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Review

# Interplay of plastic pollution with algae and plants: hidden danger or a blessing?

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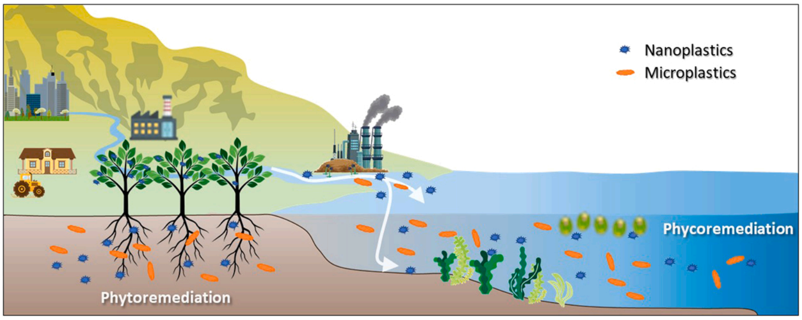
## HIGHLIGHTS

- Plants can absorb nanoplastics mainly via root.
- Transport of nanoplastics from root to shoot is possible.
- Detection of plastic in plant aerial parts points to possible phytoremediation uses.
- Phytoremediation of plastic pollutants can be considered as a future prospect.

## GRAPHICAL ABSTRACT



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## ABSTRACT

In the era of plastic pollution, plants have been discarded as a system that is not affected by micro and nanoplastics, but contrary to beliefs that plants cannot absorb plastic particles, recent research proved otherwise. The presented review gives insight into known aspects of plants' interplay with plastics and how plants' ability to absorb plastic particles can be utilized to remove plastics from water and soil systems. Microplastics usually cannot be absorbed by plant root systems due to their size, but some reports indicate they might enter plant tissues through stomata. On the other hand, nanoparticles can enter plant root systems, and reports of their transport via xylem to upper plant parts have been recorded. Bioaccumulation of nanoplastics in upper plant parts is still not confirmed. The prospects of using biosystems for the remediation of soils contaminated with

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plastics are still unknown. However, algae could be used to degrade plastic particles in water systems through enzyme facilitated degradation processes. Considering the amount of plastic pollution, especially in the oceans, further research is necessary on the utilization of algae in plastic degradation. Special attention should be given to the research concerning utilization of algae with restricted algal growth, ensuring that a different problem is not induced, "sea blooming", during the degradation of plastics.

**Nomenclature**

| | |
|---|---|
| ABS | acrylonitrile butadiene styrene. |
| GC-MS | gas chromatography-mass spectrometry. |
| ICP-MS | inductively coupled plasma mass spectrometry. |
| LDPE | low-density polyethylene. |
| MPs | microplastics. |
| NPs | nanoplastics. |
| NGS | Next-Generation Sequencing. |
| PE | polyethylene. |
| PET | polyethylene terephthalate. |
| PP | polypropylene. |
| PVC | polyvinyl chloride. |
| PS | polystyrene. |
| Py-GC–MS | Pyrolysis-gas chromatography-mass spectrometry. |
| ROS | reactive oxygen species. |
| UV | ultraviolet. |

## 1. Introduction

Today, plastics represent the most widespread environmental pollutant: their production exceeds 350 million tons per year (Galgani et al., 2015), with plastic fragments and waste detected in every environment, including the Mariana Trench’s depths (Galgani et al., 2015; Allen et al., 2019). The annual production of plastics increased from an initial 1.7 million metric in 1959 to more than 380 million metric tons nowadays (Geyer et al., 2017), which is equal to 40 kg of plastic produced per year per every human on Earth (7 billion) (Hohenblum et al., 2015). Plastics can accumulate in water bodies such as oceans and form structures known as plastic islands (Garaba et al., 2018) because of marine currents and wind. Once plastics end up in the environment, their degradation can take up to several hundred years, making them persistent pollutants. Degradation of plastics has different routes depending on the environmental matrix in which they are found and plastics’ chemical composition. The most common process is light-induced photodegradation (Ultraviolet – UV radiation; Yousif and Haddad, 2013), but it can also include mechanical, thermal, and biological degradation (Lambert and Wagner, 2016). It has been shown that the digestive tract of Antarctic Krill and some bacteria can degrade ingested fragments of plastics into smaller fragments that are then dispersed into the environment via faeces (De Tender et al., 2017; Dawson et al., 2018).

In general, it is agreed that plastic debris can be categorized into three main classes: (a) macroplastics, fragments larger than 5 mm, (b) microplastics (MPs), fragments between 5 mm and 100 nm, and (c) nanoplastics (NPs) smaller than 100 nm (Duis and Coors, 2016). The plastic itself is derived from different sources and can be dispersed differently. Terrestrial debris is usually derived from household and industrial wastes, automobile tire abrasion, and residues from the textile industry (Napper and Thompson, 2016). These pose a risk to terrestrial organisms due to obstruction of the digestive and respiratory tracts and by reducing the motility and ability of animals to hunt for food (Ng et al., 2018; Blettler and Mitchell, 2021). Dispersion patterns can be related to particle size; e.g., in city dust, mainly fibrous materials can be found (Abbasi et al., 2019). Wind can move the residues across vast regions and facilitates exposure of humans by inhalation (Gasperi et al., 2018; Evangeliou et al., 2020). Different animals can ingest MPs/NPs that impact their health and development (Rezania et al., 2018). MPs/NPs in organisms can cause a series of adverse effects, including inhibiting their growth and development, affecting food intake and behaviour, and inducing reproductive toxicity, immune toxicity, and genetic damage (Tang et al., 2020; Chen et al., 2021).

Today plastics can be found in all environments, from the soil, and fresh aquatic environments to the deepest waters of oceans (Wan et al., 2019). In water systems, plastic is distributed along the water column, but some of the plastic tends to settle and accumulate in the sediments including polypropylene (PP), polyethylene (PE), polystyrene (PS), polyvinyl chloride (PVC), nylon, cellulose acetate, and polyethylene terephthalate (PET) (Prata et al., 2019; Ahmed et al., 2021). The number of plastic particles per $m^3$ in marine water masses ranges from 0.051 in the Mediterranean Sea (Schmidt et al., 2021) to 5.5 particles per $m^3$ at Cape Verde, Atlantic Ocean (Silvestrova and Stepanova, 2021). It is estimated that in the top water layer of the Atlantic Ocean (200 m depth), 21.1 million tonnes of plastic particles mostly comprised of micro- and nanoplastics (Kataoka et al., 2019). Fresh waters are no exception, an average of 0.8 particles per $m^3$ in Lake Ontario (Grbić et al., 2020) was found with a strong correlation with urbanization (Kataoka et al., 2019; Grbić et al., 2020).

