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The treatment of the organic fraction of municipal solid waste (OFMSW) as a possible source of micro- and nano-plastics and bioplastics in agroecosystems: a review

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Abstract

Plastics fragmentation into smaller debris, namely, micro- and nano-plastics (MPs and NPs), is a matter of global concern because of their wide distribution in terrestrial and marine environments. The latest research has focused mainly on aquatic ecosystems, and fragmentation of bioplastics into micro- and nano-particles (MBPs and NBPs) is not considered. The distribution, concentration, fate and major source of MPs, NPS, MBPs and NBPs in agroecosystems still need to be understood. The use of composts and sewage sludge from the organic fraction of municipal solid waste (OFMSW) treatment plants as soil amendments is likely to represent a major input of these debris. The present review provides insights into the current evidence of pollution from micro- and nano-particles of both fossil- and bio-origin in the OFMSW treatment, and aims at evaluating if the recycling of organic waste and its application as a soil fertilizer outweigh the risk of pollution in terrestrial environments. Huge unpredictability exists due to the limited numbers of data on their quantification in each source of possible solution. Indeed, the major hurdles arise from the difficult to quantify the micro-, especially the nano-, particles and subsequently assess the concentrations in the environments, as well as bioaccumulation risks, and toxic effects on organisms.

Keywords: Anaerobic digestion, Composting, Disposal, Food waste management, Polymers, Pollution, Sewage sludge

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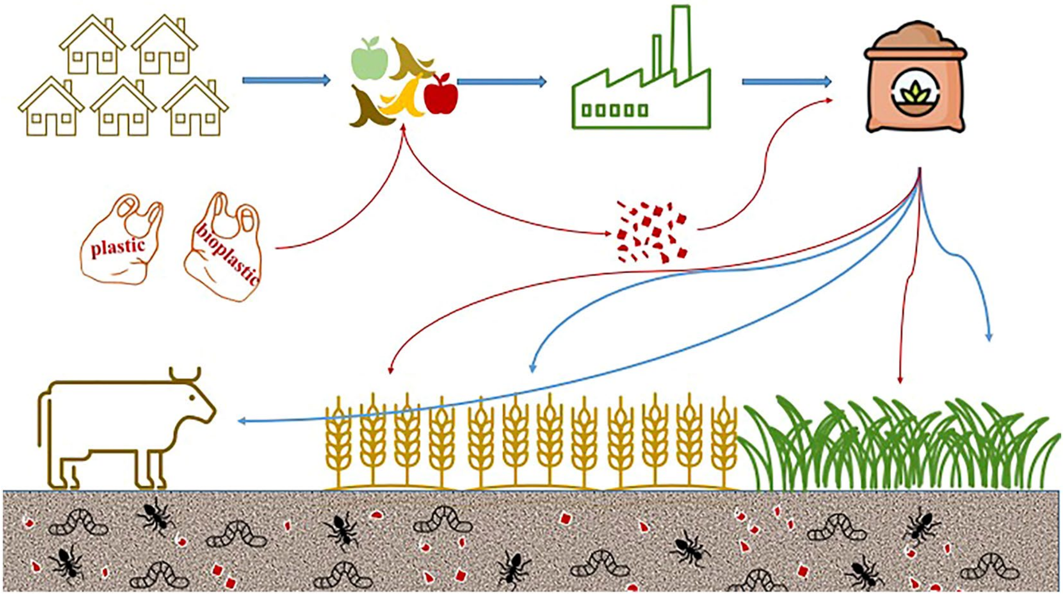
Graphical Abstract



Introduction

Plastics have played a crucial role in the development of modern society due to their material properties, affordability and ease of manufacture [1] in a wide range of applications. Global annual plastics production in 2019 reached 370 Mt, while in Europe, it was 58 Mt (PlasticsEurope, 2020). Plastics are often complex composites made of organic polymers and chemical additives, such as bisphenols, phthalates and flame retardants [2]. Their complex nature makes plastics hard to recycle and often non-biodegradable; almost half of the post-consumer plastic waste is sent for energy recovery, while the remaining 32.5% is sent to recycling and 24.9% ends up in the landfill (PlasticsEurope, 2020, Conversio Market & Strategy GmbH). Nevertheless, a large amount of plastic polymers is still abandoned in the environment [3] or not properly managed. Therefore, plastic pollution is considered a relevant threat for ecosystems around the globe and all the related organisms [4].

Biodegradable plastics were introduced as a possible solution to the ecological and environmental impacts associated with conventional fossil-based plastics. These bio-based alternatives are often biodegradable and/or compostable under certain conditions and comprise a family of materials with different properties and applications (EuropeanBioplastics, 2020). Today, the market of bioplastics is constantly growing with a strong diversification of materials, applications and products, and the global annual production capacity is around 2.11 Mt [5]. Bioplastics waste can be managed in the same way as conventional plastics waste, such as mechanical or chemical recycling, incineration, landfill, or it can follow specific end-of-life options, such as energy or organic recovery. However, some plastics labelled as biodegradable may disintegrate only or cannot be completely biodegraded [6].

Recent studies have focused on the fragmentation of plastic and bioplastic materials into smaller debris which can be classified according to their diameter into micro-plastics (MPs) and nano-plastics (NPs). While MPs are defined as particles sized from 1 μm to 5 mm [7, 8], debate is on-going for the characterization of NPs. Some studies defined NPs as fragments with diameters between 1 and 100 nm [2, 9], whereas others adopted the whole nanometer range from 1 to 1000 nm [2, 10]. In this review, we consider NPs the particles with diameter ranging from 1 to 1000 nm. Due to their ubiquity, MPs and NPs have become a global concern. NPs are potentially more hazardous than MPs as they may permeate biological membranes [11]. Latest research has often focused on marine environment and reported severe impacts on aquatic ecosystems, such as the accumulation of harmful pollutants, the release of chemicals and the transport of pathogens [7, 12–14]. However, the impact of both MPs and NPs from conventional fossil-based plastics and from bio-based plastics (MBPs and NBPs) in agroecosystems is a growing, but often overlooked, concern. Particularly in soils, literature bears fragmentary information. We know that agroecosystems are the most plastic-contaminated terrestrial ecosystem after landfills, urban spaces [15] and beaches [16]. However, the most abundant polymer type and size still need to be clarified. The size and the shape of the residues may influence their fate and stability in the environment, since these properties correspond to a different surface being exposed to chemical, physical and biological biodegradation factors. Different additives and chemical components are associated with each type of polymer, and their respective MPs, NPs, MBPs, and NBPs may have various effects in soil. MPs as possible contaminants in agriculture are not currently on the regulatory agenda and little is known about the released of toxic substances and their consequences for sustainability and food security [17]. In 2016, the EFSA Panel on Contaminants in the Food Chain raised a number of questions about bioaccumulation and biomagnification of these materials after the adsorption by various organisms [18]. The role of MPs, NPs, MBPs and NBPs as vectors for the transmission of microorganisms, including pathogenic ones, and their ability to increase gene exchange between different species is another concern [13, 14]. This is a new research topic that is worth expanding due to the biological invasion and severe ecotoxicological impacts that these particles can cause [19].

