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Review

Emerging Contaminants in Agriculture and Ways to Reduce them Emerging Contaminants in Agriculture

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Abstract: The accelerated development of modern agriculture in order to feed a growing world population is one of the main causes of contamination in soil, water, and air, causing diseases in animals and humans. Among the most common pollutants are nitrogenous fertilizers, pesticides, hydrocarbons, and nanomaterials. As more food is produced, pollution increases, making it necessary the transition to sustainable agriculture, in which organic agriculture and precision agriculture stand out as ways to reduce emerging pollutants together with bioremediation. This review paper addresses three of the most common emerging pollutants in agriculture (pesticides, nanomaterials, and polycyclic aromatic hydrocarbons), their general description, biological effect, toxicity, norms of the maximum permissible values in Mexico, and ways to reduce them. Pesticides, nanomaterials, and polycyclic aromatic hydrocarbons are contaminants that can remain in soils damaging the ecosystem so strategies to reduce their effects include physical and chemical methods, the substitution of polluting products for organic equivalents, the use of plants and microorganisms alone or in combination as remedial agents and more recently nanotechnology and genetic engineering. The need for more food for the growing population is up today and directly related to the generation of more pollutants, deeper studies are needed to improve the effectiveness of these strategies and/or reduce their costs, in search of cleaner productions. From this review paper is possible to conclude that most of the pesticides used in the fields can affect biota, or are incorporated into the water table, the application of nanomaterials in agriculture, despite its usefulness, has also become a source of pollution because they can remain in the soil for long periods and polycyclic aromatic hydrocarbons have poor solubility so their removal is particularly difficult. In Mexico, even taking into account the damage caused by the pollutants described, there are currently no clear norms of the maximum permissible values for them.

Keywords: Bioremediation, Hydrocarbons, Nanomaterials, Organic Agriculture, Pesticides, Precision Agriculture

Introduction

Emerging pollutants (EC) are compounds with diverse chemical origins and nature that are currently not monitored or regulated in the environment; their possible damages and effects are the object of a recent study by different researchers with the aim of knowing the impact they cause both on ecosystems and on humans and animals. Within the EC are agrochemicals: Fertilizers, pesticides, and fungicides; drugs: Hormones, antibiotics; industrial additives, plasticizers, surface active agents, household hygiene, and personal care products. These contaminants are characterized by being present in a trace concentration (nanograms and micrograms) (García-Gómez *et al*., 2011).

Most ECs are made up of Persistent Organic Pollutants (POPs) that are chemical substances threatening human health and the environment of the entire planet, because they remain in the environment, being resistant to degradation and bioaccumulative. They are incorporated into the tissues of living organisms, being able to increase in concentration through the higher levels of the food chain; they are toxic to human health and the environment and also have the potential to be transported over long distances, reaching regions where have never been produced or used (Tardón, 2022).

The proliferation of ECs in diverse ecosystems is fundamentally due to anthropogenic activities such as industrial waste disposal, mining, and agriculture (Bali *et al*., 2021) being the agricultural soils one of the most important destinations of these contaminants. This contamination affects living organisms that are part of the food chain and the high levels of ECs in aquatic environments and in the soil represent a great threat to human health and ecosystems (Srikanth *et al*., 2019).

In general, according to Dey *et al*. (2019); Abdulrazaq *et al*. (2020) ECs are classified and categorized into pharmaceuticals (prescribed and illegal drugs), personal care products (food additives, cosmetics, disinfectants surfactants, domestic biocides), industrial chemicals (pesticides, antimicrobial substances, food additives, polychlorinated biphenyls, polycyclic aromatic hydrocarbons), disinfection by products (from water treatment plant: Halonitro methanes, nitrosamine, halo acetic acids, haloacetonitriles, trihalomethanes), algal toxins (toxic released from some algae: Cyanotoxins, microcystin), biocides and their metabolites (plants and agricultural preventive agents [pesticides, nanomaterials]) and bioterrorism and disruption devices (biological and chemical weapons).

At present, not enough attention is given to these contaminants that may exist in trace concentrations but are very dangerous to humans if they enter the food chain (Petousi *et al*., 2019).

The present review was done by searching google scholar, research gate, PubMed/Mediline, web of science, and Scopus databases, so the aim of this article review is to analyze three of the most harmful emerging contaminants in agriculture and the ways to reduce them.

Pesticides

The world population is estimated to be ten billion by 2050. This exponential growth will generate greater demand for food and, in parallel, agricultural practices will be intensified to increase crop yields. This agricultural intensification has impacted, with a variable magnitude, the natural processes of resources such as water, air, and soil (Sun *et al*., 2012).