The problem of plastic pollution in the soil has been identified by Rillig (2012), with identified levels of pollution ranging from 160 particles per kg of soil in the forest ecosystems to 1108 particles per kg of soil close to road traffic infrastructure. Plastics in the soil impact microbial communities as well as plants (Choi et al., 2021) including effects on soil aggregation, bulk density, water holding capacity, pore structure (Ng et al., 2021), soil cycling (organic carbon and nitrogen), soil microbes’ activity, and nutrient transfer, or can stimulate soil enzyme activities and the accumulation of soluble nutrients accumulation of in the soil (Qi et al., 2020a, 2020b). The biggest impact on plants is through the rhizosphere including changes in microbial communities, and arbuscular mycorrhizal fungi in the rhizosphere impact plant growth (Ng et al., 2021; Sun et al., 2022b). Additionally, MPs could affect plant characteristics through soil structure and water content changes, directly affecting competition among different plant species and suggesting that MPs could potentially threaten biodiversity in terrestrial environments (Ren et al., 2021).

Considering the ubiquity of plastic pollution and its dangers, the objective of this review was to shed light on how algae in marine environments and plants in terrestrial ecosystems are impacted by plastic pollution and future frontiers of exploitation of plants and algae in solving the plastic pollution problem.

## 2. Micro- and nanoplastics detection in plant tissues

Accumulation of nanoparticles in leaf tissues and even in grain has been recorded. Plastic particles have been detected in epidermal leaf tissues of *Lepidium sativum* (Bosker et al., 2019), in intercellular spaces of leaf veins of lettuce, flower and fruits of cucumber (Li, L. et al., 2020). Translocation and accumulation of nanoparticles can be correlated to the exposure concentration, as recorded in *Murraya exotica* (Zhang et al., 2019).

The identification and characterization of MPs in plant tissue has been achieved through Raman confocal microscopy, a fingerprinting technique that maps and characterizes cross-sections of plant tissue

(Fig. 1). As described by (Tympa et al., 2021) Raman confocal microscopy enables the characterization of acrylonitrile butadiene styrene (ABS) MPs as demonstrated in root tissue of *Raphanus sativus* where clear differentiation of MPs from other similar plant tissue structures is achieved, making detection of MPs possible.

To accurately assess the MPs and NPs toxicity in plants, there is necessary to standardize the identification and quantification methods. Nowadays, one of the methods to identify and measure polymers accurately are techniques based on gas chromatography-mass spectrometry (GC-MS). To measure these particles in water or sediments, the most common is the Pyrolysis-gas chromatography-mass spectrometry (Py-GC–MS) which analyses thermally decomposed gases from polymers compared with GC–MS profiles of virgin polymers standards. Py-GC–MS allows the detection of NPs and MPs, mass concentration and the possible products of their decomposition (Ahmed et al., 2021). With only few studies available, MS-based methods for MPs and NPs measurement in plant species are still being developed. The Py-GC/MS based method has been successfully developed to quantify NPs in *Cucumber* plants, using a small amount of tissue (Li et al., 2021). This emerging method allows the determination of NPs in complex plant matrices thanks to a 4-step pre-treatment to remove the thermal-decomposable compounds from the tissue residues without disturbing NPs nature (Li, C. et al., 2021). Another emergent MS based method to study NP and MP is based on the chelation of NPs with a non-endogenous metal tracer followed by inductively coupled plasma mass spectrometry (ICP-MS) measurement. Del Real et al. (2022) quantified NPs in wheat tissues by treating them with palladium (Pd)-doped NPs. Nonetheless, this method is only applicable in research, it has the advantage of a lower detection limit, allowing the quantification of 10 times less NPs than other techniques not based on mass spectrometry (Del Real et al., 2022). As for other molecules, targeted approaches based on dedicated isolation procedures and liquid or gas chromatography coupled to mass spectrometry are preferred for absolute quantification of micro and nanoplastics, but standardized protocols still need to be developed.

## 3. Mechanisms of absorption of micro- and nanoplastics by algae and higher plants

In marine ecosystems the biggest impact of plastic pollution in the context of the effects on plant life can be observed in algae comprising phytoplankton. Bhattacharya et al. (2010) studied the effects of 20 nm nano-polystyrene on two species of algae: *Chlorella* and *Scenedesmus*. They showed that positively charged particles are adsorbed on the surface of algae more than negatively charged ones. This is the first step in microalgal absorption, but only this contamination can reduce the photosynthetic rates of these algae affecting ocean carbon stock, and the subsequent plastic contamination in zooplankton and sea macrofauna (Shen et al., 2020a). In a second step, plastics can be introduced within the cell following active or passive transportation of the pollutant into the cell. Nano and microplastics (diameter $< 10$ μm) can passively cross eukaryotic membranes and use non-specific channels (Campanale et al., 2020). Active assimilation involves specific carriers crossing the cytoplasmic membrane, and are usually coupled to catabolic pathways to oxidize plastics for energy and biomass production. Alternatively, plastics can be imobilized within algal cell walls or in the vacuole to prevent toxic effects on the cell (Barone et al., 2020). Furthermore, microalgae can form biofilms over plastics, actively inducing cracking and increasing its surface/volume and secrete degradative enzymes, which also helps reduce the plastics' molecular weight, facilitating the introduction of the molecules within the cell (see Section 4).

In terrestrial ecosystems nanoparticles can enter plant tissues through two main entrance points: roots (root hairs) and leaves (through stomata). In the case of the root uptake mechanism, a "crack-entry" pathway through the cell wall has been proposed by (Li, L. et al., 2020). During ageing, root openings are developed as a natural consequence, but also through damage by below-ground herbivores and mechanical