Particles < 5 mm can enter the soil directly from atmosphere and through irrigation, or indirectly through the degradation of large pieces of plastic, such as plastic mulch [7]. The agriculture use of composts and sewage sludge from the organic fraction of municipal solid waste (OFSMW) treatment plants is likely to represent a major input of micro- and nano-plastics and bioplastics to agroecosystems [20]. The presence of these fragments in such amendments has already been documented in literature, but the distribution, concentration, fate and major sources of MPs and NPs as well as MBPs and NBPs in soils still needs to be understood. Based on these facts, in our review we will briefly analyze the different waste management practices for fossil- and bio-based materials at the end of their use. Later we will deal with the degradation mechanisms that lead to the formation of micro and nano fragments. Subsequently, the OFMSW composition and management processes will be investigated as a possible source of major introduction of MPs, NPs, MBPs and NBPs in the agroecosystems. The present work will contribute to the evaluation of the existing evidence of MPs, NPs, MBPs and NBPs pollution in compost and sewage sludge from OFMSW treatment. Moreover, it provides a starting point to evaluate if the recycling of organic waste and its application as a soil fertilizer outweigh the risk of pollution from plastics and bioplastics. It thus may serve to build upon the knowledge of plastic and bioplastics fate and effects in terrestrial environments.

Plastics degradation processes: form macro to micro, from micro to nano

The degradation of both conventional plastics and bioplastics is a combination of abiotic [21] and biotic [8] processes, including physical, chemical, biological synergies [22], hydrolytic degradation and mechanical disintegration [3]. As summarized in Fig. 1, when released to the marine environment and water bodies, conventional plastics weather and degrade leading to fragmentation, mechanical abrasion and/or formation of cracks [23, 24]. However, the degradation processes and products should be better understood, and some attention must be drawn to additives, persistent organic pollutants and chemicals generated during the exposure to sunlight, oxidants and physical processes in water. Indeed, fossil-based plastics exposed to sunlight or ultraviolet radiations undergo the process of photo-oxidation, namely, the transformation of the polymers into monomers by bond scission. A high level of solar radiation results in the damage of the plastic materials, breaking their chemical bond, losing tensile strength and molecular weight and turning into small fragments [25]. UV damage to plastics, such as mulching materials, is a matter of global concern, especially in tropical areas which receive intense sunlight [26]. Otherwise, the visible spectrum drives to heating and thermal degradation, resulting in thermal oxidation of polymer chains [27]. Hydrolysis is another chemical factor leading to the degradation of plastics [28]. To improve their properties, polymers are often blended with some additives/fillers, such as heavy metals (HM) and organometallic compounds. These recalcitrant additives are not chemically bound within the polymers and can thus be progressively released in the environment [29].

Microorganisms play a pivotal role in plastics adsorption and degradation processes. Indeed, plastic debris provides a colonizable substrate which can support the growth of microbial biofilms that may comprise also potential pathogens [13, 30]. Biological degradation pathways include the mechanical action of organisms that develop and proliferate in breaks of polymer surface; and enzymatic pathways which can hydrolyze the polymer into oligomers and monomers [22, 31]. Indeed, the polymer bio-degradation potential depends on the hydrolysable or non-hydrolysable nature of the polymer. Non-hydrolysable polypropylene (PP), polyethylene (PE) and polystyrene (PS) have stable backbones and are hard to degrade, while hydrolysable polyethylene terephthalate (PET), polyurethane (PU) and polycarbonate (PC) are more vulnerable to catalyzing enzymes. Moreover, microbial degradation of plastic polymers is also affected

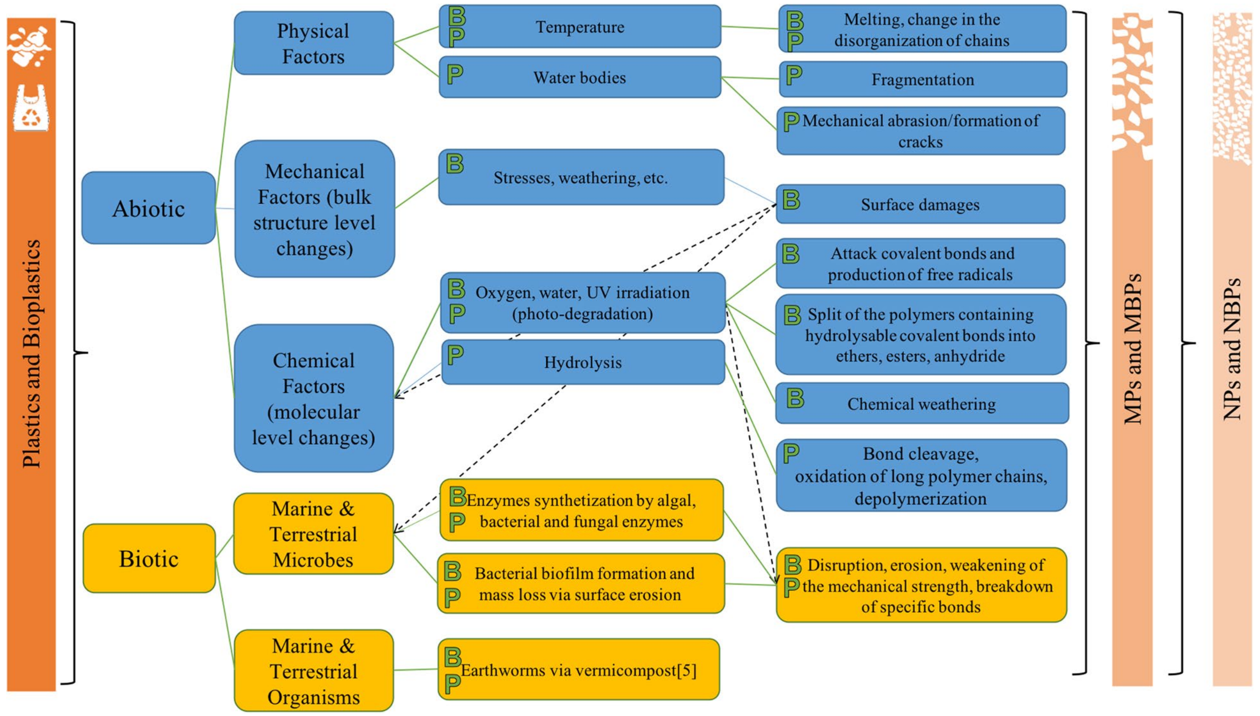


Fig. 1 Examples of abiotic and biotic pathways from plastics and bioplastics to MPs, NPs, MBPs and NBPs ("P", plastics; "B", bioplastics; dot lines refer to secondary interactions between factors)

