An overview of the potential impacts of atrazine in aquatic environments: perspectives for tailored solutions based on nanotechnology

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Abstract

Atrazine is a pre- and post-emergence herbicide used to control weeds in many crops. It was introduced in the late 1950s, but its use has been controversial because of its high potential for environmental contamination. In agriculture, the implementation of sustainable practices can help in reducing the adverse effects atrazine. This review addresses aspects related to the impacts of atrazine in the environment, with focus on its effects on aquatic species, as well as the potential use of nanoencapsulation to decrease the impacts of atrazine. The application of atrazine leads to its dispersal beyond the immediate area, with possible contamination of soils, sediments, plantations, pastures, public supply reservoirs, groundwater, streams, lakes, rivers, seas, and even glaciers. In aquatic ecosystems, atrazine can alter the biota, consequently interfering in the food chains of many species, including benthic organisms. Nanoformulations loaded with atrazine have been developed as a way to reduce the adverse impacts of this herbicide in aquatic and terrestrial ecosystems. Ecotoxicological bioassays have shown that this nanoformulations can improve the targeted delivery of the active ingredient, resulting in decreased dosages to obtain the same effects as conventional formulations. However, more detailed analyses of the ecotoxicological potential of atrazine-based nanoherbicides need to be performed with representative species of different ecosystems.

Keywords: Agrochemical; aquatic organism; ecotoxicity; nanotechnology; triazinic herbicide.

1. Introduction

Herbicides are applied in various crops, in order to kill weeds following uptake of the chemicals into the leaves, stems, or roots (Kim et al., 2017; Lushchak et al., 2018). These chemical compounds have different mechanisms of action and can be classified as growth regulators, cell membrane disruptors, and inhibitors (Lushchak et al., 2018). They can affect seedling growth, photosynthesis, and the biosynthesis of amino acid, lipids, and pigments (Lushchak et al., 2018).

Atrazine is a synthetic herbicide that has been available on the market for more than 50 years. It was patented in Switzerland in 1958 and was registered for commercial use in the United States in 1959, after which it became used worldwide (Solomon et al., 1996). However its use has been controversial due to its persistence and mobility, resulting in it being detected in the soil, plantations, pastures, reservoirs used for public water supply, groundwater, streams, lakes, rivers, seas, and even glaciers in remote areas (Carmo et al., 2013; Garcia et al., 2012; Hénault-Ethier, 2016; Jablonowski et al., 2011; Nödler et al., 2013; Solomon et al., 1996; Sun et al., 2017).

Due to the high potential of atrazine to contaminate groundwater, in 2004 it was removed from the list of approved products in the European Union (Ackerman, 2007). The use of this herbicide is decreasing in Canada, where many formulations are already restricted in the west of the country (Hénault-Ethier, 2016). However, atrazine still is widely used in agriculture in other countries, highlighting the United States, Brazil, China, and India (Balakrishnan and Athilakshmi, 2016; Rusiecki et al., 2004; Sass and Colangelo, 2006; Sun et al., 2017). It was reported in 2002 that the amount of atrazine used in China is up to 5.000 tons per year (Jin and Ke, 2002). In India, the annual consumption of atrazine reached 340 tons in 2008 (Kadian et al., 2008). In Brazil, 24.731 tons of the herbicide were sold in 2017 (Brasil, 2019), while in the United States, over 30.000 tons are applied annually (Lorber-Pascal and Laurente, 2011).

Surprisingly, even after being banned, atrazine continues to be detected in European coastal waters. An example is the Aegean Sea, which is influenced by the exchange of water with the Marmara Sea and the Black Sea, bordered by countries where atrazine is still used.

This shows that even the prohibition of chemical products at an international level is unable to prevent continuing contamination (Nödler et al., 2013). Atrazine residues were detected in the urine of pregnant women, when it had already been banned, in the Brittany region of France (Chevrier et al., 2011). In Croatia, atrazine residues were found in urine samples from rural workers, both before and after application of the chemical (Mendas et al., 2012).

