Microplastics in Agriculture Implications on Soil Health, Crop Productivity and Food Safety

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ABSTRACT

Microplastics (MPs), plastic particles smaller than 5 mm, have emerged as persistent contaminants in agricultural ecosystems due to the extensive use of plastic mulches, greenhouse films, irrigation systems, sewage sludge, compost, fertilizers, and atmospheric deposition. Their accumulation in agricultural soils poses significant threats to soil quality, crop productivity, ecosystem functioning, and food safety. Recent studies indicate that MPs alter soil physical properties by modifying aggregate stability, bulk density, porosity, and water-holding capacity, while simultaneously influencing soil chemical characteristics, including nutrient availability, pH, cation exchange capacity, and organic carbon dynamics. Microplastics also disrupt soil microbial diversity, enzyme activities, and nutrient cycling, thereby affecting essential ecosystem services. Increasing evidence demonstrates that micro- and nanoplastics can be absorbed by plant roots through apoplastic and symplastic

pathways and subsequently translocated to edible tissues, leading to reductions in seed germination, root development, photosynthesis, biomass accumulation, and crop yield. Furthermore, MPs act as vectors for heavy metals, pesticides, antibiotics, and pathogenic microorganisms, raising concerns regarding food quality, antibiotic resistance, and human health. This review critically synthesizes recent advances in understanding the sources, occurrence, transport, environmental fate, and ecological impacts of microplastics in agricultural systems. The review also discusses current mitigation strategies, biodegradable alternatives, remediation technologies, and future research priorities aimed at minimizing microplastic contamination while promoting sustainable agricultural production. Developing integrated management strategies is essential for protecting soil health, ensuring food security, and achieving long-term environmental sustainability.

INTRODUCTION:

The widespread use of plastics has transformed modern agriculture by enhancing crop production, water-use efficiency, and resource management through applications such as mulch films, greenhouse covers, irrigation systems, and packaging materials. However, the extensive use and improper disposal of these materials have resulted in the accumulation of microplastics (MPs; plastic particles <5 mm) in agricultural soils, making them an emerging environmental concern due to their persistence and resistance to degradation (Hartmann *et al.,* 2019). Agricultural soils are increasingly recognized as major sinks for microplastics because of continuous inputs from degraded plastic mulches, sewage sludge, compost, wastewater irrigation, atmospheric deposition, and other agricultural amendments (Corradini *et al.,* 2019; Machado *et al.,* 2019; Zhang *et al.,* 2023). The widespread occurrence of microplastics in cultivated soils has raised serious concerns regarding their long-term impacts on soil quality, ecosystem functioning, and sustainable agricultural production.

Microplastics adversely affect soil physical, chemical, and biological properties by altering soil aggregation, porosity, bulk density, water-holding capacity, nutrient dynamics, and microbial diversity, thereby disrupting nutrient cycling and soil fertility (Boots *et al*., 2019; Han *et al.*, 2024; Peng *et al.,* 2025; Yan *et al.,* 2025). Recent studies have also demonstrated that microplastics and nanoplastics can be absorbed by plant roots, translocated to edible tissues, and act as carriers of heavy metals, pesticides, antibiotics, and pathogenic microorganisms, posing potential risks to crop productivity, food safety, and human health (Colzi *et al.,* 2022; Bethanis and Golia, 2024; Bhargava *et al*., 2025). Despite rapid advances in this field, significant knowledge gaps remain regarding the long-term behavior and ecological impacts of microplastics under field conditions. Therefore, this review synthesizes current knowledge on the sources, occurrence, environmental fate, and impacts of microplastics in agricultural systems, with emphasis on their implications for soil health, crop productivity, food safety, and sustainable management strategies.

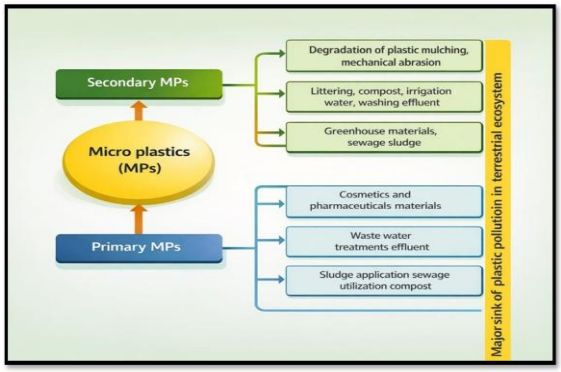


Fig.1. Flowchart of microplastics' types, source, and sink in the terrestrial ecosystem.