by other polymer characteristics, such as molecular weight or morphology [32] In the last years, there has been growing interest in the role of microorganisms in the degradation of plastics polluting the environment, with many efforts aimed at using them as a solution to pollution. There are many studies in the literature concerning the potential of certain microorganisms to biodegrade conventional plastics, such as PET [33–37], PE [38, 39], PS [40, 41] and PU [42]. Moreover, environmental factors, such as light, heat, moisture, and pH, enhance bond scissions leading to an increase in sites for microbial action on the polymer chains [21, 32].

Bioplastics also undergo (bio)deterioration leading to material fragmentation into MBPs and NBPs. The damaged surface shows weakness, discoloration, erosion signs and polymer splitting [43], and subsequently depolymerization processes will produce oligomers and monomers. As reported in Fig. 1, different abiotic and biotic factors are involved [44]. The abiotic factors include mechanical, physical and chemical factors. The mechanical ones, such as stresses and weathering, cause damages, whereas temperature among the physical ones can cause partial melting and change the organization of chains. This reorganization may facilitate the accessibility to chemical and biological degradation [45]. Moreover, oxygen, among the chemical factors, induce the degradation by attacking covalent bonds and producing free radicals, while water breaks the polymers into ethers, esters, anhydride, etc. [23]. Finally, as for conventional plastics, UV radiation causes chemical weathering [46], whereas pH and salt concentration may affect the degradation of bioplastics by providing suitable environments for microbial growth and by controlling catalytic enzymes [47]. Considering the biotic factors, as mentioned above, biofilm formations produce disruption and erosion of the polymer surface, but also penetrate into the fractures and pores [48]. Furthermore, enzymes play a key role as responsible for the breaking of specific bonds. Plastic-degrading enzymes were classified into two categories, namely, extracellular, with oxidative and hydrolytic functionality, and intracellular [49]. However, not much information is available on the biochemical properties and structural characteristics of these enzymes [32]. Marine and terrestrial organisms can interact with MPs, NPs, MBPs and NBPs facilitating surface biodeterioration and microbial colonization [50]. Organisms may fragment particles by scraping or chewing activities [51] leading to increase surface area for microbial attack. Therefore, bioaccumulation of organic compounds deriving from plastic and bioplastics fragments may provide favorable conditions for polymer biodegradation and depolymerization by exoenzymes and microorganisms in the gastrointestinal lumen [52].

The degradation of macro (>5 mm) into micro- and nano-particles is often a result of a combination of the above-discussed factors (Fig. 1). However, an incomplete biodegradation or physical–chemical degradation of polymers can lead to the generation of MPs and MBPs and subsequently of NPs and NBPs resulting in their release into different environments. The latter are of even greater concern due to their dimensions and their ability to be ingested by humans by the food web and, afterwards, to translocate across the gut epithelium into the lymphatic system, potentially affecting human health [3].

Fossil- and bio-based plastics end-of-life: waste management strategies

Omnipresence of plastic materials [53] led to a generation of considerable amount of waste, and to the unavailability of proper methods of treatment, management, and disposal in some countries [54]. Uncollected waste may be dumped in landfills or drained into sea or environment. The disposed plastic persists unvaried for the longer time, posing a major threat to plants, wildlife and human beings. However, each country has its own regulation tailored to its own needs. Since 2018, Europe has adopted the "European Strategy for Plastics in a Circular Economy" (EU, 2018) to deal with plastic waste. The Strategy includes improvements in the quality of plastic recycling, protection of the environment and citizens, and restrictions of the intentional use of microplastics. However, a report by Plastics Europe Market Research Group (PEMRG) and Conversio Market & Strategy GmbH (2018) suggest that only the 42.6% was sent to energy recovery and the 32.5% to recycling. At the heart of the current plastic waste management in the EU lies "The Prevention", i.e., avoiding creation of the waste in the first place, and, in an ideal world, this is the most preferred option. For the waste that needs to be managed, re-use options (from most to least preferred) are recycling, recovery and disposal (EC, 2017). Mechanical and chemical recycling are the most common recovery options for conventional plastics, while disposal is carried out through landfill and incineration regardless of the plastics' origin. There are, however, some preferential routes for the recovery of the biodegradable bio-based plastics (e.g., organic recycling options—aerobic composting and anaerobic digestion). Non-biodegradable bio-based plastics on the other hand can be managed through mechanical and chemical recycling to avoid landfilling and incineration options. Recovery through mechanical recycling is still an option also for the bio-based biodegradable plastics, but only when it is separated from the other types of bio-based plastics and free of chemical contamination (EC, 2017). Definition of proper management and the end-of-life alternatives for the correct treatment and the disposal options of bio-based plastics is crucial: specific valorization alternatives of biobased plastics for the circular economy are of utmost importance for the recirculation of the biobased plastics into valuable resources [55]. However, the true potential of plastic wastes recycling and their re-introduction back to manufacturing remains largely unexploited in the European Union due to collection and treatment costs [56]. The main plastics and bioplastics waste management options along with their respective advantages and disadvantages, which may vary according to local conditions, are presented in Table 1.

Most bio-based plastics, when labelled as compostable, are collected with the OFMSW and recovered through organic waste biological treatments at industrial scale. However, no specific category exists for bio-based waste and no statistics exist in EU or US [55]. Introduction of fossil-based plastics and larger items is often avoided through mechanical pre-treatments prior to the biological processes, which generally consist of sieving and/or shredding [66]. In addition to removing plastics and bioplastics before the operations, the pre-treatment also shreds the OFMSW to obtain a homogeneous pulp. However, these operations can generate micro- and nano-fragments from both the materials [67]. While MBPs and NBPs may degrade during the biological treatments, fossil-based particles will end up directly in the final products, becoming a major source of contamination in agroecosystems.