Emerging contaminants from microplastics, polychlorinated, pesticides, polycyclic aromatic hydrocarbons, biphenyls, and per and polyfluoroalkyl substances have recently been documented as contaminants of concern by the US EPA. Within this group, pesticides of chemical origin prevent the control or reduce pests and diseases that affect the development and production of agricultural crops. These substances are characterized by their toxicity, bioavailability, mobility, and physicochemical properties and can be classified according to Sharma *et al*. (2003); FAO (2000); WHO (2019) by their:

1. Target organisms (rodenticides, acaricides, fungicides, bactericides, herbicides, nematicides, and insecticides)
2. Mode of entry (systemic or contact)
3. Chemical nature (organophosphates, organochlorines, carbamates, phenylamides, pyrethroids, phenoxy alkonates, trazines, benzoic acid, phthalimides, dipyrids, among others)
4. Toxicity LD50 median lethal dose in rats by oral route (extremely dangerous, highly dangerous, moderately dangerous, slightly dangerous, unlikely to present an acute hazard)
5. Degradation DT50 degradation half time

The harmful effects that pesticides produce on the various populations of organisms depend largely on the toxicity of the substance, the time of exposure, the structure and population of the landscape, and the moment or mode of application. Furthermore, water is the most convenient medium for the dissolution and application of these substances; however, a large number of pesticides are poorly or not soluble in water; therefore, a high amount of organic solvents is required to dissolve them and this affects the cost and contamination of the environment. Thus, their proper use should be valued through a balance between the harmful effects on the environment and the obtainment of high yields in crops of agricultural interest (Osteen and Fernandez-Cornejo, 2013).

Pesticides and their Impact on the Soil Ecosystem

Pesticides, along with other chemical wastes (polycyclic aromatic hydrocarbons, heavy metals, and certain polyorganic pollutants), are important agents of soil contamination due to their persistence for long periods. These substances seriously harm the physiological and metabolic activities of the various edaphic trophic groups of microorganisms and, consequently, the contamination of groundwater through leaching, spray drift, runoff, and others. Soil organisms are associated with the cycle of nitrogen and other minerals, the decomposition of organic matter, the remediation of contaminated soil, etc., (Pajares and Ramos, 2019).

It is important to note that 99.9% of applied pesticides remain in the surrounding environment and only 0.1%

reach the target organism in the soil, causing environmental contamination, disturbing soil biota, and seeping into the chain food. The affinity of pesticides to be absorbed by minerals, organic carbon, and dissolved organic matter, the half-life of the chemical products (DT 50), and their solubility in water, among others, are factors that influence the presence of these chemical substances in the edaphic environment (Aktar *et al*., 2009).

In Brazil, a study documented soil contamination, at various monitoring depths, caused by the insecticides Chlorpyrifos and Lambda cyhalothrin and the herbicide Atrazine (Bortolozo *et al*., 2016); while, in Argentina, 17 agricultural sites with residues of the herbicide Glyphosate were reported. The authors recommended carrying out a study on the ecological risk to soil and sediments (Primost *et al*., 2017).

Also, the combination of pesticides influences their impact on their leaching, adsorption, sorption, and desorption in the soil. Regarding this, in Brazil Dos Reis *et al.* (2017) documented that the mixture of the herbicides sulfometuron methyl, Diuron and Hexazinone could promote changes in their respective behavior in the soil; in addition, they observed that Diuron has low mobility in the soil, since it remained in the upper layer, while Hexazinone leached heavily at deeper profiles.

Also in Brazil, Carneiro *et al.* (2020) reported that the mixture of Diuron, Hexazinone, and Sulfometuron methyl reduced the maximum adsorption between 50-56% and decreased the sorption coefficient k_f in the range of 24 to 89%; both results compared to these same products in isolation. In addition, it was reported that the values of the sorption coefficient k_f were higher when the products Diuron and Hexazinone were combined (Sousa *et al*., 2018).

Nanomaterials

Nanomaterials (NMs) are commonly defined as elements or particles less than 100 nm in dimension and their environmental impacts are still under study. They can be obtained through several chemical and physical procedures, given their distinctive properties like mechanical strength, electrical conductivity, and others. NMs are being used more and more in different industries and in agriculture (USEPA, 2017).

The application of NMs in soils as wastewater and biosolids was recognized as a main cause of contamination (Pan and Xing, 2012). Terrestrial ecosystems will be the largest reservoirs of NMs due to the increase of these as waste. The chemical configuration of these elements allows the absorption of heavy metals such as mercury, copper, lead, and cadmium, among others, in water, soil, and air, and due to their toxic properties, they can cause various damages in living beings (Kamal *et al*., 2021) as cancer in humans and affect growth in plants. Nanomaterials can also be carriers of toxic metals, making them more accessible to organisms (Kansara *et al*., 2022). Examples of these NMs are non-carbon NMs like iron oxide magnetite nanoparticles, metal oxide nanomaterials, layered double hydroxides, nanomembranes/fibers, and nano-polymer composites, all of them are related to heavy metal contamination of water and in environmental cleanings (Baby *et al*., 2022).