1. SOURCES AND OCCURRENCE OF MICROPLASTICS IN AGRICULTURAL SOILS

Agricultural soils have become one of the major sinks for microplastics (MPs; particles <5 mm) due to the extensive use of plastic-based materials in modern farming and inadequate waste management. Microplastics originate from both primary sources (intentionally manufactured microscopic plastics) and secondary sources formed through the fragmentation of larger plastic products by weathering, ultraviolet radiation, mechanical abrasion, and microbial degradation, with secondary microplastics being the predominant form in agricultural soils. The widespread use of polyethylene mulch films, greenhouse covers, drip irrigation systems, silage wraps, nursery trays, and packaging materials has significantly increased the accumulation of persistent plastic fragments in cultivated lands, resulting in long-term soil contamination (Rillig, 2012; Machado *et al*., 2019; Hartmann *et al.,* 2019).

In addition to agricultural plastics, sewage sludge, compost, wastewater irrigation, atmospheric deposition, polymer-coated fertilizers, pesticide formulations, and biodegradable plastics contribute substantially to microplastic contamination in soils (Corradini *et al.,* 2019; Zhang *et al.,* 2023). The occurrence and distribution of MPs vary with cropping systems, farming practices, climatic conditions, soil characteristics, and proximity to pollution sources. Polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polyethylene terephthalate (PET), and polyamide (PA) are the most commonly detected polymers, predominantly occurring as fibers, fragments, films, and pellets. Although numerous studies have confirmed the widespread occurrence of microplastics in agricultural soils worldwide, variations in sampling and analytical methods limit direct comparisons among studies, emphasizing the need for standardized monitoring protocols to better understand their environmental behavior and support sustainable agricultural management.

2. FATE AND TRANSPORT OF MICROPLASTICS IN AGRICULTURAL SOILS

Once introduced into agricultural soils, microplastics (MPs) undergo various physical, chemical, and biological processes that determine their persistence, mobility, and environmental impacts. Their fate is influenced by factors such as polymer type, particle size and shape, soil texture, organic matter content, climatic conditions, and agricultural management practices. Larger plastic residues gradually fragment into smaller microplastics and nanoplastics through weathering, ultraviolet radiation, temperature fluctuations, mechanical abrasion, and microbial activity, resulting in their long-term persistence in soils (Hartmann *et al.,* 2019). Microplastics are transported vertically through water infiltration and bioturbation by soil organisms, and horizontally via surface runoff, wind erosion, tillage, and irrigation, enabling their movement to deeper soil layers and adjacent ecosystems.

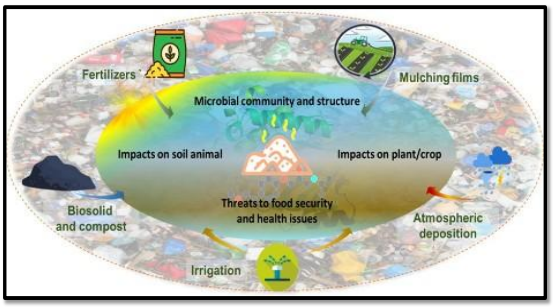


Fig.2.Sources of Microplastics in Agriculture

During transport, they interact with soil minerals, organic matter, and microorganisms, while their hydrophobic surfaces adsorb heavy metals, pesticides, antibiotics, and other persistent organic pollutants, thereby acting as vectors for contaminant transport (Peng *et al.,* 2025; Riveros *et al.,* 2023). Weathering further alters their surface characteristics, promoting microbial colonization and the formation of a unique microbial community known as the **plastisphere**, which influences nutrient cycling and contaminant dynamics. Additionally, smaller particles may be taken up by plant roots, ingested by soil fauna, or transported to groundwater and aquatic environments, extending their environmental impacts beyond agricultural soils. Despite increasing research, the long-term behavior, degradation pathways, and interactions of microplastics under field conditions remain inadequately understood, emphasizing the need for further investigation to accurately assess their environmental risks and develop effective management strategies.