MPs, NPs, MBPs and NBPs in agroecosystems: the Trojan Horse effect

While the presence of large amounts of MPs and NPs in freshwater and marine ecosystems is almost ubiquitous, the knowledge of their behavior, fate and impacts in terrestrial environments is still poor. In addition, the amount of plastics debris in terrestrial ecosystems is much higher than in that of marine ecosystems [68, 69]. However, since the problem of MPs in soils was identified [51], increasing consideration was given to pollution issues [15, 70–75]. These materials can enter the agroecosystems either directly (e.g., from atmospheric deposition, irrigation water or biofertilizer application), or indirectly (in situ degradation of large pieces of plastic, such as mulch films) [76–78]. It is now well known that the main sources of micro and nano particles (of both fossil- and bio-origin) entering agricultural soils includes plastic mulch films, biowaste fermentation and composting and biosolids (sewage sludge and anaerobic digestate disposal as soil amendments) [67, 68, 79–83].

MPs, NPs, MBPs and NBPs in agroecosystems may play a particularly important role in soil through their impact on soil physico-chemical properties and microbial communities. MBPs in soil may also alter plant growth and performance by increasing the bioavailable C as they decompose, thus affecting the plant-microbes competition for nutrients [84]. A recent case study on Chinese farmlands by Wang et al. found that the types of MPs present in fields were closely related to land-use types. Wheat and rice fields were found to be containing fibrous shapes and large MPs particles, while orchards and woodlands were likely to have fragmented shapes and smaller sized MPs [85]. The residual plastic mulch film damages the structure of soil aggregates, reducing aeration, water permeability, root growth and overall plant productivity [86, 87]. Even though biodegradable options are seen as promising alternative to low-density polyethylene (LDPE) to minimize plastic debris, MPs of both types were found to have depleting effects on aggregate-associated soil carbon and nitrogen stocks [88]. In another recent work by Liu et *al.* (2021), the composition, diversity, and metabolic function of the rhizosphere bacterial communities together with Soil Organic Carbon (SOC), Total Organic Carbon (TOC) and Soil Organic Matter (SOM) levels were found to be affected by common plastic mulch in the long term [89]. Furthermore, it was also found that MBPs may alter soil ecological functioning and biogeochemical cycling in the so called "microplastisphere", by stimulating C and nutrient turnover by creating microbial hotspots [90]. Current findings suggest that these changes are soil organic matter dependent and there seems to be a potential risk to agroecosystem's soil stability associated with organic matter additions [91]. Moreover, in a recent study it was highlighted the need to consider potential interactive effects of land use and management with plastic particles [92]. Some authors suggest that it might be even sound to use fossil-based plastics as biobased plastic's degradation process may be compromising the already delicate balance of soil nutrients, biodiversity and physiochemical properties.

Another significant input of microplastics has been identified in the application of sewage sludge containing synthetic fibers or sediment microplastics from household products [93]. The application of sewage sludge as fertilizers represents a significant source of nanoparticles in the environment [80, 94]. The sewage treatments are efficient in removing the majority of microplastics, but many are also retained in the sludge [95]. In Europe, the sewage sludge is commonly composted and pasteurized for use as agricultural fertilizer [68]. Despite more than 4 Mt dry weight of sewage sludge are applied to arable

Table 1 Summary of the main plastic and bioplastics waste management operations (P, plastics; B, bioplastic)

End-of-life option	Suitable for	Advantages	Disadvantages	Refs.
Landfilling and Incineration	P	Economically sound Volume minimization Rapid disposal Minimum land requirement Technology not required Contaminated and toxic material can be treated Electricity generation	Environmental problems, such as air, soil and water pollution Shortens the lifespan of the plastics Lots of energy required Gases released as a byproduct can be dangerous and their exposure to living beings may result in breathing disorders Generation of toxic leachate of hazardous nature Disposal in landfills results in deterioration of land and increase the risk of consumption of plastics by animals	[54, 57–60]
Mechanical Recycling	P > B	Same material can be recycled up to 7 times before it degrades to the point that mechanical recycling is not an option anymore	Needs sorting and labor intensive: the resins must also be separated, and single-polymer waste stream is needed to optimum efficiency Causes material and quality loss Contaminated plastics cannot be treated Low efficiency, recycled materials are downgraded It occurs at about 200–300 °C resulting in emission of toxic gases	[59, 61, 62]
Chemical or Feedstock Recycling	B > P	Recycled material quality is higher than mechanical recycling option as polymers broken into monomers Mixed and contaminated material can be used without sorting, thus offers a potential for household wastes and bioplastics	Economic feasibility needs to be assessed Some technologies are still being development, and some have high energy use, costs, and technology demand	[63–65]

land every year [96], there are no regulations yet on MPs as harmful substances within sludge [68]. High concentrations of synthetic microfibers were found in sewage sludge applied soils, and their presence was also reported after 15 years of last application, suggesting also a serious problem of accumulation [93]. Qi et al. estimated a topsoil contamination level of ca. 4–150 particles/kg for each year of application of biosolids, assuming an average microplastics contamination of 10^4 particles/kg and a land application rate of 1–15 t/ha/y. Whereas it has been recognized that biosolids may contain metals and pollutants [7, 97, 98], it is recently becoming clear that they may also contain amounts of plastics and bioplastics. However, current literature focuses mainly on the processes to which bioplastics undergo, and less on the presence of MBPs and NBPs in them [15, 52].

Despite the awareness that plastics of all sizes are widespread within agroecosystems, there is a dearth of studies on debris quantification. Due to difficulties in separating, extracting and, subsequently, quantifying micro and nano-plastic and bioplastic particles from soils [99], the effects and the effective concentration in agroecosystems are still poorly understood. Even though NPs have the potential to be taken into cells, they are rarely quantified, and their uptake still not has been evaluated from a risk assessment perspective. Depending on the plastic shape, the types of MPs and NPs can be divided into fibers, fragments, thin films, and particles. Fibers often represent the main form if they enter soil from biosolids or irrigation waters from municipal wastewater [100, 101]. Globally, the most frequently fossil-based polymers found in the soil environments are PE and PP from fossil origin [7], while biopolymers are still taken little into consideration. Indeed, these materials are labelled as disposable with organic waste and, therefore, undergo the same management processes. However, in recent years, many studies reported recalcitrance problems associated with these biopolymers [102, 103]. Soil, compost, sediment and sewage sludge are solid heterogeneous matrices with a high content of organic matter that should require a higher consideration as possible source of pollution in agroecosystems [104]. It's evident that understanding the sources, abundance and composition of debris present in this OFMSW process is remains a huge challenge. Therefore, next sections are dedicated MPs, NPs, MBPs and NBPs pollution in compost and sewage sludge from OFMSW treatment only; from its characteristics to two possible management options, namely, the anaerobic digestion and aerobic composting.