Nanoplastics

Plastics are necessary materials in society. Lots of kitchen utensils, packaging for cosmetics, creams, perfumes, deodorants, medicines, and bags, among others, are made of plastic, which is why they have become contaminants of agricultural soils and the waters of oceans, rivers, lakes and they are not being properly managed (Cinelli *et al*., 2019).

Nanoplastics (NPx) have a size between 0,001-1,0 mm and together with microplastics (MPx) are ECs that affect the planet. A great amount (79%) of plastic waste is accumulated in landfills, so the amount of contamination is more severe in agricultural soils than in the oceanic basins (Fig. 1) (Geyer *et al*., 2017). Also, plastics can interact with the organic matter in the soil being a critical factor for the formation of nano plastics and microplastics.

In aquatics systems NPx and MPx can be used as habitats for microorganisms such as *Arcobacter, Pseudomonas, Veillonellaceae,* and *Aeromonas*; besides, in river sediments was found that microplastics diminish the microorganism diversity (McCormick *et al*., 2014).

The presence of NPx and MPx has become ubiquitous in the environment and for this reason, it is important to study the effect on plants not only in the field but also in the laboratory. NPx affects more negatively several plant parameters more (development, several biochemical enzymes, and chlorophyll content-a, b, and total) than MPx. The exposure of plants to NPx induces the reduction in chlorophyll b content, chlorophyll a, photosynthetic rate, and total chlorophyll content. Relating to biochemical enzymes, MPx/NPx induces an increase of Malondialdehyde (MDA), Superoxide Dismutase (SOD), Peroxidase (POD), and catalase (CAT). Several plant physiological parameters are also affected negatively, like shoot biomass, root length, germination, root biomass, and plant height (Azeem *et al*., 2022).

Some examples of the biological effects of NP are: Lettuce (*Lactuca sativa* L.) plant growth reduction (leaf area, plants height, and dry weight) with foliar application of Polystyrene (PS) NP at 0.1 and 1 mgL^{-1} (Lian *et al*., 2021); cucumber plants (*Cucumis sativus* L.) with 100 nm PS NP reduced roots length and thickness (Li *et al*., 2021); in meristems of onion (*Allium cepa* L.) at 100 and 1000 mgL^{-1} an inhibitory effect of 50 nm PS NP on the Mitotic Index (MI) was observed (Giorgetti *et al*., 2020); increased C-metaphases were observed in rice plants (*Oryza sativa* L.) at 100 and 1000 mgL^{-1} of 20-200 nm PS-NP (Spanò *et al*., 2022).

Figure 2 some approaches for the reduction of NPx and MPx in soil are presented.

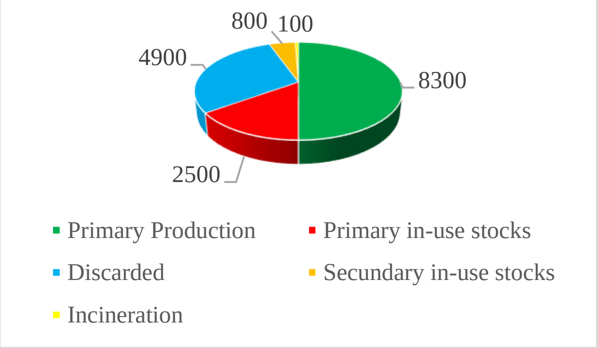
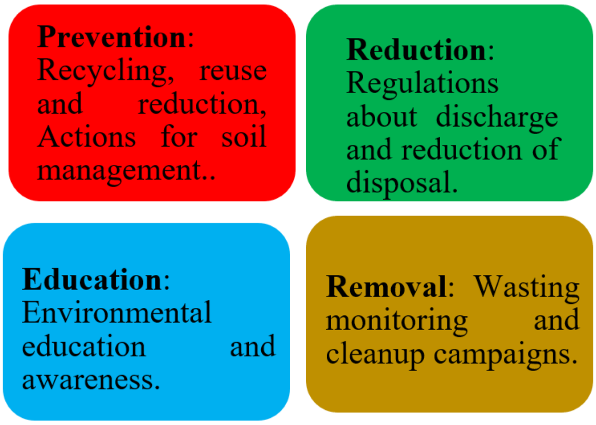


Fig. 1: International movement of plastics (between 1950-2021, in million metric tons, MMT) by diverse actions like agriculture, disposal of plastic by incineration and discarded (Geyer *et al*., 2017)



Prevention: Recycling, reuse and reduction, Actions for soil management..