Table .1. Major processes governing the fate and transport of microplastics in agricultural soils.

Process	Mechanism	Environmental consequence	Key references
Weathering	UV radiation, temperature fluctuations	Formation of smaller plastic particles	Hartmann *et al.* (2019)
Fragmentation	Mechanical abrasion, tillage	Generation of micro- and nanoplastics	Machado *et al.* (2019)
Vertical transport	Water infiltration, soil cracks, bioturbation	Movement to deeper soil layers and groundwater	Rillig (2012)
Horizontal transport	Surface runoff, wind erosion, irrigation	Spread to adjacent fields and water bodies	Riveros *et al.* (2023)
Adsorption	Binding of heavy metals, pesticides and antibiotics	Enhanced contaminant mobility and bioavailability	Peng *et al.* (2025)
Plastisphere formation	Colonization by microorganisms	Changes in microbial communities and nutrient cycling	Hartmann *et al.* (2019); Yan *et al.* (2025)
Plant uptake	Root absorption and vascular transport	Entry of microplastics into edible plant tissues	Colzi *et al.* (2022); Bhargava *et al.* (2025)

3. EFFECTS OF MICROPLASTICS ON SOIL PHYSICAL PROPERTIES

The accumulation of microplastics (MPs) in agricultural soils significantly alters soil physical properties, thereby influencing soil structure, water dynamics, aeration, and root development. The extent of these changes depends on the type, shape, size, concentration, and polymer composition of microplastics, as well as soil texture and environmental conditions. Fibrous and film-shaped microplastics generally reduce soil bulk density while increasing porosity and water retention, whereas fragmented particles may disrupt soil aggregate stability, decrease hydraulic conductivity, and modify soil permeability (Boots *et al.,* 2019; Han *et al.,* 2024). Microplastics also affect soil mechanical strength by altering pore connectivity and aggregate formation, which can impair root penetration and reduce water and nutrient availability to plants. Furthermore, changes in soil moisture retention and evaporation influence microbial habitats and nutrient transport, ultimately affecting soil fertility and crop growth. These alterations are more pronounced under long-term microplastic accumulation, highlighting their potential to degrade soil quality and compromise the sustainability of agricultural production systems (Machado *et al.,* 2019; Bethanis and Golia, 2024).

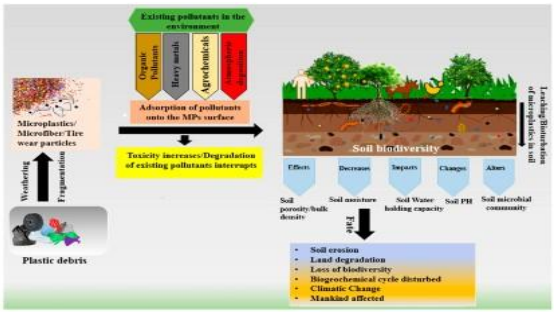


Fig.3.Impacts of microplastics on soil ecosystem functions

Table .2. Effects of microplastics on soil physical properties

Soil property	Effect of microplastics	Major consequence
Bulk density	Generally, decreases	Looser soil structure
Aggregate stability	Reduced	Increased erosion risk
Porosity	Increased or altered	Changes in air and water movement
Water-holding capacity	Variable (often increased with fibers)	Affects soil moisture availability
Hydraulic conductivity	Reduced	Restricted water infiltration
Soil permeability	Altered	Changes in drainage and runoff
Root penetration	Restricted	Reduced root growth and crop establishment

4. EFFECTS OF MICROPLASTICS ON SOIL CHEMICAL PROPERTIES

Microplastics (MPs) influence the chemical properties of agricultural soils by altering nutrient dynamics, soil pH, cation exchange capacity (CEC), organic carbon turnover, and the availability of essential plant nutrients. Owing to their large surface area and hydrophobic nature, microplastics readily adsorb heavy metals, pesticides, antibiotics, and persistent organic pollutants, thereby modifying the mobility, bioavailability, and persistence of these contaminants in soil (Peng *et al.,* 2025). Weathered microplastics exhibit enhanced adsorption capacity due to increased surface roughness and functional groups, which further influence nutrient cycling and contaminant transport. In addition, MPs can affect soil organic matter decomposition, carbon sequestration, and nitrogen transformation processes by altering interactions between soil particles and microorganisms.

