on feedstock, pyrolysis temperature, soil type, and application rate, while contaminant risks are generally low and within EU limits.

3.5.2 Risks Associated with the Use of Compost

While compost application can enhance soil fertility and plant productivity, it also has the potential to influence GHG emissions and the mobility of contaminants in the soil. Composts vary in their N and P concentrations, and composts with high available or easily available nutrient contents should be used when plants are actively taking up nutrients. Thus, careful consideration of compost application practices is necessary to optimize agricultural sustainability and minimize environmental impacts. In Mediterranean conditions, GHG emissions from dill (Martínez-Sabater et al. 2022) and rice field experiments (Fernández-Rodríguez et al. 2022) were studied while comparing composts, other organic fertilizers, and inorganic fertilizers. CO_2-C emissions were higher from fresh organic fertilizers than from composts, whereas inorganic fertilizers led to the lowest

CO_2-C emissions (Martínez-Sabater et al. 2022). Compost fertilizer tended to result in higher CO_2-C emissions compared to inorganic fertilizer in the rice field, although tillage, compared to direct seeding, had a greater effect on CO_2-C losses (Fernández-Rodríguez et al. 2022). Methane emissions were low in both field experiments, and composts did not differ from inorganic fertilizer treatments. N_2O emissions from compost-fertilized soil did not differ from soil applied with an inorganic fertilizer (Martínez-Sabater et al. 2022), while in the rice field, there was only a very slight indication of increased N_2O emissions from the use of compost (Fernández-Rodríguez et al. 2022).

Related to heavy metals, it has been demonstrated that compost addition can reduce metal uptake by plants. For example, a research reported that compost of vegetal origin reduced the uptake of Cd, Cr, Cu, and Pb by lettuce (*Lactuca sativa* L.) compared to the control treatment (Turull et al. 2021), while another one showed a lowered risk for Cd and As accumulation in rice grain when using olive mill waste compost (Fernández-Rodríguez et al. 2022). However, compost application can also increase metal and micronutrient solubility and availability if, for example, application to soil increases soluble OM content capable of complexing metals, induces reduced conditions in the soil, or decreases soil pH (Alvarenga et al. 2017; Maqueda et al. 2015). For example, increased availability of Cu, Mn, Zn, and Fe in soil has been reported for composted olive mill wastewater sludge in a 3-year incubation study (Maqueda et al. 2015). There is also a possibility of heavy metal accumulation in the soil in repeated compost applications. For example, a study emphasized a possible risk of Cu and Zn accumulation in the soil in the continuous use of composts (Alvarenga et al. 2017). They conducted a 2-year field experiment including an agricultural waste compost made from sheep manure, olive production wastes, and meat flour. After the second year, total Cu and Zn and mobilizable Zn concentrations in the soil increased with higher application rates (17.9 t OM ha^{-1} yr^{-1}), leading also slightly increased Zn concentrations in plants (*Lolium multiflorum* L.). Increased dissolved organic matter (DOM) content in the soil, for example by compost application, could potentially lead also to greater leaching of organic contaminants present in the soil. For example, in percolation studies (Chabauty et al. 2016), DOM increased the mobility of the pesticides epoxiconazole and isoproturon and the pharmaceuticals ibuprofen and sulfamethoxazole. The effect was more evident in the case of more hydrophobic compounds (epoxiconazole and ibuprofen).

Compost application may influence GHGs emissions and contaminant mobility, with studies showing generally comparable CO_2, CH_4, and N_2O emissions to inorganic fertilizers under Mediterranean conditions, while effects on heavy metals are context-dependent: compost can reduce plant metal uptake but may also increase metal solubility, accumulation, or contaminant leaching under certain soil conditions, highlighting the need for carefully managed application strategies.

3.5.3 Risks Associated with the Use of Digestate

The nutrient content of digestates varies depending on source materials and processing after digestion. Nutrient-rich digestates can enhance crop growth; however, their available nutrients are susceptible to leaching, and nitrogen losses may also occur in the form of ammonia (NH_3) or nitrous oxide (N_2O). Regarding CO_2 emissions, studies indicate that digestate application can increase soil CO_2 emissions, stressing the need for careful management practices to mitigate potential negative effects on C sequestration (Maucieri et al. 2016; Maucieri and Borin 2017). However, a study conducted in arable fields (soil: Luvisoil, crop: triticale) showed a relatively low impact of the emissions of CO_2 and CH_4 from the field fertilized with digestate on total emissions from agriculture (Czubaszek and Wysocka-Czubaszek 2018). A study revealed that the use of digestate could contribute to a potential increase in NH_3 emissions, necessitating strategic application methods to minimize emissions (Wolf et al. 2014) such as injection into the soil (Riva et al. 2016). When applied with biochar, digestate showed relatively low N_2O emissions (Dicke et al. 2015), and this addition can reduce NH_4^+ concentration and N losses from liquid digestate (Mohamed et al. 2025). The use of digestate requires precise management to harness its full potential while addressing environmental concerns associated with GHG emissions and nutrient leaching.

Related to various contaminants in digestates, our SR results were very limited. However, according to two reviews, the capability of anaerobic digestion to remove antibiotics and antibiotic-resistance genes is limited (Bünemann et al. 2024; Urra et al. 2019). However, anaerobic digestion in thermophilic temperatures (55 °C) or in mesophilic temperatures (39 °C), together with pre-treatments such as pasteurization or thermal hydrolysis conducted in high temperature and pressure, enhances the removal of antibiotic-resistance genes as well as pathogens (Bünemann et al. 2024; Urra et al. 2019).