Reduction: Regulations about discharge and reduction of disposal.

Education: Environmental education and awareness.

Removal: Wasting monitoring and cleanup campaigns.

Fig. 2: Approaches for the reduction of NPx and MPx in soil

Nanoparticles

Nanoparticles (NPs) have a size ranging from 1-100 nm with different shapes and sizes. They can be used for numerous applications such as pharmaceutical purposes, drug delivery, agriculture (Bhagat *et al*., 2015), and some other fields. Several NPs have become a source of environmental contamination, so they are considered ECs.

Samim (2022) reported that palladium NPs are used in vehicles for exhaust catalysts so the level of these NPs has increased considerably not only in urban zones but also in living organisms like aquatic animals and plants. In urban areas, people are susceptible to being exposed to these NPs showing chronic toxicity.

One common practice of sustainable agriculture is the application of biosolids; this is a way to introduce NPs into agricultural soils and for the proper use of these substances, a place to treat wastewater efficiently is needed (Pérez-Hernández *et al*., 2020).

Nanoparticles of several metals like zinc, copper, and silver are used in agriculture for microorganism control (fungi, bacteria) as metals or metal oxides, so they can also affect the beneficial microorganisms that live in the soil at very low concentrations (1.0 ppm) (Simonin and Richaume, 2015).

Nanoparticles are being utilized as metal nano pesticides for control of microorganisms; also, they are being applied to the soil for crop growth as nano fertilizers, for their better absorption and sometimes for biofortification with iron, magnesium, zinc, and potassium. What remains of these metallic NPs, either persist in the soil without being able to be absorbed or go on to contaminate the waters of the water table.

Nanoparticles have several adverse effects on terrestrial and aquatic plants. For example, according to Tarrahi *et al*. (2019), the adverse effect of cadmium selenide NPs increased the concentration of several enzymes of the oxidative stress (catalase, superoxide dismutase, flavonoids, and phenols) and also affected the morphology of *Lemna minor* (L.) Griff. 1851, while zinc selenide NPs affect the growth in this plant (Tarrahi *et al*., 2018); carbon nanotubes increased oxidative stress in red spinach (*Amaranthus tricolor* L.) (Begum and Fugetsu, 2012); high levels of silver NPs induced oxidative stress in *Spirodela polyrhiza* (L.) Schleid due to the increment of reactive oxygen species and affections to chloroplast function and structure (Jiang *et al*., 2014).

Polycyclic Aromatic Hydrocarbons

Polycyclic Aromatic Hydrocarbons (PAHs) are undoubtedly among the most abundant contaminants in soils (Chauhan *et al*., 2008). The sources of origin of these compounds are two: One, natural, less abundant, are volcanic eruptions and forest fires; the other is a direct result of anthropogenic activity and comes from industrial activities, oil exploitation, and spills, as well as the partial combustion of various substances. However, it must be considered that a significant amount of the forest fires that occur today are not of natural origin, but are also the results of the actions of man, either due to carelessness or as a consequence of multiple events associated with climate change.

PAHs have as a common element in their structure the presence of two or more interlinked heterocyclic aromatic rings (Fig. 3). The molecular weight and solubility of these substances depend on the number of rings that appear, as well as the amount in which they are found in the environment. Thus, naphthalene and anthracene are more common, less heavy, and more soluble, while other PAHs such as coronene and olivine, much heavier and less soluble, occur rarely in nature or as contaminants. At the same time, these high molecular weight PAHs are less soluble in water and their disappearance from the environment under natural conditions is much more difficult because environmental factors such as light, rain, and temperature have little effect on them (Agrawal *et al*., 2019).