The magnitude of these effects varies with polymer type, particle size, concentration, and soil characteristics; however, long-term accumulation of microplastics has the potential to impair soil fertility, reduce nutrient-use efficiency, and adversely affect sustainable agricultural productivity (Riveros *et al*., 2023; Bethanis and Golia, 2024).

Table .3. Effects of microplastics on soil chemical properties

Soil chemical property	Effect of microplastics	Agricultural implication
Soil pH	Slight alteration	Influences nutrient availability
Organic carbon	Alters carbon dynamics	Affects carbon sequestration
Nutrient availability	Reduces or modifies nutrient availability	Lower nutrient-use efficiency
Cation exchange capacity (CEC)	Alters ion exchange processes	Reduced nutrient retention
Heavy metal mobility	Increases adsorption and transport	Greater metal bioavailability
Pesticide and antibiotic behavior	Adsorbs and transports contaminants	Increased environmental persistence
Nutrient cycling	Disrupts N and P transformations	Decline in soil fertility

5. EFFECTS OF MICROPLASTICS ON SOIL BIOLOGICAL PROPERTIES

Microplastics (MPs) significantly influence the biological functioning of agricultural soils by altering the diversity, abundance, and activity of soil microorganisms that regulate essential ecosystem processes. Their presence modifies the habitat and physicochemical environment of soil, affecting microbial community composition, enzyme activities, organic matter decomposition, and nutrient cycling. Weathered microplastics provide surfaces for

microbial colonization, forming a unique microbial habitat known as the **plastisphere**, which may harbor both beneficial and pathogenic microorganisms. Several studies have reported that MPs reduce microbial biomass, suppress key soil enzymes, and disrupt carbon, nitrogen, and phosphorus cycling, ultimately affecting soil fertility and ecosystem functioning (Yan *et al.,* 2025). Furthermore, interactions between microplastics and soil biota, including earthworms and other soil fauna, may alter soil aggregation, aeration, and decomposition processes. Although the magnitude of these effects depends on polymer type, concentration, soil properties, and exposure duration, long-term microplastic accumulation poses a significant threat to soil biodiversity, biological health, and sustainable agricultural productivity (Boots *et al.,* 2019; Han *et al.,* 2024).

Table .4. Effects of microplastics on soil biological properties.

Biological property	Effect of microplastics	Agricultural implication
Microbial diversity	Alters community composition	Reduced soil biodiversity
Microbial biomass	Generally decreases	Lower biological activity
Soil enzyme activity	Inhibits enzymes (dehydrogenase, urease, phosphatase)	Reduced nutrient mineralization
Carbon cycling	Disrupted	Reduced organic matter decomposition
Nitrogen cycling	Affects nitrification and mineralization	Lower nitrogen availability
Soil fauna	Adversely affects earthworms and microfauna	Impaired soil structure and aeration
Plastisphere formation	Promotes microbial colonization on MPs	Alters microbial interactions and may harbor pathogens

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	microfauna	aeration
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7. PLANT UPTAKE AND TRANSLOCATION OF MICROPLASTICS

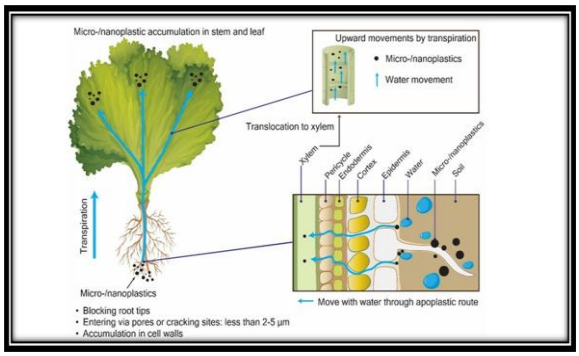


Fig.4. The potential internalization route of micro-/nanoplastics in plants

Recent studies have demonstrated that microplastics (MPs), particularly particles of smaller size and nanoplastics, can be absorbed by plant roots and translocated to aerial tissues, raising concerns about food safety and human exposure.

