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Impact of the sustainable agricultural practices for governing soil health from the perspective of a rising agri-based circular bioeconomy

Ugo De Corato [a,*], Egidio Viola [b], Chetan Keswani [c], Tatiana Minkina [c]

[a] Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), Department of Bioenergy, Biorefinery and Green Chemistry (TERIN-BBC-BIC), Territorial Office of Bari, Via Giulio Petroni, 15/F, 70124 Bari, Italy

[b] Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), Department of Bioenergy, Biorefinery and Green Chemistry (TERIN-BBC-BIC), Trisaia Research Center, S.S.106 Jonica km 419 +500, Rotondella, Matera 75026, Italy

[c] Academy of Biology and Biotechnology, Southern Federal University, Stachki 194/1, Rostov-on-Don 344090, Russia

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ABSTRACT

Soil is a precious and nonrenewable source for agroecosystems of which own health state over time is becoming a focus of global concern. A healthy soil is a harmonious and very complex social system with a good structure, an optimal functional state, and an efficient buffering capacity to maintain a dynamic balance among all productivity factors. There is an urgent need to develop new approaches for the sustainable management of soil quality in depleted soils from a long-term perspective for increasing agricultural productivity and maintaining food security due to global population expansion. Since high crop yield mainly depends on the improvement of soil quality, further efforts must be addressed to develop advanced technologies/processes in reusing waste biomass accordingly with the circular bioeconomy principles. Although the knowledge of relationships between intrinsic factors of soil fertility and crop productivity is the baseline for the optimal soil management, this issue is nevertheless overlooked by stakeholders. Soil organic matter (SOM) associates carbon availability with the plant nutrients (mainly nitrogen, phosphorus, and potassium) leading to the strongest positive impacts of the environmental functions and food production. Unfortunately, there is a progressive trend to lose the SOM stock, so altering the biological functions of the soils. Despite, farmer overlooks the mechanisms for preserving SOM accumulation by adopting inappropriate practices to counteract soil decline consequently to climate change and deterioration of agroecosystems. A wide spread of microplastic and nanoplastic pollutants (MNPs) in the environment have added further concerns due to their potentially hazardous risks for soil health thanks to their ubiquitousness and persistence. Nonetheless, the interactions of MNPs with the soil components, microbial communities, plants, and fauna that could determine the strongest impacts on the nutrient availability and food security are still poorly explored. This review work launches some challenges to reader by providing practical solutions, viewpoints, future challenges, and new perspective for restoring soil health by contrasting soil decline from a long-term perspective in organic farming systems in a sustainable agri-based circular bioeconomy system.

1. Introduction

Authors defined a soil is "*A non-renewable resource and a harmonious social system with a good structure, an optimal functional state, and an efficient buffering capacity to maintain a dynamic balance among all productivity factors of the soil due to its ability to support biological activity and agricultural productivity by maintaining the environmental quality*", while a healthy soil as "*An ecosystem service characterized by adequate texture and structure; optimal physicochemical properties, moisture, porosity, and air/water ratio; suitable nutrient richness/availability/turnover; good microbial biomass, growth, and biodiversity; and high resilience to soil-borne plant diseases due to own natural suppressiveness*" (Coyne et al., 2022). Authors considered a healthy soil can "*A co-occurrence network of microbial communities that determine the evolution of soil organic matter (SOM) and macro- micronutrients through their primary and secondary metabolism*" (Zhu et al., 2017).

Soil gives multiple ecosystem services for sustainable systems that affect human health and allow agricultural productivity (Lambers and Cong, 2022). The maintenance of soil health over time is a global critical issue under the light of soil quality decline, food security need,

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* Corresponding author.
E-mail address: ugo.decorato@enea.it (U. De Corato).

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environmental issues, and emerging consequences due to climate change (Liang et al., 2015). Indeed, longer period of drought alternate with intense rainfall causes soil degradation up to reach intolerable levels of depletion in the world (Karlen et al., 2019). As soil scientists will meet such issues in the coming years, we can remember that soil degradation is mainly characterized by aridity, structure degradation, compaction, salinization, sodium accumulation, acidification, low nutrient content/utilization ratio, scarce turnover, low SOM stock or scarce humification degree, poor biological/biochemistry functionality, low microbial biomass per unit of organic carbon, high pollutant content, difficult to crop succession, and plant disease conduciveness (Fig. 1).

Soil health assessment is mainly addressed on measurement of simple indicators such as SOM content, water permeability and retention, exchange capacity, aggregate structure stability, biological and biochemistry activities, microbiota abundance and diversity, resilience to manipulation by agricultural practices, and plant disease suppressiveness (Wu et al., 2021). Regarding the primary role of soil biology, as well as the soil biological properties and biochemistry processes that lead to the sustainability in agroecosystems, there is broad consensus among the scientific community about these topics (Hermans et al., 2020). Since soil degradation is driven by many factors, two global strategies that integrate multilevel indicators based on the physicochemical and biological characteristics of the soil were recently implemented, the 'Comprehensive Assessment of Soil Health' and 'Soil Management Assessment Framework'. Nonetheless, it is still very difficult to achieve a real mapping of healthy soils for huge cropland areas (Wu et al., 2021).

As soil heath is becoming a topic of major global interest in the new era of decarbonization in terms of safety and sustainability, the greatest challenge of soil scientist is represented by its proper management which obliges stakeholders to share international/interdisciplinary research, to develop integrated technologies or processes, and to stimulate multilevel networks among scholars (Shen et al., 2020). Therefore, the management of soil quality by microbial assemblages and bio-indicators is becoming a global issue due to climate change, intensification of unsustainable agricultural activities, irrational use of chemical fertilizer, wide spread of intensive monoculture, and dramatic environmental episodes such as floods and landslides (Astudillo-García et al., 2019).

To reverse degradation process in contrasting the substantial threats due to climate change and global population growth, some new frontiers are considered the main drivers of soil science (Shen and Teng, 2023). The most recent studies based on the use of recycled residual biomass (organic fraction of municipal solid waste, green manure, agri-food waste, crop waste) including refined co/by-products (compost, biochar, digestate, and bio-organic fertilizer) were overall focused in enhancing over time soil suppressiveness against soil-borne plant pathogens (De Corato, 2020a, 2020b, 2023), as well as in giving practical solutions for reusing *in-situ* recycled biomass as soil improvers and plant stimulators in organic cycles (De Corato, 2020c). Particular attention was given to maintenance of soil health in agroecosystems disturbed by human activities for developing the global food supply chains (van Zanten et al., 2016), conversion of food waste to energy (Paritosh et al., 2017), and integration of biogas production into soil nutrient cycling in a climate change era (Koppelmäki et al., 2019). Despite, the role of biosolids (raw sewage sludge, composted sewage sludge, and anaerobic digestate from sewage sludge) as nutrient recycler and organic matter converter is still partially unexplored and often contradictory (Kanteraki et al., 2022). As well, the impact of the agricultural practices at the lowest inputs based on the principles of agriculture conservative and regenerative on crop diversity is poorly studied (Massawe et al., 2016). Also, the proper management of microplastic and nanoplastic pollutants (MNPs) in soil should be still strongly implemented within a circular economy framework (Keswani, 2021). Therefore, many problems have remained unsolved and much more research is needed to overcome them from the perspective of an agricultural bioeconomy (Keswani et al., 2023).

2. Aim of the work

Some issues are becoming the main drivers for ensuring a sustainable and profitable agriculture due to increased global population and food security requirement. Among them, severe soil tillage, massive use of chemicals (*e.g.*, fertilizers and phytosanitary agrochemicals), and extensive employment of no-biodegradable plastics are the main critical points for soil health in the sustainable management of advanced agricultural systems according to the agri-based circular bioeconomy