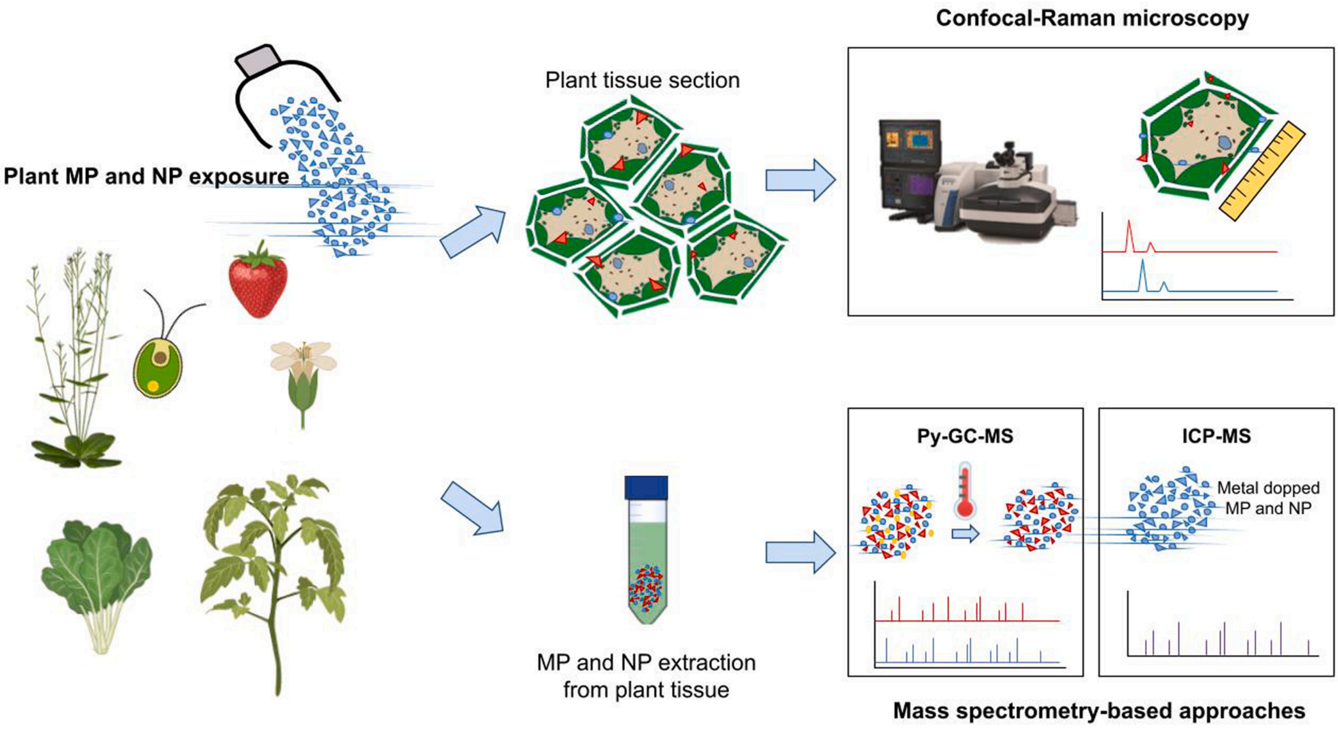

**Fig. 1.** Methods for MP and NP detection in plant samples, Confocal-Raman microscopy allows the identification and characterization of shape and size of MP/NPs in plant tissue sections. Mass spectrometry-based approaches allow the accurate identification and quantification of MPs/NPs from a plant extract. Pyrolysis-Gas chromatography mass spectrometry (Py-GC-MS) is based on the pyrolysis of the extract, leaving the plastic components resistant to high temperatures which are MS measured. Plant exposure of metal doped MP/NPs allows its quantification with Inductively Coupled Plasma (ICP-MS).
Modified from: BioRender, ThermoScientific.

injuries. When nanoparticles enter through the openings and reach the central cylinder, they are self-assembling. Regardless of the point of entry, and when nanoparticles are in the vascular system, they can be transported away from the entry point to other plant tissues all the way up to the leaves (Azeem et al., 2021). Microplastics can penetrate different plant organs only to a certain degree due to their high molecular weight, preventing them from penetrating through cellulose-rich plant walls (Dietz et al., 2011). This fact led to the presumption that microplastics are unlikely to be absorbed by plants, but degraded nanoparticles are more likely to enter plant cells reported for different plants (Kumari et al., 2022). Polystyrene beads above 100 nm can be trapped in the root hair mucilage cap (Li et al., 2020a), while particles 20–40 nm in diameter can easily cross various biological membranes and be transported into the above-ground plant tissues (Bandmann et al., 2012). Some larger nanoparticles (100–700 nm) have been recorded in aboveground plant structures in cases of cucumber hydroponics (Li, L. et al., 2020; Li, H., 2020; Li, Z. et al., 2020).

Penetration of nanoparticles into the root has been recorded for rice (Zhou et al., 2021a), onion (Giorgetti et al., 2020), wheat and lettuce (Li, H. et al., 2020). Blockage of nanoparticles in the mucilage region results from the accumulation of negatively charged root exudates, inhibiting the uptake of positively charged nanoparticles (Avellan et al., 2017). Further research using fluorescence labelling indicated that 0.2 mm particles could pass through intracellular channels and enter an apoplastic transport pathway enabling the particles to enter apical meristem as recorded in wheat and lettuce. Entrance to apical meristem was possible due to incomplete casparian strip, with translocation to the vascular tissues of lettuce, indicating a possible entry pathway (crack--entry mode) of plastics into plant tissues (Li, L. et al., 2020).

In the rhizosphere, microbial enzymes involved in the nutrient cycle, such as β-glucosidase, urease, and phosphatase, can affect the substance uptake of plant roots (Zhang et al., 2021). Once nanoparticles enter the root cells, transpiration pull can translocate the particles by pushing them to the pericycle and then to xylem from where particles are transported to aerial plant parts (Schwab et al., 2020; Azeem et al., 2021). Larger particles (2 mm) can enter the root through crack-entry mode at the primary root initiation site (Li, H. et al., 2020b). Water potential gradient created through transpiration pull can facilitate the transport of 2–0.2 mm particles as recorded in xylem sap and leaves of lettuce and wheat (Lian et al., 2020). Furthermore, the ability of plastic particles to adsorb pollutants such as heavy metals may facilitate their entry into plant cells (Wang et al., 2022). In a study conducted by Dong et al. (2021), arsenic caused cell wall deformation and facilitated the entry of plastic particles into the plant.

Liu et al. (2022) performed experiments to test root uptake and translocation and transport to the rest of the plant, demonstrating greater susceptibility of younger plants to nanoplastics. Two-week-old *Lactuca sativa* and *Triticum aestivum* plants accumulate more microplastics in the intercellular spaces and transport some of them via the xylem to the leaves. On the other hand, one-month-old plants showed less root accumulation, and no transport to the leaves was observed. In another study using another very important species from an agri-food point of view, they have seen that in *Cucumis sativus* nanopolystyrene with a diameter range between 100 and 700 nm enters the roots and accumulates both in fruits and flowers. In particular, the highest concentrations were observed with those of 100 nm diameter (Azeem et al., 2021).