Microplastics enter plants through natural openings, root cracks, or the apoplastic pathway and are subsequently transported via the xylem to stems, leaves, fruits, and other edible parts. The extent of uptake depends on particle size, polymer type, concentration, plant species, root morphology, and soil properties. Nanoplastics exhibit greater mobility than larger microplastics due to their ability to penetrate plant cell walls and membranes more readily. Experimental studies have reported the accumulation of microplastics in vegetables such as lettuce, carrot, broccoli, spinach, tomato, and cucumber, where they may impair nutrient uptake, photosynthesis, and plant growth while facilitating the transfer of associated contaminants such as heavy metals and pesticides into the food chain (Colzi *et al.,* 2022; Bhargava *et al.,* 2025; Bethanis and Golia, 2024).

8. EFFECTS OF MICROPLASTICS ON CROP PRODUCTIVITY

Microplastics (MPs) adversely affect crop productivity by altering soil conditions and directly interfering with plant physiological and biochemical processes. Their presence in soil can reduce seed germination, inhibit root elongation, impair nutrient and water uptake, decrease chlorophyll content and photosynthetic efficiency, and induce oxidative stress, ultimately resulting in reduced biomass accumulation and yield. The severity of these effects depends on the type, size, shape, concentration of microplastics, as well as crop species and soil characteristics. While low concentrations of certain microplastics may occasionally stimulate plant growth by improving soil aeration, prolonged exposure or higher concentrations generally exert negative effects on plant development and productivity. Furthermore, microplastics can facilitate the uptake of co-contaminants such as heavy metals and pesticides, exacerbating phytotoxicity and reducing crop quality. These findings highlight the potential of microplastic pollution to compromise agricultural productivity and food security, emphasizing the need for sustainable plastic management practices (Boots *et al.,* 2019; Colzi *et al.,* 2022; Bethanis and Golia, 2024).

Table 7. Effects of microplastics on crop productivity

Crop parameter	Effect of microplastics	Agricultural implication
Seed germination	Delayed or reduced	Poor crop establishment
Root growth	Inhibited root elongation and branching	Reduced water and nutrient uptake
Photosynthesis	Decreased chlorophyll content and photosynthetic rate	Lower biomass production

Nutrient uptake	Impaired absorption of essential nutrients	Nutrient deficiencies and poor growth
Plant biomass	Reduced shoot and root biomass	Decline in overall plant vigor
Crop yield	Decreased grain, fruit, or vegetable yield	Reduced agricultural productivity
Crop quality	Increased accumulation of contaminants	Deterioration of food quality and market value

9. FOOD SAFETY AND HUMAN HEALTH IMPLICATIONS

The accumulation of microplastics (MPs) in agricultural soils has emerged as a significant food safety concern due to their uptake and translocation into edible plant tissues. Recent studies have demonstrated the presence of microplastics in vegetables, cereals, and fruits, indicating that contaminated soils can serve as an important pathway for their entry into the human food chain. In addition to the plastic particles themselves, microplastics can adsorb and transport heavy metals, pesticides, antibiotics, and pathogenic microorganisms, increasing the likelihood of co-contaminant transfer to crops (Bhargava *et al.,* 2025). Continuous dietary exposure to microplastics may induce oxidative stress, inflammation, cellular toxicity, endocrine disruption, and alterations in the gut microbiome, although the long-term health effects remain under investigation. The potential accumulation of microplastics and associated contaminants in food crops highlights the need for effective monitoring, risk assessment, and management strategies to safeguard food quality, public health, and sustainable agricultural systems (Bethanis and Golia, 2024; Colzi *et al*., 2022).

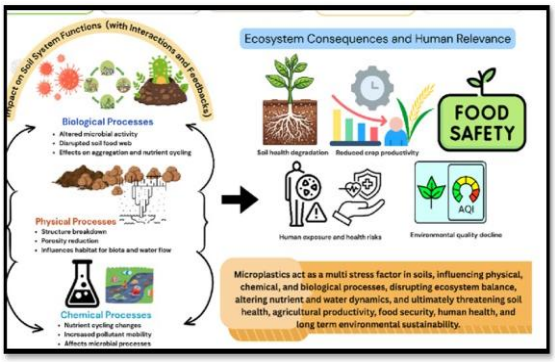


Fig.5. Conceptual Framework Illustrating the Effects of Microplastics on Soil Health, Crop Productivity, Food Safety, and Environmental Sustainability

10. Mitigation and Remediation Strategies

Effective mitigation of microplastic (MP) pollution in agricultural soils requires an integrated approach combining sustainable agricultural practices, improved plastic waste management, and innovative remediation technologies. Reducing the use of conventional plastic mulches through biodegradable alternatives, promoting the recycling and proper disposal of agricultural plastics, and minimizing the application of contaminated sewage sludge and compost are essential preventive measures.