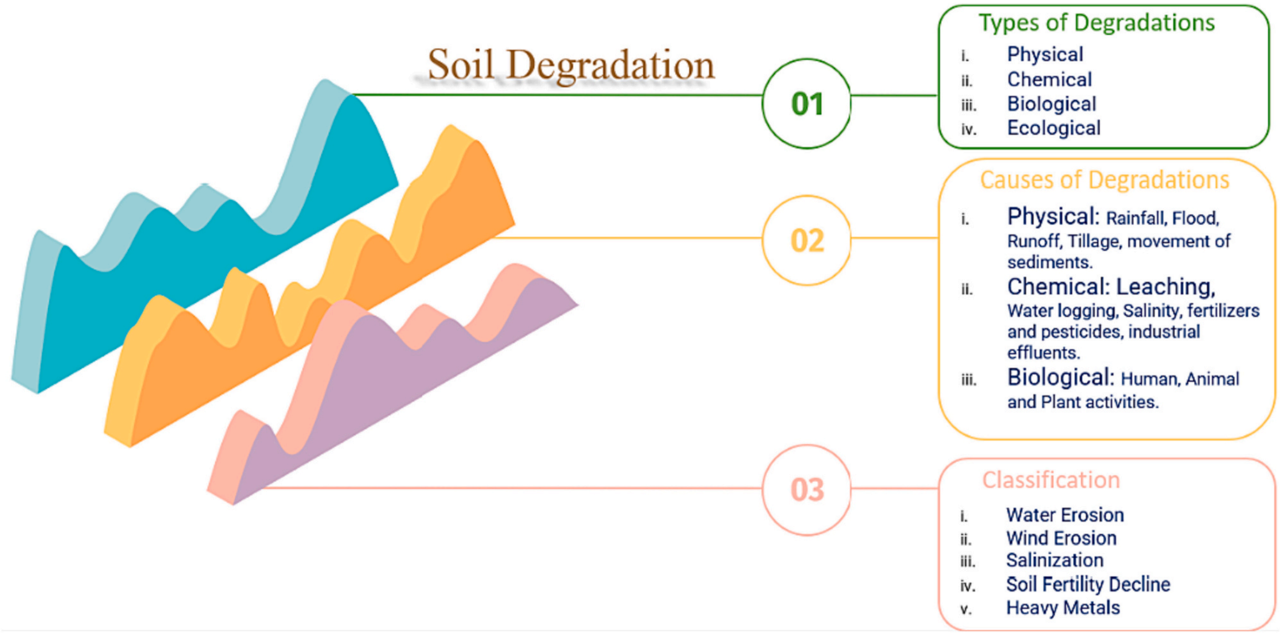

Fig. 1. Main factors, causes, and consequences of soil degradation in agroecosystems. [Original elaboration of the authors].

paradigms (Keswani, 2020).

The aspects covered by the present review work have probably filled some of these gaps, being derived from a logical consequence of issues described in the previous section of the paper. We think that it may be of interest for farmers and growers because it could represent an opportunity to launch new challenges and to critically discuss different viewpoints, often contrasting among them, for the implementation of a sustainable management of soil quality from the perspective of a sustainable agri-based circular bioeconomy. Indeed, three pillars were considered [(a) maintenance of soil intrinsic fertility over time, (b) prevention of SOM loss and restoration of SOC stock, and (c) management of MNPs] to restore a good soil quality level overall in organic farming systems.

3. Policies and strategies for contrasting soil quality decline from the perspective of a agri-based circular bioeconomy

A circular economy system is currently defined as "*An economic system that replaces the end-of-life concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes*" (Kirchherr et al., 2017). Suárez-Eiroa et al. (2019) postulated that "*a transition process from the utilization of virgin nutrients into nutrient recycling can be achieved only when soil nutrients are recirculated together with bioeconomy*". Three topics have driven the circular economy background (MacArthur, 2015; Muscat et al., 2021): (a) the preservation and improvement of the natural capital, (b) the optimization of the resource efficiency, and (c) the promotion of the efficiency of the system according to the circular economy paradigms.

The implementation of efficient agricultural models was aimed at reducing the impacts generated by traditional and no ecofriendly productive systems. This strategy emerged as a priority asset for the international political agenda in recent decades. In this context, organic farming was identified as a primary player in realizing '*Sustainable Development Goals*' outlined in the United Nations' Agenda 2030, as well as in the EU initiatives such as '*EU Green Deal's Farm to Fork*' or those contained in the '*EU Soil Mission*' program (Jander and Grundmann, 2019). Therefore, there is an urgent need to implement new strategies based on a circular bioeconomy approach for the sustainable management of depleted soils to improve agricultural sustainability (Muscio and Sisto, 2020). A model of circular economy optimizes the use of renewable resources and minimizes the generation of agricultural and agro-industrial waste. To obtain long-term sustainability, the opportunities that circular economy can offer to farmers are wider than those derived from the intensive cropping systems under greenhouse and plastic tunnel. Agricultural activity generates a significant amount of biomass waste in the forms of animal manure and slurries; unsold residual biomass from cultivated green residues, plant wastes, non-marketable products; agrowaste coming from the crop cultivation fields, and minimally-processed fruit and vegetable industries; food waste and agro-industrial by/co-products from the olives, grapes and milk processing. Thus, the most recent research focused on the valorisation of fruit and vegetable wastes as the main challenge to solve the logistic-related problems, as well as the management of the perishability and heterogeneity of such waste (Esparza et al., 2020). Furthermore, the increasing amount of disposable biomass waste from the agricultural activities, including agri-bioenergy co-products from the biofuel chains (De Corato et al., 2018) should be reduced, or even avoided rather than wasted, especially those coming from the greenhouse cultivation and warehouse processing. The management of renewable resources is challenge in a new era of decarbonization and fossil resource diminishment. The EU policies have launched agreements which lead to transition from a linear economy into a bio-based economy including investments in innovative and eco-friendly technologies based in reusing waste biomass. Bioeconomy overall includes the conversion of renewable bio-based waste from organic farming systems into diversified value-added co/by-products (*e.g.*, compost, digestate, biochar, bio-organic fertilizer). To achieve a resource-efficient biomass use, the European bioeconomy strategies increasingly consider the concept of a circular bioeconomy that identify strategies regarding the clusters' feedstock and product focus, and investigate what role biorefineries, nutrient circulation, recycling waste, and cascading co-products should play in future (Stegmann et al., 2020).

Soil quality is continuously threatened by the progressive deterioration of own intrinsic fertility due to SOM losses, scarce reintegration of soil organic carbon (SOC) stock, and massive accumulation of MNPs in soil. The "Green Deal" agreement of the European Union (EU) has designed news and sustainable models to solve, at least partially, these issues from the perspective of the new era based on green revolution (Pellegrini and Fernández, 2018). By starting from the recommendations given by the regulatory framework to maintain a good level of soil quality in agroecosystems, stringent global safety rules were increasingly imposed by the transnational Institutions, being mainly addressed to maintain a good soil quality over time by reduction of agricultural inputs for global lands and agri-food sectors (McElwee et al., 2020). The ecological transition essentially points to highlight the concept of circularity in the existing linear economy models by reducing the fossil sources in intensive cropping systems thanks to technological innovation that can replace it with eco-friendly and renewable bio-based products for the soil. The application of a circular economy strategy in the soil health management leads to reducing the use of hazardous chemicals from fossil sources in the agricultural production cycles to close the nutrient cycles, to minimize wastes, and to recover agri-food co-products (Toop et al., 2017). A circular economy system recirculates the nutrient flows and induces the SOM turnover by models of which nutrients were recruited among four production steps (plant growth, livestock farming, animal waste, and organic fertilizer) as happened in the sustainable management of an integrated agricultural-zootechnical system (Fig. 2) that reflects the economical, agricultural, and environmental sustainability of a possible circular model in each step by which we can draw that nutrient recirculation, SOM turnover, and carbon:nitrogen (C:N) ratios were notably increased compared to a linear model.

By re-placing linear economic models with the circular ones for the soil health management can be drawn valuable opportunities for increasing crop productivity, for contrasting soil quality decline, for reducing the dependence by fossil resources, and for minimizing the amount of organic waste including MNPs (Khan et al., 2021). New models of sustainable agricultural practices based on green circular economy should be implemented in next decades for restoring soil fertility to reach valuable levels of soil health in organic farming from a long-term perspective (Hidalgo et al., 2021).

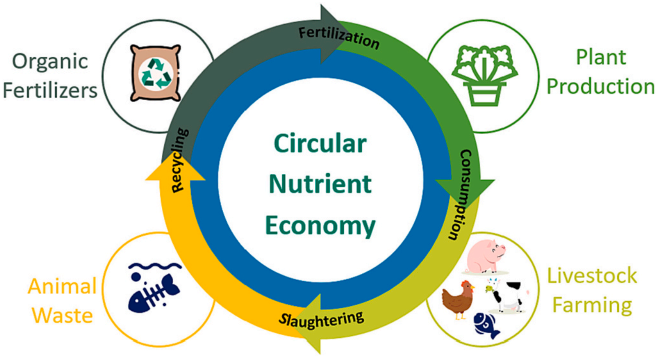

Fig. 2. A circular economy model where nutrients are recruited among four production steps (plant growth, livestock farming, animal waste, and organic fertilizer) in an integrated agricultural-zootechnical system.
[Adapted from Bhunia et al., 2021 according to the terms of the Creative Commons Attribution (CCBY) license (https://creativecommons.org/licenses/by-nc-nd/4.0/)].

4. Maintenance of soil intrinsic fertility over time

4.1. Background

Authors identified three main types of soil productivity that underpins agricultural sustainability: restrictive, available, and intrinsic (Zhang, 2023). The first one is influenced by environmental stresses and adverse soil conditions. The second one is supported by the contribution of chemical fertilizer. The intrinsic fertility is based on the synergistic effect of SOM, nutrients, aggregates, and microbiota that provide a suitable environment for plant growth with high buffering capacity and aggregate stability for increasing crop yield (Fan et al., 2013).