Absorption of nanoparticles through leaves can encounter barriers as recorded for metal-based nanoparticles, where cuticles can play a significant role as a barrier for nanoparticles transport, especially in higher plants where waxy cuticles can be a significant barrier (Lv et al., 2019). In some cases, depending on their nature (particles smaller than 4.8 nm), nanoparticles can cross the cuticular and enter the plant tissues layer (Lv et al., 2019), but in the case of the nano-plastics main route of the entrance is through stomata (Adeel et al., 2018). Furthermore, nanoparticles accumulated in the leaves due to the entrance through stomata can move to the leaf veins and be translocated to the root by xylem as recorded in lettuce plants (Lian et al., 2021). In foliar absorption through stomata, negatively as well as positively charged nanoparticles can enter plant tissues and further be transported through xylem to other plant organs, including the root (Sun et al., 2020).

## 4. Effects of micro- and nanoplastics on algae

### 4.1. Effect on algae

When plastic interacts with algae, the accumulation of plastic particles can result in reduced photosynthetic capacity of the organism due to the reduction of the amount of light passing to the algae, resulting in reduced survival, and increased oxidative stress. Similarly, Casado et al. (2013) and Bergami et al. (2017) observed a reduction in the growth of *Pseudokirchneriella subcapitata*, *Dunaliella tertiolecta*, and *Artemia franciscana*. In contrast, Long et al. (2017) observed no effect on the physiology of the algae *Chaetoceros neogracile*, *Tisochrysis lutea*, and *Hormophysa triqueta* in case of particles larger than 1 μm but instead noted a tendency of particles to aggregate. Lagarde et al. (2016) demonstrated the same tendency to aggregation in particles ranging from 400 to 1000 micrometres in diameter. Sjollema et al. (2016) found no effect on photosynthesis but a dramatic reduction in algal growth. Laboratory research on *Scenedesmus obliquus* (Besseling et al., 2014) and *Scenedesmus costatum* (Zhang et al., 2017) demonstrated a reduction of chlorophyll content, but the concentrations of plastic particles in the experiment exceeded the concentrations that are recorded in aquatic ecosystems. When particle concentrations were closer to the environmental ones, the effects are more contained, and in some cases, enhanced growth is recorded (Sjollema et al., 2016). However, in experimental setups, exposure times are short compared to environmental exposure of algae to plastic pollution, and obtained results must be taken with caution. *In vivo,* prolonged exposure of algae to even lower particle concentrations would reduce growth rate and, in some species, chlorophyll content and photosynthetic rate. Plastic biodegradation exhibited by microalgae occurs in four essential steps, as described by Dussud and Ghiglione (2014): biodeterioration (microalgal biofilm over plastic surface, increasing pore size and provoking cracking, which may be helped with modifying the pH inside plastic pores), biofragmentation (extracellular enzymes which reduce the molecular weight of polymers in order to be assimilated), assimilation (use plastics as carbon source) and mineralization as the ultimate step excreting completely oxidized metabolites ($CO_2$, $N_2$, $CH_4$ and/or $H_2O$). Not all microalgae species can perform these four steps, neither all plastics can be processed, so a wide range of metabolic responses can be observed ranging from a carbon storage compound enhancing cell growth (PHB in the model cyanobacterium *Synechocystis* (Wu et al., 2001) to a near-complete metabolic disruption (Bisphenol A in *Mycrocystis aeruginosa* (Yang et al., 2020). As an example, the bioassimilation involves several enzymatic steps, for instance, the metabolic incorporation of PHB only requires two steps for being processed by ß-oxidation enzymes, and four to reach the form of acetyl-CoA while polystyrene requires 12 steps to be transformed into succinyl-CoA (Jacquin et al., 2020). The toxic effects of plastic particles on algae largely depend on the characteristics of the algae membranes and their species-specific physiology and the type of polymer considered (Zhang et al., 2017). Further research is necessary to fully understand these effects, as to how the different nanoplastics disrupt metabolism is still not clear. Special attention should be given to investigation of sorption/absorption of micro and nanoplastics to/by edible algae such as seaweed *Fucus vesiculosus* and nori. In sorption of microplastics, it is possible to remove the particles by simple washing (Sundbæk et al., 2018) but in the case of nori seaweed, microplastics were detected commercially and factory-processed nori seaweed (H. Li q. et al., 2020; Z. Li q. et al., 2020; Q. Li q. et al., 2020; L. Li q. et al., 2020).

Because of their density, microplastics sediment on the seabed brings other elements and promotes a recirculation of nutrients and minerals, resulting in eutrophication and algal bloom. Nitrifying bacteria have been shown to be found especially associated with suspended materials. Microplastics could therefore favour the substrate suitable for the proliferation of these bacteria with increased production of $N_2O$ and $CO_2$ caused by their nitrifying and carbon crystallizing activity, respectively. The consequences would also lead to changes in the pH of the water as well as the release of greenhouse gases (Rillig et al., 2021).

### 4.2. *Effect on terrestrial plants*

The interaction between plastic particles and terrestrial plants causes oxidative stress and adversely impacts photosynthesis, metabolism, genetic expression, and other growth parameters. Furthermore, the combination of MP/NP pollution with other contaminants makes the joint effect more complex. Once absorbed, MPs/NPs can have several impacts on the roots, including impairing the uptake of water and nutrients and reducing the transpiration rate, resulting in adverse effects on other tissues or the entire plant, which are also affected by particles transported from the roots (Fig. 2). MPs/NPs also impact the development of seedlings, shoots, stems, leaves, and fruits (Chen et al., 2022).

#### 4.2.1. *Physiological effects*

Although the effect of MPs on plant health remains understudied, there are indications of some effects on photosynthesis and plant growth (Tang et al., 2021). Beyond the direct effects on plant health, it has been shown that MPs presence in the plants' environment can positively or negatively influence the plant developmental stage (Bosker et al., 2019; Qi et al., 2020a, 2020b). Studies on the presence of MPs in plants reveal negative impacts, like in the organs of wheat, in both vegetative and reproductive development (Qi et al., 2018), and the accumulation of MPs in the tissue of the edible parts of *Raphanus sativus* (Tympa et al., 2021). Moreover, when this refers to edible root plants, the risk of nanoplastic contamination is transferred to the food chain posing a risk to human health where MPs contamination might trigger inflammatory and immune reactions (Vethaak and Legler, 2021). In contrast, other studies show that no MPs were present in plant tissues beyond root cap (Taylor et al., 2020).