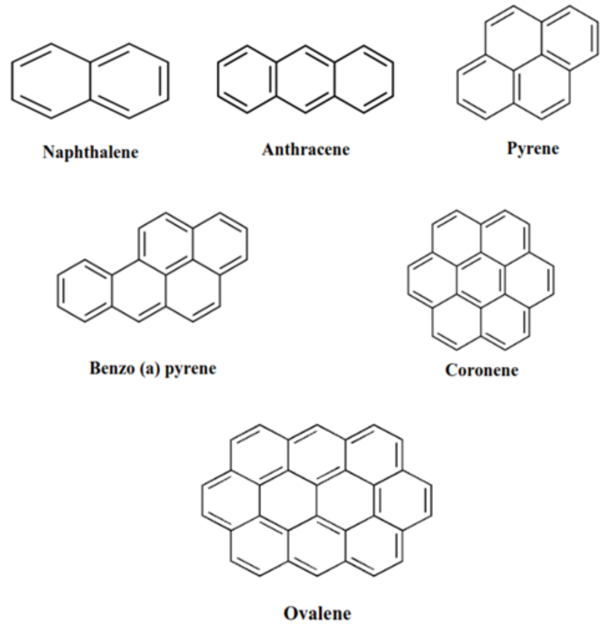


Fig. 3: Chemical structure of some polycyclic aromatic hydrocarbons

Although PAHs can be found indistinctly in soil, water and even in the air, their low solubility in water and the possibility of being adsorbed on soil particles mean that they are mainly deposited in soils (Kuppusamy *et al*., 2017). However, under certain conditions resulting from secondary processes and especially in large cities, compounds derived from PAHs may appear, called Oxygenated Polycyclic Aromatic Hydrocarbons (OPAHs) and nitrogen polycyclic aromatic hydrocarbons (Azaarenes or AZA). These PAH derivatives are even more toxic (Bandowe and Nkansah, 2016).

PAHs are ubiquitous, appearing anywhere there is a source of origin. It is difficult to find data on the total area of contaminated soil on the planet; instead, they are known to be present on all continents, including Antarctica, in ranges from a few to several hundred thousand nanograms per gram of soil (Singh and Haritash, 2019).

The diversity of the toxic effects of PAHs includes their mutagenic, teratogenic, carcinogenic, immunotoxic, and ecotoxic action and covers many microorganisms, plants, fish, birds, and humans. The degree of affectation depends largely on the concentration, mode, and time of exposure to the contaminant. In humans, in addition to long-term effects such as the occurrence of mutations and tumors, acute symptoms such as skin and eye irritation, vomiting, and diarrhea, and chronic symptoms such as difficulty breathing, damage to internal organs, anemia, and immunosuppression are seen (Patel *et al*., 2020).

The persistence of PAHs in soils depends not only on their structure (those with fewer rings are more degradable and less persistent) but also on soil properties, such as clay content and amount of organic matter (Duan *et al*., 2015). The degradation of PAHs in soils can occur through physical-chemical pathways (volatilization, photo-oxidation, adsorption in organic matter, leaching) and through biological pathways involving plants and microbes (Okere and Semple, 2012).

There are physical-chemical pathways, mentioned above, by which PAHs can be degraded in the soil. However, the remediation processes that can be carried out in these ways consume a large number of resources; in some cases, the removal of contaminated soil is necessary to be treated and later returned to its original location. In addition, further problems can be created, including soil erosion and loss of fertility (Kuppusamy *et al*., 2017). The volume of soil to be treated, the complexity of the operations, and the risk of affecting the soil make these procedures, particularly expensive tools.

Future Perspectives

The massive contamination of soils with Polycyclic Aromatic Hydrocarbons (PAHs) is a phenomenon resulting from modernity, which appears as an undesirable by-product of industrialization, oil phenomena such as forest fires. Consequently, concerns about the presence of PAHs in soils and research on how to mitigate their impact are also relatively new.

Significant advances have been made in understanding the natural degradation of PAHs and in the development of technologies to achieve it with human intervention. The physical-chemical processes, although effective in terms of results, are time-consuming and highly costly due to the operations they comprise, in addition to contributing to the loss of soil properties, including its fertility.

The knowledge acquired about the role of plants and microorganisms in the degradation of PAHs has allowed advances in phytoremediation and bioremediation of soils contaminated with these substances. The main drawbacks are linked to the structure and solubility of PAHs since those with higher molecular weight are quite inaccessible to the activity of many organisms. Plant-microbe associations have contributed to this purpose and so far, they seem to be the most economical and efficient way.

Given the different nature of PAHs and the selectivity of organisms over them, the future of these technologies seems to be linked to an integrated approach for each case, in which remediation pathways are chosen on this basis. The most in depth studies that are being carried out today on these issues should contribute to shedding light on which plant microbe combination may be more useful for the degradation of this or that PAH, in each of the conditions that are determined by environmental factors such as the type of soil, PAH type, temperature, moisture, and others.

Emerging technologies such as the use of nanoparticles to contribute to the physical chemical or biological degradation of PAHs and the use of compost to support the development of microorganisms and plants can be useful when incorporated into this integrated management approach. The identification of genes linked to the regulation of PAH degradation will also be decisive, both from the point of view of contributing to the knowledge of the phenomenon and the possible creation of genetically modified organisms that make the activity of plant microorganism complexes more effective.

Omics are already beginning to provide significant insights into the role of genomes, their expression in transcription, the protein products involved, and the metabolism of PAH degradation, which will undoubtedly contribute to the creation of more efficient integrated technologies.