The effects of atrazine are not restricted to the target organism, with the presence of this herbicide in terrestrial and aquatic environments having the potential to affect a great diversity of species, consequently threatening environmental sustainability (Singh et al., 2018). The present review discusses the adverse impacts of atrazine, focusing on its harmful effects on species present in aquatic environments. Particular attention is given to new technologies that could assist in reducing the toxicity of this herbicide, such as micro/nanoencapsulation techniques.

2. Principle of action of atrazine and its potential for contamination

Atrazine (2-chloro-4-ethylamino-6-isopropylamino-s-triazine) is a selective pre- and post-emergence herbicide used to control weeds in cultivations including maize, sorghum, sugar cane, and pineapple, as well as in landscaping (Nwani et al., 2010; Solomon et al., 1996). This pesticide acts on the target organism by inhibiting photosynthesis, with blocking of electron transport in photosystem II (Forney and Davis, 1981). The blocking occurs because atrazine attaches at the plastoquinone Q_B (electron acceptor) binding site, consequently interrupting the flow of electrons between the photosystems (Fig. 1) (Marchi et al., 2008). With this inhibition, the electrons are not converted into chemical energy (adenosine triphosphate (ATP) and nicotinamide adenine dinucleotide phosphate (NADPH)) and impose a high energy load on chlorophyll molecules, leading to lipid peroxidation in the membranes, destruction of leaf chlorophyll, inhibition of carbohydrate synthesis, reduction of the carbon stock, and accumulation of carbon dioxide within plant cells (Marchi et al., 2008; Shabana, 1987).

In the case of pre-emergence application, atrazine is absorbed by the plants through the roots, subsequently being transported in the xylem to the leaves, where its action causes chlorosis, necrosis, and death. In post-emergence application, the chemical is absorbed by the leaves (Fig. 1) (Souza et al., 2012).