In higher plants, roots represent the main uptake pathways. Bosker et al. (2019) demonstrated how nanoplastics of 50–4800 nm in diameter adhere to seeds and remain attached to the roots, reducing plant growth. On the other hand, Taylor et al. (2020) did not observe uptake by the *Arabidopsis thaliana* roots or other effects on photosynthesis and development. Studies have shown adverse effects of plastic contamination on plant growth and development, and prolonged exposure (four months) to low-density polyethylene (LDPE) induced reduction in plant growth, including reproductive organs (Li, Z. et al., 2021). The results are interesting since shorter exposure to PET induced an increase in root mass (Gopinath et al., 2019), suggesting that laboratory experiments need to consider the duration of the exposure. The entry of micro- and nanoplastics into plant cells can affect plant processes at cellular, causing growth defects and plant development malformations due to increased oxidative stress and increased synthesis of antioxidant enzymes has been recorded in *Vicia faba* (Etxeberria et al., 2006). The presence of other contaminants might also promote a synergistic effect with increased adverse effects (Qi et al., 2018), but it is a complex topic and confronting results have been recorded. In the case of co-presence of micro- and nanoplastics and heavy metals, growth inhibition and excess carbohydrate content was recorded in *Triticum aestivum* (Lozano and Rillig, 2020; Zhou et al., 2021b), while in some cases reduced metal uptake is recorded due to micro- and nanoplastics complexation with metals (Taylor et al., 2020). During the degradation process of polypropylene, polystyrene and polyethylene, ethylene and methane are released with a consequent increase in the greenhouse effect. An estimated 2.129 Mt of methane is released per year (Shen et al., 2020b).

#### 4.2.2. *Impact of soil plastic contamination on the plant ionome*

MPs and NPs have been shown to adsorb and accumulate a variety of inorganic elements, hence altering soil characteristics (Khalid et al., 2020; Zhou et al., 2019). This can lead to abnormal absorption and translocation of plant mineral elements (Besson et al., 2020), thus representing another indirect aspect of toxicity of plastic particles since adequate mineral nutrition is fundamental for plant growth and development (Marschner, 1995). Element adsorption to MPs and NPs can be best explained by electrostatic interactions and pore-filling mechanisms (Maity et al., 2020). It can vary according to several factors that affect whether substances adsorb onto the surface of microplastic particles. The latter can depend on the type, size, polarity and age of the material and the pH and salinity of the soil (Okeke et al., 2022). Therefore, the bioavailability of elements can be either increased or decreased depending on the interaction of microplastic particles and nutrients with

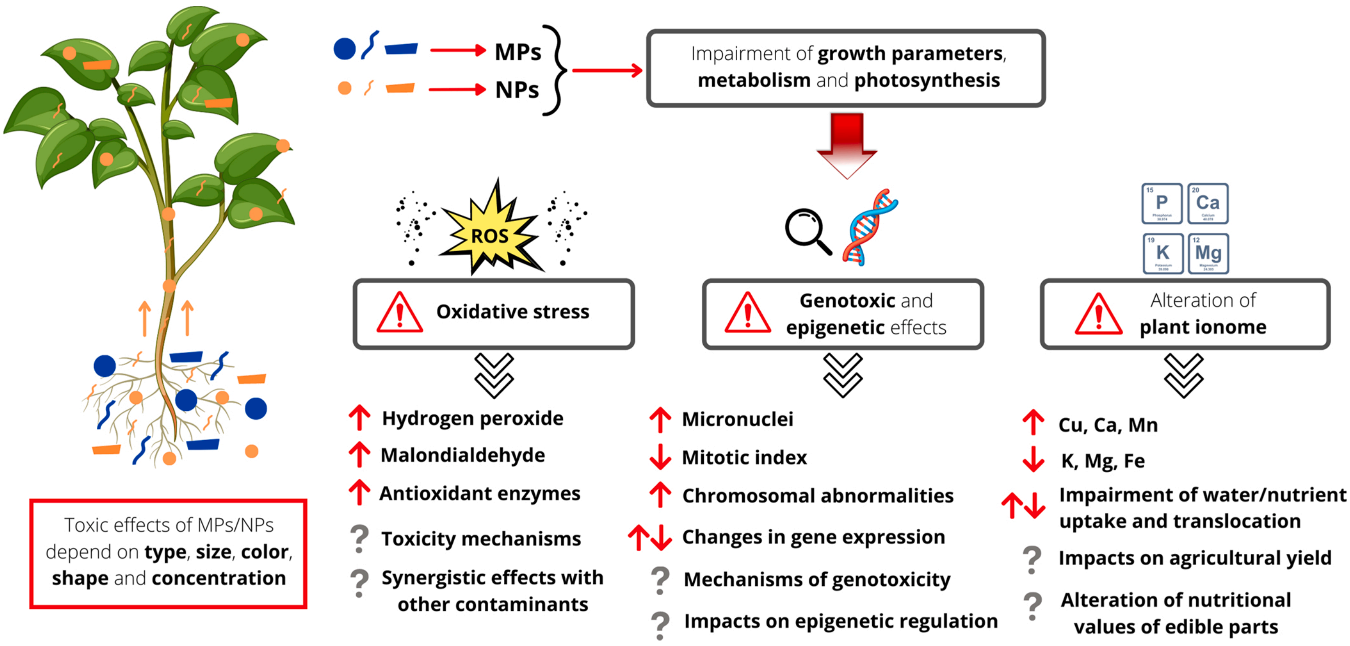

**Fig. 2.** A summary of plants interplay with plastic pollution and its effect on plant growth and development.

the environment they are in (Nicole et al., 2017; Bradney et al., 2019; Yu et al., 2020). Consequently, both excess and depletion of the mineral elements can occur in soils contaminated by plastic particles, thus reflecting alterations in the plant's nutritional status. Moreover, microplastics can indirectly affect the bioavailability of elements through their effect on the soil microorganism, influencing the levels of several soil enzymatic activities (Huang et al., 2019a, 2019b; Zhang et al., 2017). On the plant side, as Bosker et al. (2019) reported, plastic particles might disturb the typical development of root structure and the formation of root hairs. The consequent limitation of water uptake can affect the nutrient accumulation in the plant body. Finally, direct microplastic toxicity on root development and functioning, as demonstrated in PE hydroponically exposed plants (Urbina et al., 2020), can be another factor to further impair plant element absorption and translocation.