Toxicity and Norms of the Maximum Permissible Values of Pesticides, Nanomaterials and Polycyclic Aromatic Hydrocarbons

The governments of each nation have implemented policies to minimize the contamination of water and food by various ECs. In the case of pesticides, the reference levels and limits of chemical residues were established in the "Official Mexican standard project PROY-NOM-000-SAG-FITO/SSA1-2013. Maximum Residue Limits (MRL). Technical guidelines and authorization and review procedures" of the "Official Gazette of the Federation" 2014, which states: The MRL proposed by the interested party will be subject to the following criteria:

- The authorization of an MRL may be based without distinction on MRLs from any of the following sources:

a) Those generated through field studies carried out in the national territory
b) Those published by the Food and Agriculture Organization of the United Nations (FAO) and the World Health Organization (WHO), through the codex Alimentarius
c) The definitive and temporary ones established by the Environmental Protection Agency of the United States of America (EPA)
d) Those established by the Canadian Pest Management Regulatory Agency (PMRA)
e) Those established by the member countries of the European community
f) Those established by the member countries of the OECD
g) Those established by Brazil, Argentina, and Japan

In an agricultural system, different components can be affected by the use of nanomaterials, which is why their toxic effects are of great concern, mainly the toxicity in the soil and in crops (Rienzie and Adassooriya, 2018).

The nitrogen cycle is one of the main processes that improve agricultural productivity, so if the microorganisms associated with this cycle are affected, crop productivity will be decreased. In this context, ZnO (zinc oxide) NPs are bactericidal to the nitrogen-fixing bacterium *Sinorhizobium meliloti* (Bandyopadhyay *et al*., 2015) and affect the thermogenic metabolism of Azotobacter species, which participate in the nitrogen fixation process (Chai *et al*., 2015). Kumar *et al*. (2011) reported that Ag NPs (silver nanoparticles) have long-term effects on *Bradyrhizobium* spp. in arctic soils. The single-wall carbon nanotubes (SWCNTs) cause a decrease in soil fungi whose function is to decompose organic matter, which is why they are important in nutrient recycling (Jin *et al*., 2013). These fungi are also negatively affected by ZnO NPs (Rashid *et al*., 2017).

According to Du *et al*. (2011), ZnO and TiO_2 (titanium dioxide) NPs considerably decreased the activity of some soil enzymes like soil peroxidase, protease, and catalase.

Regarding the toxicity of nanomaterials in crops, CuO (copper oxide) NPs retard wheat (*Triticum aestivum* L.) growth, specifically the roots when it was grown in sand, as well as affected negatively photosynthesis by reducing the chlorophyll content and the activity of enzymes such as catalases and peroxidases (Dimkpa *et al*., 2012). Ag NPS can damage root cells and vacuoles of rice plants (*O. sativa*) as reported by Mazumdar and Ahmed (2011), as well as decrease root growth and ultimately aboveground biomass (Nair and Chung, 2014). Rice plants were also susceptible to SWCNTs as they damaged DNA affecting cell viability (Shen *et al*., 2010). TiO_2 NPs accumulated in maize roots (*Z. mays*) (Larue *et al*., 2012), causing oxidative stress and inhibition of root growth (Laware and Raskar, 2014). Silicon NPs (Si NPs) in pumpkin crops (*Cucurbita maxima* Duchesne in Lam) caused a reduction in plant growth and transpiration (Hawthorne *et al*., 2012) in addition to the inhibition of seed germination (Stampoulis *et al*., 2009).

Regarding the norms that regulate nanomaterials in agricultural areas up to the present, despite the exponential increase in the applications of NPs and products with nanomaterials already available in the world market, there is a deficiency in terms of well-defined legal tools, due to the insufficient information on the subject, the technical limitations and the complexity of the materials to be regulated (Saldivar, 2020). In Mexico, there are only technical standards (NMX) such as NMX-R-12901-1-SCFI-2015, nanotechnologies occupational risk management applied to manufactured nanomaterials that apply to manufactured materials consisting of nano-objects such as nanoparticles, nanofibers, nanotubes, and nanowires, as well as the aggregates and agglomerates of these materials, including those with a size that exceeds the nanoscale without establishing permissible limits for them.

The official Mexican standard (NOM-138-SEMARNAT/SSA1, 2012) regulates the maximum permissible limits of hydrocarbons in soils, based on the number of carbon atoms present in these substances. However, as described above, the toxicity of PAHs is directly proportional to the number of rings in their structure and not to the number of carbon atoms. In this way, the aforementioned standard is not specific to PAHs and adjustments will be necessary in this regard.

Ways to Reduce Pesticides, Nanomaterials, and Polycyclic Aromatic Hydrocarbons

Some practices, methods, and strategies are addressed that, through their synergy and optimization, seek to directly or indirectly eliminate or reduce pesticides, nanomaterials, and polycyclic aromatic hydrocarbons in the field with the purpose of reducing their harmful impact on the ecosystem land (Table 1).