Digestate nutrient composition and environmental impacts vary with feedstock and processing, as its application can enhance crop growth but also increase risks of GHG emissions and nutrient leaching, which can be moderated through correct management practices or co-application with biochar.

3.6 Risks Associated with the Use of Non-Conventional Soil Improvers

While composting and anaerobic digestion are currently the most important methods for processing agri-food residues, and biochar production has been studied widely in recent years, some soil improvers are produced through thermal treatments, fermentation, or are marketed without any special processing. Studies examining nutrient losses from these materials are mostly based on incubation experiments, and there are no data from field trials. The following two examples are drawn from such incubation studies. Blood meal, horn and hoof meal, and meat and bone meal are examples of animal by-products subjected to thermal treatment and when applied to soil and compared to mineral fertilizers, these materials slightly increased CO_2 emissions and decreased N_2O emissions in sandy soil, but not in loamy soil (Cayuela et al. 2010). Fresh materials, such as dairy processing sludge, typically result in increased GHG emissions from soil (Hu et al. 2023). However, Hu et al. (2023) also observed that converting this sludge to biochar reduced soil GHG emissions compared to the untreated material. The literature search did not yield any specific studies dealing with human or plant pathogens and products not belonging to the group of biochars, composts, and digestates. The review by Urra et al. (2019) notes that raw and untreated materials can contain pathogenic organisms. Thermal treatments used to process animal by-products will almost eliminate the risk of pathogens. For materials such as vinasses, olive mill waste, and winery wastes, there is most likely only a small amount of pathogens due to the nature of feedstock and processing involved in food preparation. Untreated dairy processing sludge has been recognized as a potential source of pathogens, although the risk is lower than in, for example, sewage sludge (Hu et al. 2021).

Regarding contaminants, the studied soil improvers were concentrated and depotassified sugar beet vinasse, olive mill wastes, aquaculture sediments, and winery wastes. Concentrated and depotassified sugar beet vinasse was reported to increase the availability of Mn and Zn in a 3-year incubation experiment (Maqueda et al. 2015). Regarding olive mill wastes, in addition to their beneficial effects as discussed in the previous section, negative effects on plants and surface and groundwaters have been reported. According to a recent review, the application of olive mill wastes may cause phytotoxicity depending on factors such as application method, rate and timing, soil type, crop plant, and its phenological stage (Enaime et al. 2024). The phytotoxicity is, at least partly, related to the phenolic compounds in olive mill wastes, and these compounds also hinder anaerobic digestion and composting of these wastes. Some of the phytotoxic compounds are still found in the olive mill waste digestates. On the other hand, aquaculture sediments are an example of agri-food side-stream containing the risk of ARG in cases antibiotics are used during operations (Bünemann et al. 2024). This risk could be mitigated by various processing technologies such as pasteurization, pyrolysis as well as composting, and anaerobic digestion in sufficiently high temperatures or anaerobic digestion combined with thermal pretreatments. However, the removal efficiency varies among the technologies and the genes in question (Bünemann et al. 2024). Regarding winery wastes, it has been reported that the use of perlite and bentonite wastes in an 18-month field study in an acid vineyard soil (Rodríguez-Salgado et al. 2017). The bentonite waste had total Cu content exceeding the threshold value set by the EU (European Union 2019), and water-soluble Cu concentrations in soil increased, being one possible reason for the detected reduction in soil phosphomonoesterase enzymatic activity. Thus, the authors highlighted the need to avoid continuous applications of bentonite waste.

Studies on non-conventional soil improvers are largely limited to incubation experiments, indicating variable effects on GHG emissions, potential pathogen risks in untreated materials, and contaminant concerns (i.e. heavy metals, or ARGs), underlying the need to perform field studies and careful management to ensure their safe use.

4 Conclusions and Future Perspectives

This review forms part of the DeliSoil project "Delivering safe, sustainable, tailored & societally accepted soil improvers from circular food production for boosting soil health" funded under the European Union "A Soil Deal for Europe". The work contributes to broader efforts to protect and restore European soil through sustainable management practices and the responsible use of circular bio-based amendments. It highlights the importance of developing robust environmental assessment methods to quantify the impacts of recycling processes. In addition, harmonized regulatory frameworks and standardized monitoring protocols are needed to ensure that soil improvers derived from agri-food residues can be safely and effectively integrated into circular economy strategies. Strengthening the link between agronomic performance, environmental safety, and life cycle assessment would enable a more comprehensive evaluation of their sustainability and support the development of evidence-based management guidelines. However, most of the reviewed studies assessed the effects soil improvers only in the short term, typically within a few months after application, whereas long-term evaluations, extending over several years, were rarely conducted. This represents a critical gap in the current body of knowledge.

Future research should therefore prioritize long-term field trials to comprehensively evaluate the overall impacts, effectiveness, and sustainability of soil improvers over time. Moreover, addressing interactions between soil improvers and different soil types, climatic conditions, and cropping systems will be essential to better predict context-specific effects and support tailored application strategies.

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Data Availability All relevant data are within the manuscript and its supporting information files.

Declarations

Conflict of Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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