Despite the abundant information about the changes in the soil mineral status by plastic pollutants (Wang et al., 2022), studies assessing the interaction between soil plastic pollution and the plant ionome are still extremely scarce. The few information present in literature reports that micro/nanoplastics can factually alter the plant concentration of macro- and micro-nutrients depending on contaminant type, concentration, and organ considered. Colzi et al. (2022) demonstrated that the presence of PE, PET, PP and PVC microparticles, in a concentration ranging from 0.02% to 0.2% in the soil, induces several significant variations in root, stem and shoot element concentration in *Cucurbita pepo* plants, thus negatively affecting plant biomass production. They reported that the most toxic microplastic was PVC, which was shown to induce the highest number of significant variations in element concentration in all the organs studied, whereas the less toxic was PE, whose presence in the soil perturbed the plant ionome only to a minimal extent. Particularly, microplastic-impaired root growth depended on material-specific decreases in the level of some elements, such as K, Mg, Zn and Fe, and increases in the levels of others, such as Cu, Ca, and Mn. Microplastic-induced variations in the root ionome were found to correspond to alterations of element accumulation in stems and leaves, probably due to a mutual effect of the studied materials on ion uptake and, even more, on translocation (Colzi et al., 2022). Microplastics were reported to induce excessive increases in the shoot concentration of the micronutrients Zn and Cu and a significant decrease in the amount of the macronutrient K below the normality range for plant shoots (Marschner, 1995; Kabata-Pendias and Pendias, 2001), thus largely concurring to the reduction in plant growth. Colzi et al. (2022) reported that the large decline in leaf chlorophyll content that occurred in PVC-exposed plants could be linked to the strong capability of this plastic material to reduce the plant concentration of Fe, an element that is involved in the biosynthesis of that pigment (Marschner, 1995). So far, and to the best of our knowledge, the only other work present in literature that examined whether microplastic treatment can affect the plant ion composition is a study by Fu et al. (2022) on PE-treated *Zea mais* plants. They demonstrated that PE pollution altered the soil element adsorption capacity, thus leading to differences in the bioavailability of the elements. This indirectly affected the uptake, translocation, and distribution of the nutrients by the root system to the whole plant. The greatest interference of PE-particles in mineral accumulation was present in the roots, followed by the stems, and then by the leaves. In particular, the root concentrations of Mg and K were significantly lower in plants grown in the presence of the microplastic in respect to control samples. The leaf amount of Mg and P was significantly lower in PE-treated plants compared to control samples. The negative influence of PE on the plant photosynthetic performance was explained by such plastic-induced impact on the elemental profile of the leaves (Fu et al., 2022).

Overall, the information reviewed here about the capacity of the presence of microplastics in the soil to affect the plant ionome negatively appears fundamental in directing future research to more comprehensive research on this aspect of plastic pollution. The identification of microplastic-treated plant element composition is essential to assess not only the general threat that such contaminants can have to the plant organisms but also the possible negative effects of such materials on the mineral nutritional values of vegetables destined for the human diet and on the actual productivity of the agroecosystems.

#### 4.2.3. Genotoxic and epigenetic effects of micro- and nanoplastics on plants

Plants must adapt to several stressful conditions, among which, nowadays, the accumulation of plastic pollutants in the environment represents one of the most threatening (Yin et al., 2021). A key role in plant adaptation is played by phenotypic plasticity, that is the potential expression of various phenotypes by a single genotype (Arnold et al., 2019; Nicotra et al., 2010) and can be mediated at molecular level: differential gene expression, determined by epigenetic processes or other modifications (i.e. post-translational modifications of transcription factors), can result in adaptive, neutral or maladaptive plasticity according to its relationship with individual fitness (Nicotra et al., 2010). In this context, an influence of plastic contaminants on plant genomes and/or epigenomes can be expected, not only because micro- and nanoplastics exert a negative impact on plant growth, changing the soil properties, but also because they can be directly toxic, both interacting with the plant surface and entering the plant body.

Microparticles are mostly adsorbed on plant surfaces (i.e. root epidermis), but nanoparticles can be up-taken by plants through various mechanisms: passive diffusion, facilitated diffusion, endocytosis, stomatal openings and wound or lesions on roots (Wu et al., 2021). Submicrometric plastic particles have been demonstrated to penetrate even inside vascular tissues, consequently being transported from roots to the aerial parts (Li, L. et al., 2020; Sun et al., 2020). Nanoplastics are thus expected to have a major impact concerning microplastics, mainly because they can enter inside the cells and interact at a molecular level thanks to their extremely small size (≤100 nm) (Wu et al., 2021; López de las Hazas et al., 2021). For now, no nuclear localization of plastics has been demonstrated in plant cells, even if Wang et al. (2022) proved the accumulation of polymethylmethacrylate (PMMA) nanoparticles inside the protoplasts of *Hordeum vulgare*.

The entrance of nanoplastics inside cellular organelles can explain their ability to damage plant cells and affect plant genome functioning, which has been reported in several works (Matthews et al., 2021). For instance, using *Allium cepa* as a model for the evaluation of cytotoxicity and genotoxicity of environmental pollutants, Maity et al. (2020) and Giorgetti et al. (2020) studied the harmful effects of PS particles with a diameter of 100 nm and 50 nm, respectively. In both cases, a time and dose-dependent decrease in the mitotic index of root tips was reported with a parallel increase in the number of micronuclei. Together with the occurrence of nuclear and chromosomal abnormalities, these observations reveal the potential cytogenotoxicity of micro- and nanoplastics, even if the tested concentrations (from a minimum of 0,01 g/L to a maximum of 1 g/L) may not be realistic because of their difficult assessment in natural environments.

Oxidative stress and inhibition of cell cycle regulators (i.e. CDC2) have been proposed as the main mechanisms by which plastics exerts this type of toxicity (Maity et al., 2020; Giorgetti et al., 2020). It is important to note that these studies used traditional microscopy techniques. Consequently, the genotoxic effects of plastic particles have to be verified with molecular techniques (i.e. PCR-based methods or Next-Generation Sequencing - NGS techniques). Lagarde et al. (2016) observed an increase in the expression of genes involved in xylose and galactose biosynthesis followed by exposure to nanoparticles. Similarly, it has been demonstrated that rice exposure to nanopolystyrene particles (19 micrometres) enhances the expression of genes involved in the metabolism and synthesis of sucrose and soluble sugars (Dong et al., 2021).