The massive chemical fertilizer supply and the incorrect management of agronomic practices in soil determined serious imbalances of the productivity factors with the consequent instability of the vulnerable soil system. Because as soil health deterioration increases as crop productivity decreases, is needed a good soil health state so that an optimal crop yield with high quality standards of harvested products can be sustained over time by the microbial formation of stabilized SOC that is more efficient from belowground than aboveground input (Sokol and Bradford, 2019).

In last decades, the maintenance of soil intrinsic fertility was overall aimed at manipulating soil microbiomes by rational use of agricultural resources (*e.g.*, conservative agriculture, organic farming, C-sequestration, co-occurrence of microbial network in amended soil, *etc.*). Particularly, relationships between biological indicators, soil health assessment, and crop productivity by elucidation of ecological and environmental functions have become challenge for understanding the roles and functions between Plant Growth Promoting Microbes (PGPMs) and soil nutrients. For example, assimilability of N in two rice varieties in Chinese cropland were studied by Zhang et al. (2019) that found how different PGPMs taxa were recruited between the “Indica” and “Japonica” varieties. The Indica-enriched taxa resulted more diverse than the Japonica-enriched ones since the first one included taxa overall related to N assimilation/fixation for the plant. Furthermore, Banerjee et al. (2019) investigated about the mechanisms by which soil conservative practices (*e.g.,* minimal-tillage, no-tillage and fallow) can regulate the SOM content and N conversion by reducing the microbial network complexity and the abundance of keystone taxa in roots. Liang et al. (2017) showed that long-term soil transplant significantly altered microbial temporal turnover and implemented a new theoretical framework toward microorganisms related to C sequestration during a simulation of climate change. Crowther et al. (2019) demonstrated that phylogenetic/functional ecological networks of soil microbial communities showed different pathways in response to environmental disturbance by shifting their microbiomes toward a fast nutrient turnover instead of slowing down the biogeochemical cycle of sodiun (Na), phosphorous (P), and potassium (K). Bünemann et al. (2018) find that the evaluation of soil health with respect to soil legacy, soil functions, and ecosystem services were rarely implemented since very fewer approaches have given clear interpretation schemes of the measured indicators. This strongly limits the adoption of proper land management in the countries by stakeholders, as well as incisive policies of soil recovery. Finally, undisturbed soil microbiomes were revealed as a promising strategy for contaminated soil remediation (Teng and Chen, 2019).

4.2. Impact of bioeconomy on soil fertility: state of the art

Since long-term (23-years, at least) application of compost and green manure have increased SOC accumulation and crop yield >2 and 7 times with respect to unamended soil, respectively, such practice results very promising (Xin et al., 2016). Exogenous inputs of organic matter accelerated SOC accumulation and promoted nutrient transformation and their availability for bacterial community (Li et al., 2017). Unfortunately, the accumulation process of humified SOM is too slow in natural agroecosystems and often incompatible with the advanced agricultural cropping systems, thereby representing the main limiting factor (bottleneck) for the improvement of soil intrinsic fertility. Nonetheless, some old strategies which have anticipated the paradigms of green economy are still usefully employed. Indeed, by combining wheat straw soil return with green manure soil addition in no-tillage or minimum-tillage croplands, the intrinsic soil productivity was improved by the increase of SOM stock. The abundant supply of SOM through fast decomposition of cereal straws combined with long-term manure application has stimulated microbial activity and preserved soil structure in Chinese croplands (Ma et al., 2021). As well, soil return of leguminous manure triggered decomposition of exogenous organic material and increased the SOM content in a peanut and arbuscular mycorrhizal fungi system with the application of hairy vetch (Xiang et al., 2022). Long-term application of manure and green waste stimulated the growth of some useful bacteria such as *Bacillus* spp. and *Pseudomonas* spp. or fungal genera belonging to *Mortierella* spp., and *Trichoderma* spp. more than others taxonomic groups, thereby becoming the dominant taxa related to accumulation of SOM in promoting plant growth (Feng et al., 2015; Li et al., 2018). Legume-barley intercropping stimulated soil N supply and crop yield in the succeeding durum wheat in a rotation under rainfed conditions, thereby showing promising perspectives in improving the intrinsic soil productivity (Scalise et al., 2015).

Because bioeconomy might impact on intrinsic soil fertility by recovering and recycling biomass into new production cycles, this strategy should be further implemented to reach the objectives of a virtuous re-use of organic agricultural and agro-industrial wastes and co-products into many cropping systems (Pergola et al., 2018a). However, a circular agriculture model should be always designed and adopted after a preliminary analysis by which the specific features of the area of study must be previously defined to identify all the aspects that can be improved by the assessment of the different alternatives in accordance with the preferences and interests of stakeholders (Pergola et al., 2018b, 2020).

4.3. Impact of bioeconomy on soil fertility: challenges and perspectives

Although there are many agricultural practices that can contribute to improve the circularity models of a sustainable agriculture, nevertheless the production and use of tailored compost and bio-organic fertilizers from agrowaste, agricultural residues, and agro-bioenergy co/by-products can be a very promising change of perspective by transforming wastes into high quality co/by-products to improve soil health whenever the SOM content results very low (<1 %) or scarcely humified (Sayara et al., 2020). As regard, scientists proposed some innovative solutions to speed up SOM accumulation by complementing and integrating the key pathways based on the knowledge of the mechanisms underlying evolution of SOM using value added co/by-products from agrowaste. From these studies we can draw three main ways to meet the increasing food demand of the world population with a proper management of depleted croplands from the perspective of a circular bioeconomy.

A first way has stimulated soil application of manure as cattle, swine, and poultry to restore soil health. Long-term soil amendment of green manure as rice straw associated to compost and mineral fertilizer has notably improved the soil physical properties and the C balance point in Chinese croplands due to high C:N ratio of rice residues (Xin et al., 2016). Application of manure has the potential to enhance soil health by increasing the SOM content and to stimulate dormant soil-borne microorganisms. However, this strategy could also determine the serious risk of the invasion and spread of manure-borne pathogens because manure could pose a greater risk of microbial contamination in soils characterized by low microbial abundance and scarce activity (Zhelezova et al., 2024). Nonetheless, green manures were tested in intensive cropping systems for suppressing soil-borne plant pathogens as Pythium damping-off on cucumber (Manici et al., 2004). Soil application of green manure from *Brassicaceae* residues should be considered for their biocidal effects due to the highest content of glucosinolates and their derivatives co-products (*i.e.,* isothiocyanates and an array of other secondary metabolites). Bio-fumigation of brassicaceous residues was extensively used in last decades for controlling plant parasitic nematodes (Ntalli and Caboni, 2017) and the vascular fungal pathogen *Fusarium oxysporum* (Ren et al., 2018; Siebers et al., 2018) in horticultural nursery thanks to emission of volatile organic compounds (VOCs) coming from the breakdown of glucosinolates mediated by the myrosinase-hydrolysis enzymatic complex in the soil (Mazzola et al., 2001; Mazzola and Brown, 2010; Wang and Mazzola, 2019). Although VOCs resulted be toxic for the pathogen, any influence on the suppressive property of the fumigated soil was found (Motisi et al., 2010). Thus, brassicaceous residues should not be promoted as a good mean for increasing SOM into a circular bioeconomy system, but rather as a suitable tool of suppression against certain plant pathogens and/or plant parasitic nematodes by soil bio-fumigation carried out in greenhouse or tunnel under controlled environmental conditions (Gabler et al., 2006). In consideration of their dry weight greatly lower than cereals and many other crops residues, brassicaceous crops can be proposed in a circular system only to increase biodiversity in intensive cropping systems within specific rotation cycles rather than to increase the SOM stock in open field (Wang et al., 2012).

A second way has developed soil application of tailored compost and bio-organic fertilizers based on compost artificially enriched with selected microbial consortia or specific microbial strains having biostimulating effects on native soil microbiota (Ruano-Rosa and Mercado-Blanco, 2015). By promoting long-term use of tailored compost and fortified bio-organic fertilizer can be provided stabilized SOM and specific microbial consortia that drive the main evolution processes of the SOM (Costantini and Lorenzetti, 2013). The main effects of such microbial consortia on soil health overall regard: (a) acceleration of the SOM transformation and turnover, (b) stimulation of the soil microbiota activity, and (c) adjustment of the C:N ratio (Scotti et al., 2015). To active biological activity of soil microbiota and to increase nutrient availability, bio-organic fertilizer should be applied to soil before cereal residues during the amendment planning because *Graminaceae* crops have too high C:N rate for reaching a proper humification degree of the SOM. Indeed, crop residues which have too high C:N rates (cereals) need of proper stimulators before their soil application to stimulate biological activity of microbiota and nutrient turnover. For instance, soil co-incorporation of rice straw and leguminous green manure increases N availability and reduces C losses when compost-based bio-organic fertilizer was added (Zhou et al., 2020). Bio-organic fertilizers are also suitable means for the regulation of the nutrients ratio in soil in preventing the fast decomposition and mineralization of SOC. We should consider that the maintenance of higher microbial activity in amended soil than the unamended ones can drive decomposition and further evolution of organic molecules as humic acids and umina that can significantly contribute to accumulation and stability of SOM stock over time due to the diversity and co-occurrence network modularization of bacterial communities that determine soil fertility and crop yield (Ye et al., 2021).