Advanced wastewater treatment technologies can further reduce the entry of microplastics into agricultural fields. In addition, remediation approaches such as phytoremediation, bioremediation using plastic-degrading microorganisms, biochar application, and conservation agriculture have shown potential in reducing microplastic mobility and improving soil health. Strengthening environmental regulations, adopting circular economy principles, increasing farmer awareness, and developing standardized monitoring protocols are equally important for minimizing microplastic contamination and ensuring sustainable agricultural production (Peng *et al*., 2025; Bethanis and Golia, 2024; Zhang *et al.,* 2023).

Table 9. Mitigation and remediation strategies for microplastic contamination in agricultural soils

Strategy	Approach	Expected outcome
Plastic reduction	Minimize use of conventional agricultural plastics	Reduced generation of microplastics
Biodegradable mulches	Replace polyethylene mulches with biodegradable alternatives	Lower plastic residue accumulation
Plastic recycling	Collection and recycling of agricultural plastic waste	Reduced environmental pollution
Improved wastewater treatment	Removal of microplastics before irrigation reuse	Reduced MP input into agricultural soils
Sustainable organic amendments	Use well-screened compost and sludge	Minimized contamination from amendments
Biochar application	Immobilization of microplastics and contaminants	Improved soil quality and reduced mobility
Bioremediation	Use of plastic-degrading microorganisms	Enhanced degradation of plastic residues
Phytoremediation	Use of suitable plant species to stabilize contaminated soils	Reduced environmental risk
Policy and awareness	Regulations, monitoring, and farmer education	Sustainable management and pollution prevention

11. Research Gaps and Future Perspectives

Despite significant advances in microplastic research, several critical knowledge gaps remain regarding their long-term impacts on agricultural ecosystems. Most studies have been conducted under laboratory or greenhouse conditions using relatively high concentrations of microplastics, which may not accurately represent field conditions. Limited information is available on the long-term behavior of different polymer types, interactions with multiple environmental stressors, effects on tropical and subtropical soils, and the fate of nanoplastics in agricultural systems. Furthermore, the lack of standardized methods for sampling, extraction, identification, and quantification hinders comparisons among studies and risk assessment. Future research should focus on long-term field experiments, standardized analytical protocols, the mechanisms of plant uptake and trophic transfer, interactions between microplastics and soil microorganisms, and the development of sustainable plastic alternatives and remediation technologies. Such efforts are essential for improving our understanding of microplastic pollution and supporting evidence-based policies for sustainable agricultural production and food security.

CONCLUSIONS

Microplastics have emerged as persistent contaminants in agricultural ecosystems, posing significant challenges to soil health, crop productivity, and food safety. Their continuous accumulation from agricultural plastics, organic amendments, wastewater irrigation, and atmospheric deposition alters soil physical, chemical, and biological properties, disrupts nutrient cycling and microbial functions, and adversely affects plant growth and yield. Increasing evidence also indicates that microplastics can be absorbed and translocated within crop plants, facilitating the transfer of plastic particles and associated contaminants into the food chain and raising concerns regarding human health. Although considerable progress has been made in understanding the occurrence and impacts of microplastics, important knowledge gaps remain regarding their long-term environmental behavior, ecological risks, and effective remediation under field conditions. Therefore, adopting sustainable agricultural

practices, improving plastic waste management, developing biodegradable alternatives, and implementing standardized monitoring and regulatory frameworks are essential to mitigate microplastic pollution. Future interdisciplinary research integrating soil science, environmental chemistry, plant physiology, microbiology, and toxicology will be crucial for developing science-based strategies to protect soil quality, ensure food security, and promote sustainable agricultural production.

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