Within this framework, micro- and nanoplastics can be expected also to affect epigenetic regulation, one of the mechanisms through which plants and other living organisms are able to modify gene expression and adapt to different environmental conditions. Epigenetic modifications do not refer to changes in DNA sequence, but include DNA methylation, histone modifications and small RNAs (Thiebaut et al., 2019). A few studies have reported that micro- and nanoplastics are able to influence the epigenome of animal cells (López de las Hazas et al., 2021). For example, nanoplastics exposure for 72 h in *Caenorhabditis elegans* increases the expression of cell death protein type 3 (*ced-3*). Increased expression of this protein is maintained across generations because of hypomethylation in the promoter region, resulting in increased germline apoptosis (López de las Hazas et al., 2021; Yu et al., 2021). Furthermore, microplastics have been reported to alter the DNA methylation status of *Lepomis macrochirus* cells in vitro, independently of dose and time of exposure (Wilkinson et al., 2020). Nothing is known about epigenetic effects on plant organisms since the interaction between plastic particles and plants has gained attention only in the last years, mainly due to potential plastic trophic transfer and the abundance of plastic pollutants in agroecosystems (Ng et al., 2018; Yin et al., 2021).

Oxidative stress is thought to be strictly linked to epigenetic regulation during plant development. For example, the activity of two DNA demethylases (ROS1 and DME) is altered by oxidative conditions. Therefore, DNA methylation patterns are clearly connected to ROS metabolism (Huang et al., 2019a, 2019b) and reactive oxygen species (ROS) metabolism in *A. thaliana* has been reported to be altered by nanoplastics. Plants exposed to such contaminants show $H_2O_2$ accumulation in the roots, which correlates to downregulation of various peroxidases (Sun et al., 2020). In addition, Pignattelli et al. (2020) have reported a high concentration of $H_2O_2$ in *Lepidium sativum* grown for 21 days in the soil supplemented with polyethylene and polyvinylchloride microplastics. Another plant species that has exhibited ROS accumulation after microplastics exposure is rice (*Oryza sativa*) (Wu et al., 2021). Micro- and nanoplastics can thus have relevant epigenetic effects on plants by impacting ROS production and ROS scavenging processes.

The need to further explore this topic comes primarily from the fact that various nanomaterials and nanoparticles, different from plastics in chemical composition, have a relevant impact on epigenetic mechanisms, both in vitro and in vivo (Pogribna et al., 2021); being so widespread, plastics deserve undoubtedly more attention. On the other hand, there can be the opportunity of understanding molecular processes and identifying key genes involved in plant responses to micro- and nanoplastics exposure (Sun et al., 2020).

DNA methylation of cytosines at position 5 of the pyrimidine ring (5-Me-C) is the best-studied and the most widespread epigenetic modification: 20%− 30% of cytosine residues in plant genomes are methylated under non-stressful conditions (Sun et al., 2020; Thiebaut et al., 2019). Exploring DNA methylation patterns in various contexts is essential because not only they are crucial for the correct regulation of growth and development, but also variations in these patterns are heritable across generations, triggering stress-induced gene evolution (Chwialkowska et al., 2017; Duan et al., 2018; Sun et al., 2020).

## 5. Plant biotechnological approaches for micro- and nano plastics management

Plastics can be classified into non-biodegradable and biodegradable polymers. The process of plastic biodegradation depends on multiple parameters including the polymer type and structure, the environmental, physicochemical conditions, oxygen level, as also on microorganisms, and others. Significant biodegradation rate changes can be observed between the structural and physiochemical properties of polymer surfaces (Nakasaki et al., 2006) since they affect the level of interaction with microorganisms (Bátori et al., 2018, Volova et al., 2010). The presence of oxygen plays another strong role in the biodegradation rate due to the microbial enzyme activity (Thakur et al., 2018). The decomposition rate is also highly affected by environmental conditions (Endres et al., 2017, Nakasaki et al., 2006), which often results in incomplete mineralization of the polymers (Folino et al., 2021). The several kinds of soil environments influence it in nature, which have different characteristics, different microorganisms' population, as well the different pH. (Emadian et al., 2017; Arcos-Hernandez et al., 2012; Boyandin et al., 2013). Furthermore, all those factors can change from one location to another, and between different seasons (Siracusa, 2019). Lastly, it is found that the biodegradation rate is higher in seawater than in fresh water sources, and specifically at the water-sediment interface (Volova et al., 2010).

Plant-based biotechnological approaches for plastics management include algae for biodegradation of plastics and the new emerging possibility of using hyperaccumulating plants for soil and water remediation using plants to extract plastic pollutants. Phytoremediation (green remediation, vegetative remediation, agroremediation) uses vegetation and associated microbiota to contain, render or remove environmental contaminants (Sumiahadi and Acar, 2018). In the past ten years, using plants for plastic waste management has emerged as an eco-friendly option through the use of hyper-accumulating plants for plastic contamination removal (Rai et al., 2019). The selection of appropriate remediation plants is subjected to many factors, including but not limited to properties of micro/nano-plastic contaminants, soil properties and physical characteristics of the site, type, and the level of contamination (Ebere et al., 2019). Recent research has demonstrated promising results for the potential use of plants to remove microplastic in terrestrial ecosystems (Bandmann et al., 2012; Ebere et al., 2019). One of the examples of how plants can facilitate nanoparticle remediation from water systems is research done on wetland ecosystems. Dense wetland soil vegetation can filter nanoparticles, including polystyrene and synthetic rubber (Helcoski et al., 2020). Similarly, mangrove ecosystems were able to trap marine litter and microplastic fragments through the action of mangrove associated plants such as wetland duckweed (*Lemna minor*) or sediment rooted *Myriophyllum spicatum* and *Elodea* sp. plants (Mateos-Cárdenas et al., 2019; van Weert et al., 2019).

Phytoremediation of microplastics can be achieved in three ways (Ebere et al., 2019):

1. through phytoextraction (phytoaccumulation) – where plants tolerant to plastic pollution can accumulate plastic particles in above-ground parts with high biomass yield, rapid growth, and high bioaccumulation rate. Many plants could be used for such purposes, including fruits, vegetables, and root crops but such plants would have no value for consummation and would be used solely for microplastics extraction purposes.
2. Phytostabilization – can decrease the amount of water that percolates through the soil matrix and act as a barrier to direct contact with contaminated soil. In this method, pollutants are only stabilized in the rhizosphere, and there is no actual removal of the pollutants from the soil. Some ornamental plants can be used for phytostabilization.
3. Phytofiltration – enables accumulation of pollutants in profuse root systems of a tolerant plant, removing the pollutant from the soil. Some plants that could be used for phytofiltration of microplastics are sunflower, Indian mustard, spinach, corn, cattail etc.