A third way has valorized soil application of value added co/by-products coming from the bioprocessing of agrowaste for supplying the biofuel chains based on the production at industrial level of ethanol, biodiesel, biohydrogen, and biometane (Riazi and Chiaramonti, 2018). Among them, digestates coming from the anaerobic digestion of sewage sludge (Toscano et al., 2013; Arizzi et al., 2016) have resulted as a valid alternative/integration to composts in the production of tailored soil amendments for increasing soil fertility (Bianchini et al., 2016; Kanteraki et al., 2022) after remotion of the toxic metals (Camargo et al., 2016). Again, oil-less co-products (seed cake, meal, and pellet) coming from the *Brassicaceae* oleaginous crop bioprocessing for the biodiesel chain (*i.e., Camelina sativa*, *Brassica juncea*, and *Sinapis alba*) have biocidal properties in increasing soil suppressiveness to plant pathogens by manipulation of the soil microbiomes (De Corato, 2021). In addition, agrowaste that can be used as raw material to produce biochar (*e.g.*, paddy straw, wood, shells, sugarcane trash, algae, coconut fonds, sewage sludge, poultry waste, and animal manure) by pyrolysis carried out at low temperatures, low heating rates, and with a very short residence time, may be considered as further option to recycle such residual biomass. Biochar is beginning to be utilized in agriculture only in the last years due to the lack of understanding on how it drives soil quality, on the technical issues related to the optimization of the pyrolysis parameters for each source material, on the cost involved in biochar production, and on the quality of the feedstock required (Agegnehu et al., 2017). Application of biochar to soil was experimentally tested and proven to have a positive effect on crop productivity in wheat, bean, cucumber, sweet pepper, tomato, and strawberry whenever biochar was used as manure either directly or after composting with other organic manures. At present, it is used only in controlled cultivation technology like greenhouses and poly houses for vegetable and floriculture, unless it is considered for the control of plant pathogens (Sneha and Babu, 2023). Thus, biochar application as soil amendment in agricultural fields on a large scale is still strongly limited. However, there are others residual biomass typologies based on the bioprocessing of fruit and vegetable waste (Esparza et al., 2020) and food waste such as wasted bread, spent coffee ground, and brewers' spent grains that could have a very interesting perspective as soil improver so long as they were previously composted or however properly conditioned in the farm before being used to fertilize the soil (Paritosh et al., 2017). Now, we can also mention and discuss the bioprocessing of animal manure, a biomass simpler than compost, biochar and digestate, for its reuse as soil improver by using specific microorganisms alone or associated among them into *ad-hoc* consortia. For instance, pig manure can be converted into tailored bio-based fertiliser by stripping, scrubbing, liquid-solid separation and bio-drying, besides anaerobic digestion, pyrolisis and composting (Luo et al., 2022). At this regard, the H2020 EU project FETIMANURE (Innovative nutrient recovery from secondary sources – Production of high-added value fertilizers from animal manure, Grant Agreement No. 862849) was aimed at developing the most advanced nutrient management strategies in recovering nutrients (overall N) and other by-products (minerals) of relevant agronomic value from several animal manures (i.e., pig, poultry, and cattle) within the REcovered Nitrogen from manURE (RENURE) fertilizers category (Saju et al., 2023). This is a subcategory of tailored bio-based fertilizers recently proposed by the EU Directives of which their production chain was described by using *ad-hoc* microbial consortia as specific bioinoculants based on bacteria belonging to the *Azospirillum*, *Ensifer*, *Lactiplantibacillus* and *Rhizobium* genera and fungi of the *Trichoderma* and *Rhizophagus* genera (Herrera et al., 2023).

Considering these three scenarios, soil application of green manure, on-farming green compost and bio-organic fertilizer, biofuel value added co-products, digestate, and biochar can play a key role in circular economy toward the best environmental sustainability of organic cropping systems by transforming residual biomass into profitable resources. Production of high-quality composts and their derivative products such as compost teas and humic substances represents one possibility for exploiting richer and marketable sources of eco-friendly organic molecules and beneficial microorganisms from agricultural wastes whenever co/by-products can become available over time (Scotti et al., 2016). These authors lead on how such recycled biomass waste could be a formidable tool either to reduce organic residuals or to guarantee the supply of humified C, N, P, minerals, and beneficial microbial consortia associated to soil health. Soil supplementation with on-farm green compost and bio-organic fertilizer represents one among the best agronomical practices for their benefits on soil health. Moreover, on-farm composting has more environmental benefits than the industrial ones, from the lowest greenhouse gas (GHGs) emissions in the atmosphere to the lowest leachate generation when compared to landfilling and anaerobic digestion (Viaene et al., 2016). Authors focused on the improvement of soil fertility once compost is applied in a tomato cropping system and on the overcoming of concerns due to compost application when it exceeded the recommended application rate (Pane et al., 2015). The success of these strategies is based on knowledge of the mechanisms, interactions, and effects between the soil microbiota manipulation to speed up the SOM accumulation process and the improvement of soil fertility and crop productivity correlated with the variability of the production factors that characterize soil health (Xiong et al., 2020). To improve soil health and crop yield, the understanding on how microorganisms can interact with plants and among themselves in the natural soil systems through their rhizosphere microbiomes and phytobiomes, respectively, could be used to address the correct manipulation of the microbiota, either directly or indirectly (Berg and Smalla, 2009; Compant et al., 2010; Singh et al., 2011; Vannier et al., 2019). If is true that the microbial community and the root system are closely connected, they can be manipulated by adding tailored amendments as microbiome disturbance through the sustainable management of the agricultural resources that minimize the negative impact of pathogens can develop novel microbiome patterns. From this framework, the proper management of biotic and abiotic soil indicators that promote the activity of beneficial microbiota is challenge for the sustainable agriculture. In the complex soil system, it is possible to reconsider diversified approaches with a potential improvement of optimized microbial inoculants and microbiomes by bio-engineering strategies for enhancing crop yield and environmental sustainability in the field (Bender et al., 2016; Ram et al., 2018; Qiu et al., 2019). In this context, Rabelo de Faria et al. (2020) find that the main manipulation strategies and related drivers in assembling beneficial communities for the plant productivity has resulted in the dynamic changes of beneficial microbial communities. Such microbiota can be influenced by the interactions among the soil amendment with compost and soil moisture. Plant diversity in the space (intercropping) or in the time (crop rotation, cover cropping) can also drive beneficial shifts of the rhizosphere microbiomes (Liu et al., 2007). From a long-term perspective, the cause/effect relationships among soil fertility and organic amendment will be studied with long-term experiments and under different conditions and climate areas to reach valuable advancements in recovering soil fertility and in increasing crop productivity without damaging soil health.

In conclusion, the continuous maintenance of nutrient balance with long-term application of tailored organic amendments remains the main challenge to maintain the soil intrinsic fertility over time given the great amount of potentially recyclable lignocellulosic biomass produced in the world (Ullah et al., 2015). Furthermore, the emerging omics and metabolomics technologies applicable to the study of microbial communities of the manipulated soils by the agricultural practices to maintain the soil intrinsic fertility over time could be of great help in supporting the researchers (Scotti et al., 2020).

5. Prevention of SOM loss and restoration of SOC stock

5.1. Background

Already at the beginning of the 20th century Snyder and Marcille (1941) predicted reduction of SOM stock after just 15–20 years from the conversion of natural lands (woodland or grassland) into croplands, much earlier that farmer began using pesticides, heavy plowing, widespread mineral fertilization, and genetically modified organisms. Swanson and Latshaw (1919) demonstrated that the SOC losses were estimated under different climatic conditions up to 30 % in topsoil (0–20 cm soil layer), ranging from 27 % in semiarid climate to 33 % in humid climate; and 6 % in subsoil (20–50 cm soil layer), ranging from 1 % in semi-arid climate to 11 % in humid climate conditions; after just few decades from the conversion of abandoned lands into fertile croplands. The SOC losses in France were associated with the increased difficulty of soil tillage due to compaction and erosion of the soil (Hénin and Dupuis, 1945).

It is well known that global warming and incorrect agricultural practices can determine soil degradation and depletion of the SOM stock by inducing progressive reduction of crop productivity, increase of environmental issues, and more else damages to humans and animals at the global level (Fig. 3). After many years of underestimating of the SOM loss, soil scientists are today seriously concerned by bringing it back to the core of their research topics under the light of the increasing erosion, aridity, pollution, and climate change. Since SOM loss in healthy soil resulted in the emission of significant amounts of carbon dioxide (CO_2) into the atmosphere, thus contributing to climate change, has been suggested that the storage of the SOM stock would be the smartest and most efficient way to mitigate land degradation. For instance, good agricultural practices were promoted in France for increasing the C stock in the soil by 0.4 % per year to offset CO_2 emitted from fossil fuels (http://4p1000.org). Obviously, to propose solutions, soil scientists should first identify the causes of the SOM loss before to restore the C stock in a lasting way (Lal, 2004). Severe tillage operations, being considered in the past years as the only practice available for weed control (before the advent of herbicides) and seedbed preparation (before the use of conservative agronomic practices), were highlighted as the first responsible for the oxidation of the SOM stock (Snyder and Marcille, 1941). In order to immobilize greater amount of nutrients for promoting microbial activity and for making stable macroaggregates, accumulation and maintenance over time (for 20-years, at least) of adequate levels of humified SOM is a crucial issue for the agricultural sustainability (Zhang et al., 2015).