The organic fraction of municipal solid waste (OFMSW): composition and characterization

The organic fraction of municipal solid waste (OFMSW) represents almost 50% of the global generated waste [105], and it is predicted to rise from current 2 Bt to 3.40 Bt by 2050 [106]. Population growth, increased consumption, economic development, and rapid urbanization are main drivers of increasing rate of OFMSW generation [107, 108]. Efficient waste transformation approach is needed as the OFMSW is a non-edible and plentifully available resource which can be transformed and valorized for bioenergy and biomaterials recovery [109]. The use of renewable energy sources can aid to reduce negative environmental impacts, e.g., GHG emissions [110]. Policymakers are accordingly increasingly moving in this direction.

The definition of OFMSW differs regionally and nationally, and its composition and production depend on geographic region, number of habitants and their socioeconomic activities, food habits, climatic conditions and collecting systems [111, 112]. Moreover, the municipal waste generation rate depends directly on overall development of a Country [107]. The OFMSW can comprise heterogeneous scraps from gardens, parks, households, restaurants, catering, retail and food industry. It is usually composed of food waste, yard waste, paper, newspaper and other organic wastes. Each of these fractions have different characteristics of particles size, calorific value and density, C:N ratios, pH, and humidity content [105, 113]. Due to its high moisture content and organic biodegradable matter, it is suitable to valorization processes [114]. Integrated waste management is composed of a set of principles for handling waste in an environmentally and economically sustainable manner [115, 116] and the aims are to control all its resulting solid, liquid, and gaseous emissions. This approach holds principles which allow locales to develop their own systems in response to their contexts. In the following section we will discuss about the disposal of the OFMSW and its management.

Disposal and management options for OFMSW: a focus on the fate of plastics along the anaerobic digestion and composting processes

The OFMSW was disposed in landfills for years, but due to its environmental impacts, the actual trend is to reduce, reuse, recycle, recover and treat the waste [117]. The domestic separation of organic waste and the recycling was initially promoted in 90 s [118]. Nowadays, researchers, companies and governmental agencies are aiming to find OFMSW energy recovery alternatives to convert the organic matter into valuable products, such as biogas and compost. However, the OFMSW management depend on institutional capacities and on local waste characteristics, which change with cultural, climatic and socioeconomic variables [119]. Among the total quantity of municipal waste generated, 74% in Japan, 54% in Denmark, 50% in both Switzerland and Sweden are still incinerated [120, 121], whereas globally more than 130 Mt/year are treated to generate electricity (ISWA, 2012). Developed countries, such as Netherlands, Belgium, Denmark and Germany, prefer to use recycling/composting techniques [122]. In contrast, many developing countries have not yet fully recognized the potentials of waste to energy technologies [107]. This is influenced not only by economic necessities and energy recovery, but also by the environmental regulatory compliance requirements of the concerned area [107]. Moreover, the international differences in social attitudes, education and investment in waste management lead to disparities and variations between waste generation and disposal [68]. Therefore, from next section on, this review focus on anaerobic digestion and composting as two of the main OFMSW recovery and recycling techniques in Europe.

Anaerobic digestion

Anaerobic digestion of OFMSW is a viable alternative for waste stabilization and renewable energy recovery, e. g. biogas and digestate [105, 123]. A wide range of different raw materials are suitable for anaerobic digestion. This biological conversion process is based on microbial decomposition of the organic matter in the absence of oxygen, accompanied by series of phases. Hydrolysis is the initial stage, in which the complex organic compounds, such as carbohydrates, proteins and fats are converted into soluble organic materials. The second stage is fermentation, where the organic molecules break into acetic acid, H_2 and CO_2. The final stage is the methanogenesis, in which CH_4 developed. The anaerobic digestion can be "wet", with 10–15% of dry matter content and more liquid waste, or "dry", with 24–40% of dry matter [124, 125]. The types of processes, of the reactors and methane yield, depend on the region, quality of the feedstock and product requirements [107, 108]. The anaerobic digestion is the most promising and sustainable process for the treatment of food and yard wastes, because, compared with incineration or landfilling, this renewable source of energy may be used as a fuel to minimize carbon emissions and reduce air pollution [107, 126–128]. On the other hand, the recovery allows to produce a nutrient rich digestate which may be processed or distributed to fields directly as a fertilizer [124, 129]. Not stabilized digestate is usually composted to ensure that the product is suitable for agricultural application [130]. This provides the reduction of consumption of mineral fertilizers and the minimization of water pollution [131]. It is essential to know the OFMSW characteristics and composition to evaluate its toxicity towards agroecosystems [132, 133]. Co-digestion of municipal solid waste, sewage sludge and food waste is often used to reduce the toxicity of digestates [134, 135]. This may lead to the simultaneous presence of non-biodegradable waste (plastics, metals, glass, and other packaging materials) and biodegradable waste (eggshell, biobags, and bones). Bio-based plastics, labelled as compostable according to EN 13,432, are not certainly biodegradable under anaerobic conditions [136]. To avoid these physical impurities that can have a negative influence on the process, the on-site grinding, chopping and mechanical separation are applied which in return may negatively contribute to the defragmentation of plastics and bioplastics into MPs, MBPs, NPs and NBPs [137]. Moreover, plastic bags, packing materials and voluminous garden wastes are considered as harmful materials for the anaerobic digestion, delaying the biogas production process [123, 138, 139].