In the last decade, various investigations have been carried out in Brazil, China, India, Israel, Malaysia, Poland, and Spain where the effectiveness of the use of bacteria and fungi to degrade triazines has been reported (Table 2).

Table 1: Techniques to reduce ECs

Ways to reduce ECs	Pesticides	Nanomaterials	Polycyclic aromatic hydrocarbons	References
Tillage	The loss of pesticides by leaching is favored in sandy loam soils; organic matter drives desorption and clay particles favor the adsorption of the herbicide pretilachlor in the soil in Punjab			Kaur *et al*. (2016)
Conservation tillage	This technique in strips reduced the amount of pesticides by 75% in runoff water and in fields with vegetation, the sediment runoff of these toxic compounds were much lower in relation to fields without weeds or vegetation			Potter *et al*. (2015) Niu *et al*. (2020)
Biological and organic products	*Fusarium equiseti* is efficiently controlled by the species *B. amyloliquefaciens* in broad beans, while *Rhizobium radiobacter* controls *Agrobacterium tumefaciens*, a phytopathogen that causes "crown gall" disease *Trichoderma* can control *Pythium* spp., *Fusarium oxysporum*, *Alternaria* spp., *Rhizoctonia solani*, among others *Trichoderma* can control postharvest fungi such as *Penicillium* spp in citrus, *P. expansum* and *Botrytis cinerea* in apple and *Colletotrichum musae* in bananas Some products can act as synthetic analogs of chemical pesticides, examples of this are the fungicide Strobilurin, chitosan, the proteinaceous inducer Harpin, the extract of the *Reynoutria sachalinensis* plant that is used as a natural fungicide for the management of powdery mildew in tomato and cucumber			Haddoudi *et al*. (2021) Zin and Badaluddin (2020) Ballet *et al*. (2015) Antonious *et al*. (2014)
Bioremediation and biodegradation	Atrazine can be efficiently degraded by by bacterial strains of *Pseudomonas* sp. The biodegradation of Atrazine, using a bacterial consortium was reduced by adding urea and ammonium nitrate The metabolization of Triazine and Simazine by corn seedlings through enzymatic and chemical reactions of been reported; furthermore, it was documented the partial detoxification of triazines with the help of phytotransformation molecular weight PAHs	A wide variety of bacterial PAHs of different *of pentaromativorans*, capable of	genera (*Pseudomonas*, *Bacillus*, *Paenibacillus*, *Xanthomonas*, *by Enterobacter*, among others) and fungi (*Pleurotus*, *Irpex*, *Aspergillus*) is capable of degrading variable amounts molecular weights *Novosphingobium* degrading low, medium, and high The mnp3 gene encodes the synthesis of a manganese peroxidase in the fungus *Cerrena bicolor*; once cloned in another fungus (*Pichia pastoris*), its expression was achieved through the synthesis of the recombinant enzyme rMnP3-BBP6, capable of effectively degrading fluorene and phenanthrene The direct use of enzymes for the degradation of PAHs is very efficient, although the procedure is expensive	Govantes *et al*. (2009) Dehghani, *et al*. (2013) Marcacci and Schwitzguébel (2007) Singh and Haritash (2019) Lyu *et al*. (2014) Zhang *et al*. (2020) Kuppusamy *et al*. (2017) Agrawal *et al*. (2019)

Table 1: Continue

		Algae specific to the genera Chlorella, Scenedesmus and Selenastrum have degradative activity on compounds such as benzo(a)pyrene and fluoranthene	
Remediation	Containment Technologies: These technologies are for the contention of the pollutants hydraulically and physically to prevent their leaching or leaking. This contention can be accomplished in active or passive forms		Ratnasari *et al*. (2022)
	Immobilization Technologies: Target for this technique are specifically heavy metals. Clay is a material that can immobilize the particles of the metals using a mechanism of adsorption, so they are retained on the surface Another method that can be used is binders like calcium silicate hydrates; these substances attract and immobilize heavy metals and also the permeability of metals in the soil can be reduced		Durant (2018)
	The three *in situ* procedures frequently used are Thermal, physical, and chemical; they are not completely efficient because the contaminants can be moved into the air, so biological methods were introduced, and they are based on the use of several microorganisms that work under aerobic and anaerobic conditions accelerating biodegradation		Zhu *et al*. (2022)
Phytoremediation		*Festuca arundinacea*, *Lolium multiflorum*, *Lolium perenne*, *Dactylis glomerata*, *Festuca rubra*, *Melilotus officinalis*, *Lotus corniculatus*, *Trifolium pratense*, *Trifolium repensm*, *Medicago sativa*, *Panicum virgatum*, *Schizachyrium scoparium*, *Echinacea purpurea*, *Gaillardia aristata* and *Brassica rapa*	Singh and Haritash (2019)
		Manihot esculenta, *Cucurbita pepo*, *Cucumis sativus* and *Raphanus sativus*	Sarma *et al*. (2019)
		Zea mays L.	Košnář *et al*. (2018)
		Four species (oats and sunflower, C3), (maize and vetiver, C4) maintained 100% germination in the presence of pyrene or benzo(a)pyrene	Sivaram *et al*. (2018)
Plant-microbe associations		*Panicum maximum* grass with earthworms of the species *Pontoscolex corethrurus* and a bacterial consortium allowed the removal from the soil of 54-62% of PAHs with 2 and 3 rings, 56-92% of those with 4 rings, 80% of those with 5 rings and 70% of those with 6 rings after 112 days of treatment	Rodriguez-Campos *et al*. (2019) García-Sánchez *et al*. (2018)
		Z. mays + *Crucibulum laeve*. Managed to achieve up to 60% degradation of 16 PAHs present in the soil, with the main effects on naphthalene, phenanthrene and anthracene	