5.2. The key roles of SOM, microbial biomass, and biodiversity on soil health

On-farm recycling of straw, crop residue, green waste, agri-energy waste, sludge, animal excreta, and municipal bio-organic solid waste was a very suitable option to enrich the soil of C, N, P and K and micronutrients (Ca, Mg and Fe) to fertilizin the crops (Hidalgo et al., 2021). The use of tailored organic amendments in agriculture, being the final segment in a circular approach (Ruano-Rosa and Mercado-Blanco, 2015), should be properly implemented by inferring additional experiences and data from the literature largely available on this topic. Thus, it appears useful to briefly discuss the key roles of SOM, microbial biomass, and biodiversity on soil health.

SOM is the main component that drives soil health in supporting soil microbiota activity based on the total C content and its humification degree under qualitative and quantitative point of views (Manici and Caputo, 2010). A review on the indicators that characterize a healthy soil has classified SOM as a chemical component among the abiotic factors (Etebu and Osborn, 2012) because soil macrobiota usually account for <5 % of the SOC (Stevenson, 1994). Soil microbial biomass represents the fraction of topsoil and rhizosphere responsible for the energy source, nutrient cycling, and regulation of the SOM evolution (Gregorich et al., 1994; Turco et al., 1994). Microbial communities play a crucial role in the acquisition and recycling of nutrients required for maintenance of soil structure, degradation of pollutants, and biological control of plant diseases, as well as the sustenance of soil health, plant growth, and crop productivity (Hill et al., 2000). Nutrient recycling and organic matter decomposition are allowed by soil microbiota that is largely concentrated in topsoil. Microbial communities constitute the first line of soil inhabitants as a potential bioindicator of soil health that change under the pressure of soil microbiome disturbances determined by long-term organic matter supplementation (Pankhurst et al., 1995). Since microbial biomass is a measure of soil health and although soil microbiota constitutes a very small fraction of the total SOM, the organic matter decomposition and N mineralization rate is directly correlated to microbial biomass of topsoil and to rate at which organic matter decomposes (Carter et al., 1999). Soil biodiversity is another driver for the stability of living community inhabiting the soil that could be a measure of variability among soil biota. This includes diversity “within species” and “between species” of an ecosystem (Nielsen and Winding, 2002).

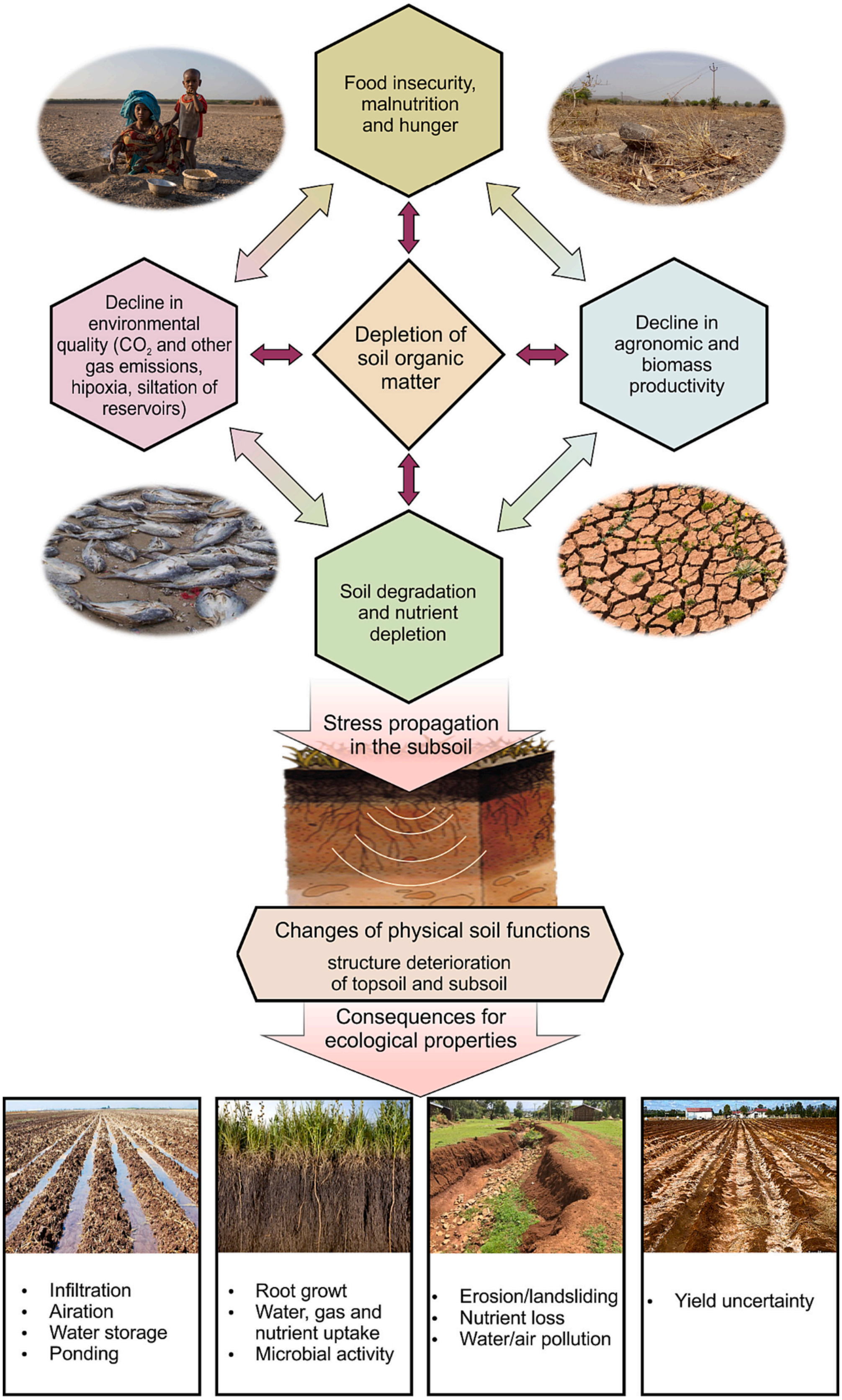

Fig. 3. Soil degradation by the SOM loss on food safety, biomass productivity, environmental quality, and nutrient availability (on the top). Potential impacts on soil quality (on the bottom).
[Original elaboration of the authors according to the terms of the Creative Commons Attribution (CCBY) license (https://creativecommons.org/licenses/by-nc-nd/3.0/)].

Since 1960s the first studies on the biodiversity of the plant and animal communities began, and microbiologists began to investigate the impact of the biodiversity on the functions and structures of microbial communities in ecological niches of aquatic environments drawing useful information on the microbial diversity (Swift, 1974). A case-study in Brazil pointed on the formulation of the "*Diversities International Research Program*" in 1991 and the "*Biodiversity Treaty*" that was issued from the United Nations Conference on Environment and Development in 1992. These institutional initiatives promoted scientific programs toward the origin and conservation of soil biodiversity and the impacts of biodiversity on the ecological functions (Colwell, 1996). Closely linked to the term of "biodiversity" is the different concept of "resilience". Ecological resilience was defined as the disturbance magnitude of an ecosystem that could withstand without altering self-organized processes and structures. This term, nowadays most used and abused in the EU policies, was first introduced into ecological parlance to explain the non-linear dynamics observed in ecosystems (Holling, 1973).

5.3. Impact of bioeconomy on the prevention of SOM losses and restoration of SOC: state of the art, challenges, and perspectives

The current use of regenerative practices based on minimum-tillage, zero tillage, and fallow in preventing natural resources loss should be strongly encouraged by the transnational policies for nutrient recycling (Valve et al., 2020). Authors demonstrated the benefits of zero tillage for the SOC storage in the whole soil profile (from its surface to bedrock, or at least at one meter depth), thereby confirming that zero tillage promotes accumulation of SOC in the superficial layers of soil profile which is compensated by the SOC losses in the deeper layers by soil C sequestration (Baker et al., 2007; Lu et al., 2010). Besides, Liang et al. (2020) demonstrated that irrigated areas of Canada do not store additional SOC, while non-irrigated grasslands accumulated SOC at the rate of 740 kg ha^{-1} $year^{-1}$ due to SOM development by microbial biomass. Ogle et al. (2019), studying the C storage in soils, concluded that abandoning cultivation or minimizing tillage carried to efficient C sequestration, accumulation of SOC in topsoil, and mitigation of GHGs emissions because can be reduced erosion which makes SOM most vulnerable to the losses.