Phytoremediation is considered economically viable with a high acceptance rate by the public and reduced risk of spreading the contamination and can be used simultaneously for remediation of more than one type of pollutant (e.g., heavy metals and microplastics). On the other hand, some of the phytoremediation types, such as phytostabilization may not remove the pollutant, and in cases of phytofiltration removal of roots with accumulated plastics can be complicated and not effective, with the potential of leaving part of the roots loaded with plastics in the soil (Ebere et al., 2019). Adhered particles to the plant roots in the process of phytofiltration can stabilize plastics, disabling the plastics from entering other plant root systems, thus decreasing contamination of crops (Bosker et al., 2019).

Accumulation of different plastics have been reported for several plants, polystyrene beads and microplastics have been recorded in wheat (Qi et al., 2018), *Arabidopsis thaliana* (Sun et al., 2020), onion (Maity et al., 2020), lettuce (Gao et al., 2019) cress (Boots et al., 2019), spring onion (de Souza Machado et al., 2019), cucumber (Li, Z. et al., 2021). Accumulation of polystyrene fibres (PES) 1.28 in length and diameter of 30 mm has been recorded in grasses (e.g., *Festuca brevipila*) and herbs (e.g., *Achillea millefolium*) (Lozano and Rillig, 2020). Additionally, transport of polystyrene microspheres through plant xylem can decrease their cohesion, leading to their degradation as recorded in cucumber leaves (Sun et al., 2020).

Due to their small size and specific surface, MPs and NPs particles are bioavailable to aquatic plants and algae, causing toxic effects (Xu et al., 2019). Plants represent an important part of the trophic chain, highlighting the key role of microalgae as essential primary producers in aquatic environments. Several advantages are associated with microalgae phycoremediation including easy cultivation and short life span together with the accumulation of high value biomolecules as lipids and proteins make these species interesting. Several research regarding phycoremediation are oriented toward biotransformation of microplastics using microalgae. It has been shown that some microalgae can use MP and NP as a carbon sources through the process of enzymatic degradation leading to enhanced growth (Priyadharshini et al., 2021). For example, the growth of *Chlorella* sp. L38 is promoted when cultivated with polyethylene terephthalate and PVC (sizes: 74 μM; concentrations 200 mg/L) (Song et al., 2020). Several studies have been investigating the potential of microalgae facilitated enzyme dependent degradation of micro and nanoplastics with promising results of overexpression of polyethylene terephthalate-degrading enzyme (PETase) in the microalgae model *Chlamydomonas reinhardtii* and the diatom *Phaeodactylum tricornutum* (Moog et al., 2019; Kim et al., 2020). In addition, recently phthalate-degrading enzymes have been identified for the first time in the diatom *Cylindrotheca closterium* (Vingiani et al., 2022) making this species a promising model for plastic bioremediation. However, further research is needed to completely understand the underlying mechanisms for scalability and efficient use of microalgae in plastic clean-up.

## 6. Challenges and frontiers in nano- and micro-plastics management

Possibilities of plastics management using plants should be considered, but at the same time there are many challenges to effective phytoremediation of microplastics. First obstacle is the diameter of microplastics particles. There must be more comprehensive research to investigate how plants interact with microplastics. Phytoextraction of nanoplastics could be one of the options, using plants for absorption and translocation of nanoplastics from the soil to the aerial plant parts. The possibility of the plant absorbing the nanoplastics has been demonstrated, but it is still unknown whether the plant can achieve bioaccumulation of nanoplastics to be an effective remediator. Other options could be the immobilization of microplastics by binding to the roots, but then the challenge would be how to remove the plant without breaking the bond between the root and microplastics. Development of pre-treatments (priming) techniques that could prime the crops for avoidance and exclusion of plastic particles can be a future prospect in the context of food security. Additionally further exploration of intercropping systems between potential microplastic accumulating plants and crop plants could ensure food safety.

For aquatic systems use of microalgae could be the optimal solution, especially in cases of enzymes facilitating micro and nanoplastics degradation. The biggest challenge in tackling plastic pollution will be the clean-up of deeper water layers since algae cannot survive beyond light penetrating depts, and having in mind that the seabed is contaminated, a different approach will have to be considered.

In the case of soil clean-up, prospects are more promising, since most of the pollution is in the upper soil layers and finding an optimal phytoremediator could enable sustainable, eco-friendly remediation of contaminated soils. Biotechnological approaches could develop enzymatic sprays that would enable plastics to degrade or introduce algae in contaminated soil. Current research only provides some in vitro results on algae and their limits, but even in the case of algae there are contrasting results suggesting some are very sensitive while others are more resilient. Prospects on plastic remediation will have to include not only an efficient system for removal but also an efficient system for recycling of the plastic accumulated by the plants to avoid moving the problem from one place to another.

## 7. Concluding remarks

Micro and nanoplastics have a complex interplay with the environment including aquatic ecosystems and land plants. Microplastics can be adsorbed to root hairs, while nanoplastics can penetrate the roots and reach above-ground plant parts via xylem. Proof of plastic particles' entrance into plants raises the issue of food chain contamination through contamination of primary producers enhancing the bioaccumulative effect in animal tissues and consequently the effects in human health. For this reason, the importance of investigations oriented towards plastic pollution solutions cannot be emphasized enough. Plants play an important resource in this fight for a cleaner environment. Some algal species show potential for phycoremediation due to the presence of polyethylene terephthalate-degrading enzyme (PETase) such as *Chlamydomonas reinhardtii, Cylindrotheca closterium* and *Phaeodactylum tricornutum* and could be considered for biodegradation processes. Use of algae or higher plants should be further investigated for uses as phytoremediators of plastic pollution from the aquatic and land ecosystems.

## Author contributions

EK mainly contributed in the writing of the original version of this review. AMP and FM conceived and supervised the work. All authors contributed on writing significant parts of this article.

## Enviromental implication

Nowadays, the presence of plastics in the environment is one of the highest concerns due to the high accumulation of plastic wastes caused by the high consumption of plastic containers by human activities. Their possible absorption by plants (particularly crops) is highly threatening the human health due to their consequent presence in our food. Microplastics and nanoplastics might enter plant tissues through stomata while they should penetrate roots. In addition, their presence in the environment is also dangerous for any animals threatening natural ecosystems, especially in water-based environment. Further research on the use of algae in plastic degradation is needed.

## Declaration of Competing Interest

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

## Data Availability

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

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