Composting

Due to its easy implementation and operation, composting is the most common method worldwide for the recovery and valorization of organic waste [140, 141]. The OFMSW, and other organic solid wastes, fit this valorization process which aims at biological stabilization of the organic substrate under controlled aerobic conditions [114]. During composting, oxygen is consumed by microorganisms, while CO_2, heat and water vapors are released in the atmosphere [55]. The anaerobically digested sludge is composted with other organic wastes, such as agricultural wastes. The coupling of anaerobic digestion and composting represent a well-established process for waste management in Europe, and aims to improve quality and stability, to control water content and contamination by pathogens, and to lowering the metals amount [142]. However, each Member State follow different approaches for the characterization of the final product [143]. The properly processed compost can be used in soil conditioning and nutrient supply [144]. Microbial activity, temperature, moisture and feedstock are important for the correct composting process [145, 146] and may influence the final organic matter content [147–150] and its phytotoxicity [151]. Since OFMSW must be contained in compostable bio-based bags [152], their disposal occurs together with the collected bio-waste and undergo the same treatments. Although there are many compostability standards for bioplastics, the literature data showed good performance at industrial composting when proper conditions are respected [55]. On the other hand, fossil-based plastics ending up in the composting process may influence the parameters reported in Table 2 and have the potential to decrease compost quality.

Finally, both plastics and bioplastics have a high probability of ending up in the OFMSW management process, but their fate and disintegration into micro- and nanoparticles must still be clarified. Indeed, it is recognized that MPs in the composts obtained from OFMSW are a source of pollution that may pose a threat to agroecosystems [153]. Furthermore, it is important to understand the consequences of the presence of fossil plastics that are not retained by the initial separation, or the opposite, to avoid plastic waste streams contaminated by organic waste, which create serious problems to the mechanical recycling process. It is crucial to understand the impact of these materials on the compost quality and the whole energy recovery process [154].

The OFMSW treatment as a possible source of plastics pollution in agroecosystems.

It should not be underestimated that compost obtained from the OFMSW treatment may be a primary source of contamination by MPs, NPs, MBPs and NBPs in the agroecosystems, leading to negative impact on soil organic carbon (C) and nitrogen (N) cycling, on microbial activity and nutrients transfer [161, 162]. In Italy, starting from 2011, the OFMSW must be collected in compostable bio-bags [152] which should be degraded by composting and/or anaerobic digestion. Their biodegradation rate depends on different factors, such as time, temperature and humidity of the process, type of source and physicochemical properties of the materials. This leads to highly variable biodegradability rate data in literature, also because this statement depends on the standards applied. Indeed, for labeling compostable material, European standards specifications, such as EN 13432:2000 [163] and EN 14995:2006, and international and American standards define different essential requirements to be met for organic recycling. The various standards on compostability of materials are similar in some aspects, but differ in details. The disintegration behavior of a products is mainly demonstrated by standard test methods performed at laboratory scale, pilot-scale, or under short timescales, while fewer studies focused on real conditions [164]. However, bioplastics labelled as compostable are expected to enter the anaerobic or aerobic biological treatments that lead to end-products applicable in agriculture, such as sewage sludge and compost. Some treatments conditions (e. g. low temperature and humidity of the operations) can slowdown the degradation process and be responsible

Table 2 Summary of anaerobic digestion and aerobic composting as two of the main OFMSW treatment operations

	Parameters	Effects of plastics	Effects of bioplastics	Refs.
Anaerobic Digestion	Dry matter content of the substrate (dry, wet and semi-dry digestion) Average temperature and fermentation process (psychrophilic, mesophilic and thermophilic processes) Loading system for substrate (continuous or batch) Number of reactors (one-stage or multi-stage technologies) Type of reactors (vertical, horizontal, mixing technology)	Increased surface area of plastics led to greater reduction in biogas yields Accumulation at the liquid surface of the digester Stretch out the process Clog the pumps Wrap around stirrers Lowering of sewage sludge quality due to the presence of MPs Reduced contact of microbes and food waste Release of plasticizers, stabilizers, and flame retardants in sludge Plasticizers negatively affect hydrolysis, acidification, and methanogenesis Modification of microbial communities involved	Decrease in biogas yields Stretch out the process Clog the pumps Wrap around stirrers Lowering of sewage sludge quality due to the presence of MBPs Modification of microbial communities involved	[55, 102, 103, 155–159]
Composting	Feedstock properties (moisture content, C/N ratio, density) pH value Temperature Aeration/oxygen supply CO_2 production Odor generation	Lowering of compost quality due to the presence of MPs Need for sieving, manual sorting or magnetic separation before or after composting Modification of microbial communities involved	Lowering of compost quality due to the presence of MPs Need for sieving, manual sorting or magnetic separation before or after composting Modification of microbial communities involved	[103, 159, 160]

for the generation of micro- and nano-particles in the final product, but their decomposition is not given much consideration. In fact, even though biodegradability standards were met, a recent study reported the release of micro- and nano-particles from biodegradable plastic under composting process [165]. Although the regulation restricts the use of fossil-based bags for the organic waste collection, these still enter to waste streams in organic treatment plants. This problem is addressed by mechanical pre-treatment to separate larger pieces [66], but, as reported in the following section, MPs, as well as NPs, residues were found in the anaerobic sewage sludge and in the aerobic compost.

Moreover, standards for compost quality vary between Countries. In Italy the regulations require that plastics > 2 mm comprise < 0.5% of compost weight mass, considering the smaller size pieces assimilable to compost. Germany has one of the strictest regulations on fertilizers worldwide, allowing up to 0.1 weight % (wt %) of plastics. In other countries, such as Spain and New Zealand, the threshold limit is 10 to 15 mm, while in some other European countries plastics are not mentioned in the requirements for impurities. However, in regulations, particles smaller than 2 mm are not even considered [166].

Given the literature data previously discussed and the evidence that even in composts and sewage sludge micro- and nano-residues from plastics and bioplastics can be present [67], the current standards for their assessment and the lack of quantification does not take properly into account agroecosystems pollution problem. Globally, there is a lack of research on the relationship between MPs, NPs, MBPs, NBPs in OFMSW feedstock, compost or sewage sludge and their effect on soil structure, physical and chemical properties, organisms and plants. To assess whether the compost and the sewage sludge obtained from the treatment of OFMSW can be a source of MPs, NPs, MBPs, and NBPs pollution in the soil, we evaluate the available quantitative data in literature on micro- and nano-particles of both fossil- and bio-origin plastics during the whole process.

From the OFMSW to the compost: current data of MPs, NPs, MBPs and NBPs.