Another strategy for avoiding the SOM loss may be suggested the reconversion of cultivated lands to pasture. For instance, intensive and extensive food crops may be moved from the depleted soils toward more fertile croplands in the same area where pasture could be practiced to their place. Although such solution is right, nonetheless it is practically impracticable particularly in the territories where intensive agriculture is usually practiced because farmers should be economically restored by the financial supporter due to a lack of income that occurs for not cultivating their fields. Otherwise, promoting the reforestation of degraded/marginal soils in many cultivated areas of the world has led to significant increases of the SOM stock, thereby favoring rain infiltration and resistance to erosion. Indeed, we can suggest the afforestation with fast growth woody species (short rotation forestry) for a consistent biomass production (poplar) after short cultivation cycles, a strategy more practicable than the previous one that however increases the soil quality of depleted lands after short-term time (Guo et al., 2021).

Cover cropping can reduce the nutrients losses caused by soil erosion if combined with a balanced soil nutrition with mineral fertilizer and organic matter. Particularly, cover cropping is strongly suggested as an efficient mean of keeping wheat grain production up to acceptable levels restoring the SOC stock at the same time. However, the recent literature is lacking on this topic as very few papers were published about this issue. Poeplau and Don (2015) have reported in a meta-analysis on C sequestration in agricultural soils that SOC meanly increased by 0.35 t ha^{-1} $year^{-1}$ with an overall median of 0.1 t ha^{-1} $year^{-1}$ in topsoil (between 5 and 30 cm) in 37 sites monitored, while a decrease in SOC stock was observed in 13 sites. Abdalla et al. (2019) reported in a critical review on the impacts of cover crops on N leaching, net greenhouse gas balance, and crop productivity an increase in SOC of 0.54 t ha^{-1} $year^{-1}$ in average in 43 sites by which 8 resulted very poor in the increase of SOC (between -0.1 and 0.03 t ha^{-1} $year^{-1}$). Therefore, such SOC recovery strategy appeared be much less promising than those expected.

However, if we assumed that the agronomical practices that had the greatest impact on the SOC loss in croplands (*e.g.*, deep tillage, absence of cover crops, and use of pesticides, mineral fertilizers, and heavy plowing, *etc.*) were absent at the end of the 19th century, what other factors may have contributed to the SOM losses? We can find as a plausible response in the massive removal of nutrients by the crops. Indeed, Chatzav et al. (2010) indicated that a grain yield of 7 t ha^{-1} $year^{-1}$ given by a winter wheat cultivation can remove up to 2.9 t ha^{-1} P, 3.3 t ha^{-1} K, 0.26 t ha^{-1} calcium (Ca), and 0.9 t ha^{-1} magnesium (Mg) in 100 years. This means that P uptake is 153 times higher in a deciduous forest and 34 times than of a pasture for beef meat production, while K uptake is between 18 and 23 times and Mg uptake is among 19 and 90 times higher, respectively. Nutrient removal from the soil into the plant occurred because plant selectively recruits soil bacteria through the selective action of their root exudates to acquire the necessary assimilable nutrients in easy manner by SOM degradation (Crecchio et al., 2018). Kallenbach et al. (2016) instead indicated that plant has a recruitment system for beneficial soil bacteria (PGPMs and rhizobacteria) to mineralize phospholipids, nucleic acids, and other organic molecules from the SOM stock. Such microbial consortium provides the needed P for plant, thereby resulting indirectly responsible for the SOM losses and release of C into the atmosphere.

Early 20th century scholars already knew how to reverse the trend of the SOM losses by adding decomposed green manure as a soil amendment which supplies nutrient without acidifying the soil, as well as the benefits given by clover crop which draws nutrient from the atmosphere by rhizobia and accumulates N in the deeper layers of the soil (Hossain et al., 2017). As previously outlined, the exogenous C inputs stimulate and accelerate the soil microbiota activity by influencing evolution of SOM (Zhao et al., 2016). For instance, fertile croplands turned into uncultivated soils were subjected to continuous removal/degradation of the SOM stock which causes progressive soil depletion in semi-arid lands of the Southern Italy. However, continuous soil application of composted sewage sludge for 3-years, at least, has restored its original fertility by changing the microbiota structure and physicochemical properties of the amended soil (Curci et al., 2020). Furthermore, the supply of organic material facilitates the formation of macroaggregates and promotes the intrinsic productivity of the soil (Peng et al., 2017). The fast decomposition of organic matter by living organisms provided by long-term application of organic manures and mineral fertilizers given sufficient humic substances, increased the SOM content into microaggregates, silt and clay, and strengthen the bond strength thus better protecting soil structure (Yu et al., 2012). Nonetheless, more weaknesses must be highlighted before spreading soil organic amendment using residual biomass as a current practice (Viaene et al., 2016). This is mainly due to: (a) high heterogeneity about the nature, origin, and composition of the raw starting materials for processing soil amendments; (b) lack of experience of farmer that usually underlines a little knowledge of the regulations framework for on-farm composting and digestate/sludge application; (c) complex EU regulations and a stringent/diversified legislation framework; (d) market competition between organic amendments (compost, biochar, green manure, sludge, digestate, co/by-products from the biodiesel supply chain and sewage sludge) *versus* mineral fertilizers; (e) too expensive processing for the bio-stabilization of compost, sludge and digestate; (f) uncertainty on short-term profitability benefits as the most frequent farmers' perception is that the on-farm composting costs and related compost application is higher than the costs of applying conventional fertilizers; and (g) high cost for farmer to monitor the physicochemical features of organic amendments, the chemical contaminants, the microbial indicators, the absence of food-borne pathogens loads, and the heavy metals content that could exceed the legal limits for agricultural purposes.

However, Kirkby et al. (2014) found that nutrient availability limits C sequestration in arable soils by concluding that the SOM stock is more easily formed rather than lost when the soil organic input meets the proper nutrient ratios needed by bacteria community. Since C amount added into topsoil by crop residues generally exceeds the bacteria requirements, Fontaine et al. (2007) assessed that 1 t wheat straw should be supplemented with 5 kg N, 2 kg P, and 1.4 kg sulfur (S) to avoid the SOM loss during its decomposition. Soil nutrient unavailability or their imbalance may explain the observed differences in increasing the SOM efficiency between reduced tillage and cover cropping (Poeplau et al., 2016). Again, the SOM losses resulting from the nutritional deficiency or imbalance among nutrients can be counteracted by addition of green manure, compost, biochar, digestate, and crop residues combined with mineral fertilizers (for example, 20 kg N, 10 kg P, 5 kg K and 10 kg S) during the crop cycles (Chaplot and Smith, 2023).

Because there is still a large gap between actual and potential crop yields, the development of circular bioeconomy models is aimed at overcoming these issues in degraded soil minimizing the depletion of soil resources and promoting the natural soil nutrient return and its turnover (Bhunia et al., 2021). From a long-term perspective, a rationale strategy with significant effects requires more else trials in field of 3-years, at least, in different experimental conditions and areas. The impact of cover cropping, tillage suppression, crop choice, crop rotation length, and intercropping on SOM accumulation needs to be studied in-depth by considering the different soil nutritional states and the continuous change of the environmental conditions.

6. Management of plastic-based pollutants in the soil

6.1. Background

The consequences of plastic accumulation in ecosystems are one of the greatest current environmental concerns. Global plastic production has grown massively to reach 368 million tons in 2019, with primary plastic projected to reach around 1.1 billion tons by 2050 (Plastics Europe, 2020). MNPs are hazardous bio-composite nanomaterials recognized as an increasing global threat due to their ubiquitousness in all ecosystems and high persistence in the food chain, drinking water, soil, and air with potential impacts on soil health (Rillig and Lehmann, 2020; Feng et al., 2022b). The extensive use and inappropriate management of MNPs spreads in agroecosystems many typologies of pollutants as conventional fibers, micro-fibers, biodegradable plastic films, and rubber with a diameter limit >5 mm (Cao et al., 2021; Luo et al., 2021). Soil has become a true storage reservoir of MNPs that contains from 4 to 23 times the MNPs stock of those oceanic (Horton et al., 2017). Thus, soil pollution by MNPs has raised increasing concerns about soil health and carbon neutrality in agroecosystems (Luo et al., 2023). This issue is really very difficult to evaluate because many factors such as abundance, polymer type, shape, and size of MNPs are becoming the main players in the different regions and countries of the world regardless of their use in agricultural, industrial, urban, abandoned soil, *etc.* For example, recent estimates calculated that the abundance of MNPs meanly ranged from 2462 to 3767 kg per MNPs item in agricultural soils of the mainland in China as a direct function of their recovery method, plowing frequency, meteorological conditions, and soil properties (Chen et al., 2022b). Therefore, soil accumulation of MNPs beyond a certain limit can lead to significant impacts on paddy soils, relevant functions, and ecosystem services (Feng et al., 2022a).