Table 2: Genera or species of bacteria and fungi that degrade triazines

Phylum	Class	Genus or species	Authors
Actino-bacteria	*Actino mycetia*	*Arthrobacter ureafaciens*	Zhu *et al*. (2020)
		Citricoccus sp.	Yang *et al*. (2018)
		Leucobacter sp.	Liu *et al*. (2018)
		Rhodococcus sp.	Desitti *et al*. (2017)
Firmi-cutes	*Bacilli*	*Bacillus* sp.	Zhang *et al*. (2014)
Proteo-bacteria	*Alphapro teobacteria*	*Ochrobactrum oryzae*	Ansari Shiri *et al*. (2016)
		Rhizobium sp.	Fajardo *et al*. (2012)
	Betaproteo bacteria	*Achromobacter* sp.	Tonelli *et al*. (2018)

Table 2: Continue

	Gamma-proteo-bacteria	*Acinetobacter* sp.	Sagarkar *et al*. (2016)
		Klebsiella variicola	Zhang *et al*. (2019)
		Pseudomonas sp.	Liang *et al*. (2021)
		P. stutzeri	Zhang *et al*. (2020)
		Shewanella sp.	Ye *et al*. (2016)
Asco-mycota	*Eurotio-mycetes*	*Aspergillus niger*	Marinho *et al*. (2017)
		A. oryzae	Pinto *et al*. (2012)
	Sordario-mycetes	*Metarhizium brunneum*	Szewczyk *et al*. (2018)
	Saccharo-mycetes	*Pichia kudriavzevii*	Das (2015)
		Saccharomyces cerevisiae	Wu *et al*. (2018)
Basidio mycota	*Agarico-mycetes*	*Lentinula edodes*	Pinto *et al*. (2012)

Conclusion

Anthropogenic activities generate residues that become pollutants to the environment and harmful to the health of living beings, directly by their toxicity or through their incorporation into the food chain. Among the main emerging contaminants are pesticides, nanomaterials, and polycyclic aromatic hydrocarbons. In recent decades, studies have been dedicated to the identification of the nature of these pollutants and the development of technologies to mitigate their effect.

Most of the pesticides used in the fields do not reach their target organism but remain in the soil damaging its properties, affecting biota, or being incorporated into the water table. The application of nanomaterials in agriculture, despite its usefulness, has also become a source of pollution. Polycyclic aromatic hydrocarbons are formed by volcanic eruptions and forest fires, industrial activities, oil exploitation, and spills and the poor solubility of many makes their removal particularly difficult.

Strategies to reduce the effects of emerging contaminants include physical and chemical methods, the substitution of polluting products for organic equivalents, the use of plants and microorganisms alone or in combination as remedial agents, and more recently nanotechnology and genetic engineering. As the obtaining of more food for the growing population is up today directly related to the generation of more pollutants, deeper studies are needed to improve the effectiveness of these strategies and/or reduce their costs, in search of cleaner productions.

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Author's Contributions

Sandra Pérez-Álvarez: Conceptualization, drafted, edited the manuscript, and drafted of the subtitle nanomaterials.

Eduardo Fidel Héctor Ardisana: Conceptualization, drafting, edited the manuscript, reviewed the manuscript, and a draft of the subtitle polycyclic aromatic hydrocarbons.

Marco Antonio Magallanes-Tapia: Conceptualization, drafted, edited the manuscript and drafted of the subtitle pesticides.

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Ethics

This article is original and contains unpublished material. The corresponding author confirms that all the authors have read and approved the manuscript and no ethical issues are involved.

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