Our literature research revealed that most works are still focusing on finding methods for the separation and the quantification of micro-particles from both fossil- and bio-based plastics in organic matter. This is even more difficult for the nano-sized fragments. There is still no established method, applicable to different matrices, for identifying and quantifying MPs, NPs, MBPs and NBPs, resulting in a lack of data. Indeed, micro- and nano-plastics may aggregate themselves or with other organic particulate materials increasing in size, density and sedimentation rate [167]. Furthermore, the growth of bacterial biofilms on their surfaces may again increase particles weight and density [168], leading to several difficulties in the method.

In Table 3, we have summarized the few quantitative data reported in the literature concerning the OFMSW as a possible source of agroecosystems pollution, covering the organic fraction feedstock, the process, and the final products. Considering the evidence that MPs, NPs, MBPs and NBPs are present in the end-products from the OFMSW treatment [169, 170], the evaluation of the incoming feedstock is of utmost importance. To our knowledge, there is still a lack of studies that quantify MPs, NPs, MBPs, and NBPs presence in the OFMSW. However, in a recent work, samples of food waste pulp after shredding pre-treatment in an anaerobic digester in Italy were investigated [171]. As reported in Table 3, a high number of micro-particles from Mater-bi, cellophane, PE and PS were retrieved, concluding that the current threshold of 2 mm for plastics quantification should be lowered, as the MPs smaller than this size are almost the double that of items ≥ 2 mm. Nizzetto et al. estimated between 63,000 and 430,000 metric tonnes of MPs in sewage sludge from wastewater treatments applied annually on European lands, resulting in 473,000–910,000 metric tonnes released annually within continental environments [68]. The estimates for North America ranged from 44,000 to 300,000 tonnes of microplastics annually, whereas between 2800 and 19,000 tonnes of MPs are applied each year to Australian agroecosystems through biosolids [20]. According to Wang et al., application of sewage sludge as fertilizers represents one of the significant sources of NPs in the agroecosystems. Otherwise, composts application in agroecosystems should enhance soil fertility, but at the same time it is also a source of contamination by MPs, which are not totally removed during the composting process [172]. As reported by Cesaro et al., in the compost obtained from the OFMSW treatment from industrial Italian plants, the content of plastics exceeded the threshold limit value, but no quantitative data are reported. The reason may be the quality of the input waste, and this can be easily improved by up-stream strategies acting on separating collection methods.

In recent years, compost and sludge have been scarcely investigated [104], and the few available data are shown in Table 3. These organic amendants for soils should be given greater consideration as major vehicle for the entry of MPs, NPs, MBPs and NBPs in agroecosystems [67]. In fact, the collected data lead to serious concerns about the overall deposition, retention, and accumulation

Table 3 Summary of the main studies on MPs, NPs, MBPs, and NBPs in the OFMSW treatment, covering different origin and sources within the whole process

Polymer's type	Source/origin	Amount	Dimension/size	Refs.
Mater-Bi	OFMSW after shredding pre-treatment, anaerobic digester	8.4±0.5 MBPs/10 g	< 2 mm	[171]
PE, Cellophane, PS	OFMSW after shredding pre-treatment, anaerobic digester	5.4±1.7 MPs/10 g	< 2 mm	[171]
PES, PE, PP, PET, Cellulose-based polymer, PVC, PA, PUR, etc.	Quality-controlled, certified biowaste compost sieved through 8 mm meshes	20 MPs/ kg dry weight	1–2 mm, 2–5 mm	[67]
PES, PE, PP, PET, Cellulose-based polymer, PVC, PA, PUR, etc.	Quality-controlled, certified biowaste compost sieved through 15 mm meshes	24 MPs/ kg dry weight	1–2 mm, 2–5 mm	[67]
PES, PE, PP, PET, Cellulose-based polymer, PVC, PA, PUR, etc.	Mature compost from household biowaste digester	70 MPs/ kg dry weight	1–2 mm, 2–5 mm	[67]
PES, PE, PP, PET, Cellulose-based polymer, PVC, PA, PUR, etc.	Mature compost from household biowaste digester	122 MPs/ kg dry weight	1–2 mm, 2–5 mm	[67]
PES, PE, PP, PET, Cellulose-based polymer, PVC, PA, PUR, etc.	Fresh digestate-fertilizer from household biowaste digester	146 MPs/ kg dry weight	1–2 mm, 2–5 mm	[67]
PES, PE, PP, PET, Cellulose-based polymer, PVC, PA, PUR, etc.	Liquid fertilizer for agricultural use from commercial biowaste digester (waste from local markets, food and drink industries)	895 MPs/ kg dry weight	1–2 mm, 2–5 mm	[67]
Heavy plastics	Municipal solid waste composts	1.2% dry matter	5–30 µm	[172]
Light plastics (PE films)	Municipal solid waste composts	0.3% dry matter	5–30 µm	[172]
LDPE film fragments	Sludge from a biogas plant	Not mentioned	1 mm	[174]
Polyester, PP, PE	Compost from rural domestic waste	2533±457 MPs/kg dry weight	1–3 mm	[175]
Polyester, PP, PE	Compost from rural domestic waste	2267±115 MPs/kg dry weight	0.1–0.5 mm	[175]
PE, PP	Compost from municipal organic waste	21±31 MPs/kg	1–2 mm	[176]
PE, PP	Compost from municipal organic waste	1750±930 MPs/kg	30 µm–2 mm	[176]
–	Compost	2.38–1200 mg plastics/kg	-	[79]
–	Sewage sludge	1000–24,000 plastic items/kg	-	[79]
–	Compost	1200 mg/kg	-	[177]
Plastics and fibers	Sieved compost from municipal bio-waste	1.35±0.59 g items/kg	5–25 mm	[178]
Plastics and fibers	Sieved compost from municipal bio-waste	1357.9±596.0 mg/kg	1–5 mm	[178]

Selected studies were those which quantified micro- and nano-plastics and bioplastics in the OFMSW, in the anaerobic digestion, in the composting process and in the final end-products (sewage sludge and composts)

of plastics and bioplastics debris in agroecosystems, and large amounts of these contaminants may be also transferred to marine environments causing further damage. Moreover, these fragments, if ingested, may pose a greater risk to organisms and subsequently this may support additional transfer and accumulation along food chains [173]. Another of the major gaps in literature is the understanding of micro- and nano-sized plastics and bioplastics particles effects on soil microbiome [20]. This may provide insights into the long-term implications of these contaminants in agroecosystems.