Contamination of terrestrial environments by plastic material has been guilty overlooked in the past years, with a very relevant study number mostly focused on the contamination and impact of aquatic environments. Scientific evidence has clearly showed that plastics are hazardous contaminants widespread in agricultural soils as they can be present in the form of microplastics and nanoplastics due to their disaggregation state caused by weathering processes (Fig. 4). This issue is related to petroleum-based plastics and composite bioplastics that can reach the agricultural soils if they are not properly disposed, treated, and managed. The fate and impact of microplastic and nanoplastic contaminants into the soil are still partly unknown, being reported in the literature the effects on the plant physiology, soil physicochemical properties, microbial diversity, and activity of soil microbiota and mesofauna, as well as the interactions with pesticides and heavy metals. Management of MNPs could also be contextualized within a most general risk screening model that includes four steps (pollutant, migration, pathway, and people) (Fig. 5).

Relationships between MNPs and soil colloids can induce changes in the MNPs properties, soil fertility, and availability of these pollutants by posing a potential threat to soil health, crop productivity, and food security. Furthermore, biodegradable MNPs may influence GHGs

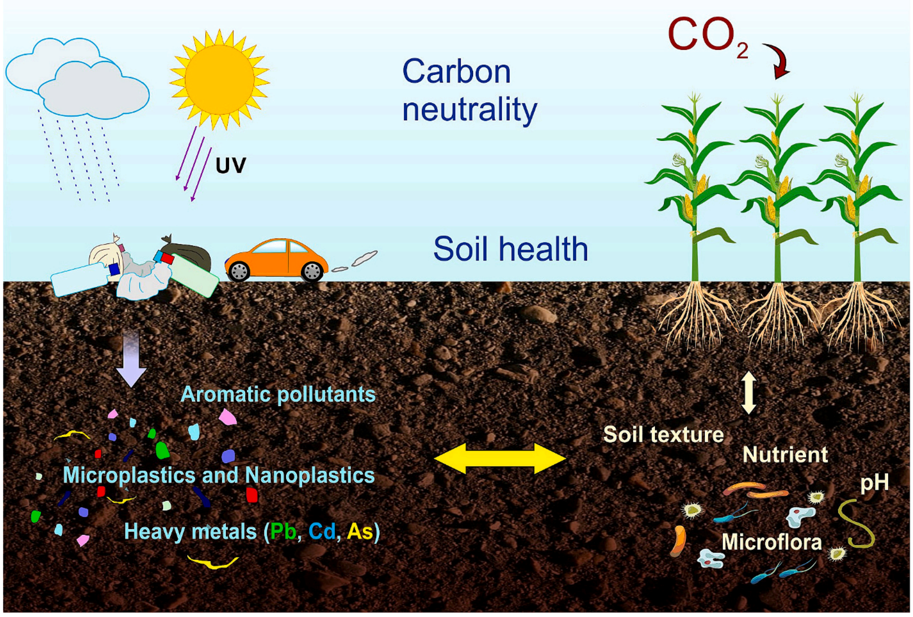

Fig. 4. Fate of microplastics and nanoplastics in soil.
[Adapted from Luo et al., 2023 according to the terms of the Creative Commons Attribution (CCBY) license (https://creativecommons.org/licenses/by-nc-nd/3.0/)].

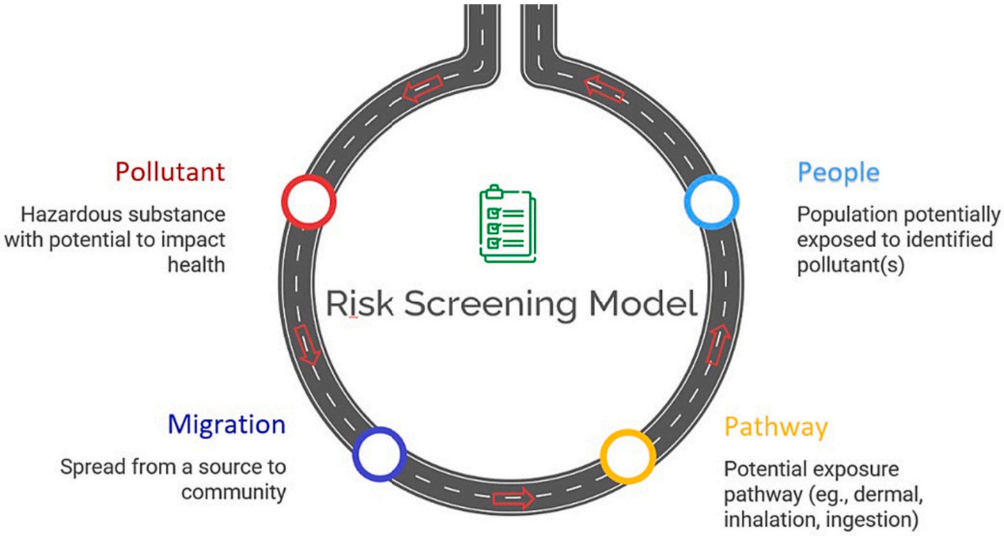

Fig. 5. A general risk screening model for the management of microplastics and nanoplastics in polluted soil. [Original elaboration of the authors].

emissions eventually leading to uncertain consequences on climate change. Although MNPs can modify the physicochemical and biological properties of soils, as well as animal survival and plant growth, nonetheless their impacts on the polluted soils can vary with the polymer type, shape, dose, size, source, soil pH, temperature, and sunlight. A meta-analysis based on 32 studies documented that microplastics has negligible impact on the water-soluble SOC and available phosphate, nitrate, and ammonium content, as well as on the crop growth, but their accumulation in soil tends to decrease the content of stable macroaggregates in water ($>$ 0.25 mm) and to increase the abundance and diversity of soil microbiota (Li et al., 2022). On the other hand, the physicochemical and biological properties of the soil, as well as its own macro- microbiota structure, can modify the characteristics of MNPs either through the mechanical action of iron oxides that induce abrasion and fragmentation of MNPs due to wind and rainfall or with the metabolic activity of algae, protists, fungi, actinomycetes, and bacteria. Such factors can interact with the MNPs surface by decreasing the amount of organic C and weakening the MNPs structure adding oxygen molecules, functional groups, radicals, and minerals capable of altering the physicochemical properties of MNPs (Chen et al., 2022a). Interactions between MNPs and soil colloids can also influence water uptake, nutrients transport, additives release, and transformation of MNPs in the soil. Indeed, soil can absorb organic and inorganic pollutants and influence the vertical distribution of these substances along its profile. In addition to this, the horizontal and vertical migration of MNPs can also be facilitated by mechanical action exerted by soil fauna that causes further dispersion of MNPs in the soils (Xu et al., 2020).

Accumulation of nanoplastics in the plant *via* root system has both direct ecological effects and indirect impacts on agricultural sustainability and food security. This depends on the polymer type, size, shape, dose, and surface charge or pH, SOM, ionic strength and aggregate stability, soil macrobiota, and crops (Iqbal et al., 2023). Indeed, nanoplastics with positive surface charge (cationic plastic) induces greater accumulation of reactive oxygen species acting as strong antioxidant that strongly inhibit plant growth than the sulfonic acid-treated nanoplastics with negative surface charge (anionic plastic) (Sun et al., 2020). This obviously influences the migration of nanoplastics from the soil into the plant with subsequent impact on food safety (Zhao et al., 2022).

On the other hand, MNPs can affect the GHGs emissions due to production of CO_2, methane (CH_4), and nitrous oxide (N_2O) as a direct function of soil properties and exposure time (Wang et al., 2022). Microplastics increase CO_2 emission but decrease N_2O emission by affecting some soil properties (Rillig et al., 2021). Furthermore, biodegradable plastics are more susceptible to fast degradation than those coming from fossil source, being mineralized more rapidly, thereby contributing to major CO_2 emission in the atmosphere (Zhou et al., 2023). Therefore, further investigation is needed to study the effects of MNPs on GHGs emissions and its contribution to climate change.

6.2. *Impact of bioeconomy on soil MNPs management: challenges and perspectives*

A virtuous example of bioplastics disposing within a circular approach was done by the natural decomposition of biodegradable material made of starch-based polymeric composite to improve soil quality and crop yield in horticultural cropping systems under greenhouse conditions (Sartore et al., 2018). Besides, authors have documented new insights on the evolution of bio-film derivatives from starch-based polymeric composite used as a soil amendment in a real on-farm composting facility (Spaccini et al., 2016). These authors investigated the decomposition pattern of specific starch-based thermoplastics for mulching films and coatings for both bulk biomasses and bio-plastic composites in horticultural cropping systems by advanced mass-spectrometry techniques during the composting process. This pioneering study highlighted the whole decomposition process of starch components in soil, thereby representing a powerful methodology to investigate composition and modification of biopolymers at molecular level in a compost-amended soil.

Despite, to promote the composting process as viable way to recycle biodegradable polymeric films in the farm for further agricultural reuses, more research will be attempted. Therefore, new challenges in managing MNPS-based pollutants should be addressed on the following topics: (a) fate and processes of plastics and bioplastics from wastes to soil with a focus on anaerobic digestion and composting of the plastic contaminated food waste, (b) advanced analytical methods for the determination of micro- and nanoplastics in soils and plants, (c) impacts on the diversity and activity of soil biota, (d) transporting processes in soils mediated by fauna, (e) the '*farm to fork*' transports of plastics from soil to food, (f) comparison between fate and the impact of microplastics and bioplastics, and (g) interaction mechanisms between MNPs and soil aggregates in polluted soils (Zhang et al., 2022).

Finally, due to environmental fate and impact of biodegradable plastic in agroecosystems, research still in progress are addressed in designing efficient tailored consortia of selected fungal and bacterial strains for improving the biodegradability attributes of biodegradation-resistant plastics from fossil source (Mo et al., 2023). Deciphering the effects of the "Linear Low-Density Polyethylene (LDPE)" microplastic films on diversity, composition, and co-occurrence network of soil fungal community, the assembly of selected bacterial strains from compost forming co-cultures with fungi or bacteria allowed to improve biodegradability of plastics in substrate enriched with LDPE (Li et al., 2023). Microorganisms isolated from compost samples at different stages of composting displayed a variety of metabolic and physiological attributes for the degradation of mass-produced synthetic polymers. Although different strains showed positive results in tests *in-vitro*, the combinations of *Bacillus subtilis* RBM2 with *Fusarium oxysporum* RHM1 or with *Pseudomonas aeruginosa* RBM21 seem be the most promising consortia for the environmentally sustainable biodegradation of plastics derived from fossil source.

7. Conclusions and perspectives

Soil quality decline is a limiting factor for ensuring food safety, quality and safety of agricultural products, environmental integrity, C neutrality, and human health. Since soil is a vulnerable resource that results be strongly degraded by impacts due to climate change and anthropogenic activity, the restoration of own health state over time is very difficult to reach in short-time. The improvement of soil productivity is mainly related to SOM accumulation in the cropping systems that is provided by crop residues, green-waste, and green manure to minimize the soil structure damages. The development of theoretical and practical approaches is urgently needed for the soil health assessment. Research priorities should include detailed knowledge on the soil formation processes and its evolution, biodiversity, and functional analysis of the key biological features of soil communities by construction of co-occurrence biological networks, characterization of spatial-temporal models, and establishment of high-throughput sequence processing methods for monitoring and evaluating the best technological approaches which would contribute to the management of soil health. For all these reasons, incisive and efficient transnational policies for the soil management are still lacking or, however, widely insufficient.

To maintain the intrinsic fertility of soil within acceptable levels of crop productivity by avoiding the SOM loss, promoting the SOC restoration, and managing the MNPs-based pollutants in intensive croplands, we addressed this paper toward a critical discussion of old and new approaches overall based on three main pillars which seemed of most practical interest for farmer. Table 1 summarizes the main solutions/options, points of weakness and strength about the governance of soil quality in organic farming systems from the perspective of a sustainable agri-based circular bioeconomy. We can see that more efforts should be encouraged in next decades by the transnational policies of the "Green Deal" for developing new economic models and policies for soil management. Indeed, the aims of soil scientists will be addressed on the progress and advancement for cultivation of healthy soils by providing theories, models, methods, and new technologies for their sustainable utilization under the light of a circular bioeconomy approach.

By concluding with a citation that strengthens our intuition on the importance of circular bioeconomy in improving soil health, we can cite Yuille et al. (2022) that argued as "*the circular nutrient economy is a pivotal element of clean growth, but its development requires an overall strong reorientation in policy, including a systemic approach, instead of working in silos with different and potentially contradictory trajectories*".

Authors' approval

The authors have read and approved the final manuscript.

Ethics approval

The authors declare of have read, understood, and approved the

Table 1
Summarization of the main solutions/options, points of weakness, and strength on the governance of soil health in farming systems from the perspective of a sustainable agri-based bioeconomy (Viewpoint of the authors).

	Maintenance of intrinsic fertility	Prevention of soil organic matter loss and restoration of soil organic carbon stock	Management of microplastic and nanoplastic pollutants
Solution/ option	• Promote the natural nutrients return and SOM turnover into degraded soil by minimizing the effects due to depletion of soil resources. • Promote the green manure return into soil by leguminous cultivation. • Promote the use of cover cropping and intercropping between cereals and leguminous. • Promote the use of crop rotation (*e.g.*, between tomato and wheat) to increase soil microbiota diversity and its abundance. • Promote the application of organic materials into soil (*e.g.*, crop residues from brassicaceous) which can improve the carbon balance point. • Promote the use of biostimulators of soil microbiota (manure and green manure). • Promote the valorization of co/by-products coming from the energy conversion of residual biomass by aerobic, anaerobic, and thermochemical processes with production of compost, digestate, and biochar, respectively. • Promote the use of natural biostimulators, as straws and brassicaceous residues that can favor the SOM transformation by providing organic substrates that adjust the C:N ratios of crop residues.	• Promote the reforestation of degraded/marginal soils and/or reduction of soil tillage in cultivated areas of the world by leading to a significant increase in the SOM stock, such favoring rain infiltration and resistance to erosion. • Promote the use of cover crops that can reduce the nutrients loss caused by soil erosion if combined with a balanced nutrition by mineral/organic fertilization. • Promote the reforestation and reconversion of intensively cultivated lands to pasture by moving intensive and extensive food crops toward more fertile areas. • Promote the recycle of by/co-products such as straws, crop residues, green crop waste, agri-energy waste, sludge, animal or human excreta, and municipal bio-organic solid waste into agroecological systems by composting, pyrolysis, and anaerobic digestion was enriched the soil stock of C, P and K and micronutrients for fertilizing the crops. • Promote the soil amendment with composted biomass that restores its original fertility by changing the taxonomic structure, abundance, richness and diversity of soil microbiota, and the physicochemical properties of the amended soil.	• Promote the reduction of fossil-based plastics for mulching films and coatings in protected agriculture (tunnel, greenhouse, *etc.*). • Encourage the users to reduce the amount of polypropylene and/or to use new bio-based materials and nanomaterials. • Promote the recycle of biodegradable mulching films and coatings into agroecological systems by on-farm composting.

(*continued on next page*)

Table 1 (*continued*)

	Maintenance of intrinsic fertility	Prevention of soil organic matter loss and restoration of soil organic carbon stock	Management of microplastic and nanoplastic pollutants
		• Promote the use of tailored biostimulators, as bio-organic fertilizers (compost or biochar enriched by tailored microbial consortia or specific microbial strains) that can accelerate the SOM evolution by providing stabilized and microbiologically activated organic substrates that adjust the C:N ratios of wheat and brassicaceous residues.	
Weakness	• Accumulation of humified SOM is too slow in natural agroecosystems. • The cause/effect relationships between soil fertility and organic amendments must be studied in-depth with long-term experiments, under different experimental conditions, and in several climate areas to reach valuable advancements.	• A rationale strategy requires long-term field trials of three years, at least, in different experimental conditions because the impacts of organic amendments on the SOM content associated to cover crops, tillage suppression, crop type choice, crop rotations and intercropping need to be studied in-depth considering the different soil nutritional states and continuous change of environmental conditions.	•Uncertainty of the results and scarce knowledge of the mechanisms and degradation profiles of bioplastics by soil microbiota.
Strength	• Long-term application in soil of organic amendments (for 3-years, at least) stimulates the growth of useful bacterial and fungal taxa. • The emerging omics and metabolomics technologies applicable to the study of microbial communities of disturbed soils by the human activities and climate changes could be of great help in supporting the researchers, if they were correlated with the variability of the production factors that characterize soil health.	• The continuous maintenance of nutrient balances in the soil through long-term supplying of organic matter recycling residual biomass in on-farm composting facilities and anaerobic digestion to produce compost and digestate, respectively, restores the SOM stock by reusing waste biomass in the farm cycles. • The supply of exogenous organic material facilitates the formation of macroaggregates and promotes the intrinsic productivity of the soil. • The rapid decomposition of organic matter by living organisms provides sufficient humic substances, increases the SOM content into microaggregates, silt and clay, and strengthens bond strength, thus better protecting soil structure. • The inputs of exogenous SOC provided by manure stimulate and accelerate the soil microbiota activity by influencing the evolution of SOM.	•Opportunity of recycling starch-based polymeric composite to improve soil quality and crop yield in horticultural cropping systems under greenhouse conditions.

ethics guidelines.

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CRediT authorship contribution statement

Ugo De Corato: conceptualization and ideas, supervision, investigation, methodology design, and writing of the original paper. **Egidio Viola**: Graphical plot and figure editing. **Chetan Keswani** and **Tatiana Minkina**: financial support, literature review, and critical revision of the final paper.

Declaration of competing interest

The authors declare that there are not any actual or potential competing interests including any financial, personal, or other relationships with other people or organizations.

Data availability

The authors do not have permission to share data.

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