Conclusions and further perspectives

Due to the possible long-term threat to the environment, food security and human health, MPs, NPs, MBPs, NBPs pollution in agroecosystems is an emerging issue which is gaining increasing scientific attention. However, the largest gap in current research relies in their environmental fate and ecological impact in agroecosystems. Huge unpredictability exists because of the limited numbers of data regarding their quantification in each possible source. Indeed, the major hurdles arise from the difficult to quantify these tiny particles and subsequently assess the concentrations, the bioaccumulation risks and toxic effects in the environments and organisms. To evaluate the true risk, a global investigation of these materials in agricultural soils is urgently required. Furthermore, a greater understanding of any potential source of these pollutants to agroecosystems is crucial.

Based on the existing literature, we collected data on contamination by MPs, NPs, MBPs, NBPs in OFMSW and during its transformation into compost and sewage sludge. This review provided insights into the distribution of MPs, NP, MBPs and NBPs in compost and sewage sludge from OFMSW as a possible source of contamination of agroecosystems, but also provided some remarks for protection and governance of terrestrial ecosystem's health. Collaboration among scientists and policy makers is necessary to help ease environmental accumulation of MPs, NPs, MBPs and NBPs. Moreover, it is crucial to evaluate the spatial scale of the problem, predicting the carrying capacity of agroecosystems, and putting the results into a wider context.

Based on the current evidence we have outlined some points for future research:

Biodegradable is not always biodegradable

Biodegradability must be assessed according to the disposal environment, pre-treatments, time and temperature conditions. Highest efficiency is only possible with upstream and downstream balance within the system through a strong communication between biopolymers producers and end-of-life managers. A huge number of studies indicated that the conditions applied at industrial scale are not sufficient to biodegrade the biopolymers used, indicating the discrepancy between industry and standards, and their distance from bioplastics management systems.

The release of MBPs and NBPs is often overlooked and underestimated

Additional investigation and calls for longer field testing are needed to ensure the complete biodegradation. The knowledge gap on the fate of these polymers during the OFMSW treatment as a possible management operation needs to be addressed as only few studies report the actual residues of MBPs and NBPs. A lack of knowledge about the fate of biodegradable residues once transported in soils through composts or sewage sludge, too, is certainly of concern.

OFMSW's collection and treatment at recycling facilities should be tailored

Plastics and bioplastics content within the processed organic waste in terms of quantity and size is crucial to determine if the final sieving step is sufficient to obtain an adequate compost. It is important to predict whether the market-share increase of the bioplastics that are labelled as “disposable within the organic waste” can cause operational problems in plants and in the final compost.

Amounts of MPs and NPs as quality criteria of the final compost and sewage sludge

No critical limits for MPs and NPs pollution in soil have been determined yet. The composting and monitoring processes usually rely on parameters enabling the indirect control of the evolution, while maturity and microbial stability are evaluated only on the final product. The control of the progress of degradation reactions may help to better characterize the compost. The use of compost and sewage sludge obtained from the OFMSW treatment is a very important strategy to comply with the “end-of-waste" policy in Europe, but Regulations still show heterogeneity and blind spots in the characterization of the quality. Moreover, there is the strong need to lower the threshold size for plastics quantification in compost, which is currently set by European legislations at 2 mm.

Nano-plastics and bioplastics particles are considered as emerging contaminants, but their environmental fate, ecosystem toxicity and potential risks have so far been less explored

A wider view of their impact on the agroecosystems and their role as a novel habitat for microbial colonization, and as a vector for pathogens, organic contaminants and metals must be urgently required. Due to their ubiquity, once introduced, complete removal of MPs and NPs is impossible. It is critical to understand what long-term effect they have on both the compost and the soil in which they end up, as well as their biotransformation and bioaccumulation. To evaluate their effect on enzyme activity, microbial diversity, crop yield and crop quality, more ecotoxicological studies are needed. In addition, plasticizers and other contaminants must be considered.

In agroecosystems, the most abundant polymers, their sizes and the extent of contamination is unknown

It is necessary to standardize the techniques for the separation and the detection of these materials, and to define size, shape, composition, crystallinity and contaminants criteria. Therefore, more standards and quantitative methods are needed. This is only a starting point to quantify the present and the future degree of environmental damage caused by MPs, NPs, MBPs and NBPs pollution.

Bioplastics are the new troublemakers for the OFMSW

New strategies are necessary, also at local level, to better manage OFMSW that is variable in composition, quantity and complexity. Public health, resource recovery, and environmental protection should drive cities and countries to improve their waste management systems.

To prevent pollution into the terrestrial environment, it is essential that each possible route of contamination to agroecosystems is analyzed in details

This literature review revealed that many studies on sewage sludge refer exclusively to the wastewater and its treatment plants. Literature bears only a limited number of researches on the fate and quantification of MPs, NPs, MBPs and NBPs during the OFMSW management cycle. In addition, most of the work focuses on the marine environment or other waste management options, such as landfills.

Communication is another gap in this long process

Consumer awareness about the problems that may arise from improper handling of these materials is still low and consumer confusion contributes to the contamination from fossil-based plastics in OFMSW collection plants, or the opposite. Misperception of "biodegradability" may cause disposal of these items in the environments without accompanied guilt. Items labelled as biodegradable, are strictly related to the environment conditions, and these materials does not necessarily degrade in natural habitats quickly.

Abbreviations

OFMSW: Organic fraction of municipal solid waste; MPs: Fossil-based micro-plastic; NPs: Fossil-based nano-plastics; MBPs: Bio-based micro-plastics; NBPs: Bio-based nano-plastics; HM: Heavy metals; PP: Polypropylene; PE: Polyethylene; PS: Polystyrene; PET: Polyethylene terephthalate; PU: Polyurethane; PC: Polycarbonate; LDPE: Low-density polyethylene; SOC: Soil organic carbon; TOC: Total organic carbon; SOM: Soil organic matter.

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Authors' contributions

FB analyzed and interpreted data, was the major contributor in writing the review and conceptualized the original draft; ET analyzed and interpreted data, wrote and conceptualized the original draft; GB reviewed and edited the drafts; FV reviewed and edited the drafts; CM reviewed and edited the drafts; MCG reviewed and edited the drafts; PSC analyzed and supervised the project; EP conceptualized, supervised and edited the drafts. All authors read and approved the final manuscript.

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Availability of data and materials

The data sets used and/or analyzed during the current review are already published available in the cited literature [179–182].

Declarations

Ethics approval and consent to participate

This review is an original paper and has not been published in other journals. The authors agreed to keep the copyright rule.

Consent for publication

The authors agreed to the publication of the manuscript in this journal.

Competing interests

The authors declare that they have no competing interests.

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