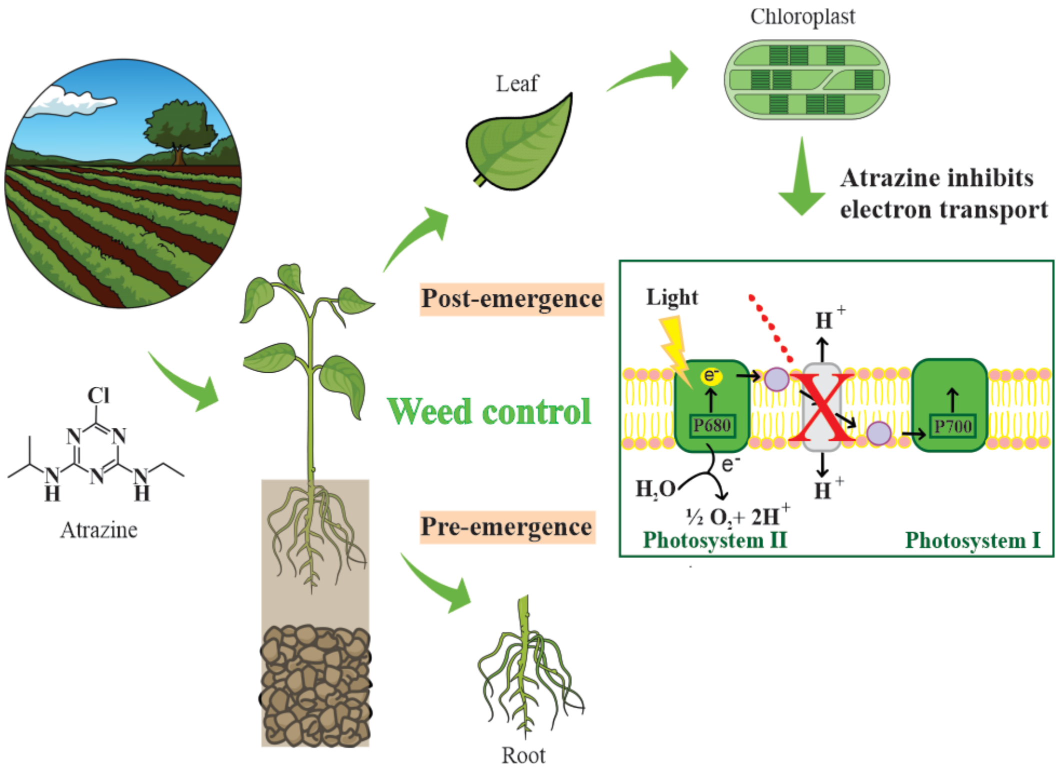

Fig. 1. Absorption of atrazine in weeds (target organisms), during the pre-emergence, it occurs mainly through the roots and in post-emergence through the leafs. The atrazine inhibits photosynthesis on target organism, blocking the electron transport in photosystem II.

Atrazine is considered to be a selective herbicide, enabling its use in several crops. Due to the different metabolic pathways and rates of metabolization of the chemical in weeds and crops, the species that are resistant rapidly convert the herbicide into nontoxic metabolites (Ebert and Dumford, 1976; Forney and Davis, 1981; Roman et al., 2007).

Atrazine has low vapor pressures, is moderately soluble in water, with solubility of 33.0 $mg.L^{-1}$ at 22 ºC, has low soil adsorption coefficient (k_{oc}) 100 cm^3 g^{-1} and an octanol partition coefficient water (log K_{ow}) of 2.75 (Balci et al., 2009; Baranowska et al., 2008; Carmo et al., 2013). However, it has high potential to contaminate groundwater, since it is poorly adsorbed in the organic fraction of the soil, consequently presenting high leaching potential, especially in a well-structured soil profile with macropores (Dias et al., 2018; Graymore et al., 2001).

When released into the environment, atrazine undergoes chemical, photochemical, and biological reactions that are responsible for its degradation to other compounds (Chevrier et al., 2011), each transformation product varying in its persistence and toxicity (Graymore et al., 2001). Examples are its transformation products deethylatrazine and deisopropylatrazine, which are frequently detected in surface and groundwater, in many regions worldwide, and can persist in water and soil for decades (Dores and De-Lamonica-Freire, 2001; Jablonowski et al., 2011).

Rainfall contributes to the dispersal of atrazine in ecosystems due to surface runoff, allowing it to be transported from the field to aquatic systems around the application area (Jablonowski et al., 2011). The transport of this contaminant in the environment can be attributed to its characteristics including resistance to decomposition by microorganisms, stability in soil and water, and half-life times varying from 14 days to 4 years in soil and from 6 months to several years in water (Guan et al., 2013; Stara et al., 2018).

Industries may also be a source of local contamination. In China (Changxing County, Zhejiang Province), high concentrations of atrazine were detected in a region close to a pesticide factory where atrazine was one of the main products (Sun et al., 2017).

Also, the application of pesticides in residential and agricultural areas can lead the simultaneous mixing of chemical compounds in aquatic environments with different mechanisms of action, causing an increase in toxicity, greater disturbance of aquatic ecosystems than expected considering the individual toxicities of the substances in isolation (Pérez et al., 2013).

3. Presence of atrazine in aquatic environments

Atrazine is frequently detected in aquatic ecosystems, where its presence affects the reproduction of aquatic fauna and flora, interfering with the structure of every community (Graymore et al., 2001), because its adverse effects on aquatic plants may alter the survival, growth, and/or reproduction of herbivores and predators (Solomon et al., 1996).

Atrazine can significantly inhibit algal growth and photosynthesis (Zhu et al., 2016). In evaluation of the ecological risk of atrazine in North American surface waters, phytoplankton were considered to be the organisms most sensitive to this contaminant, followed by macrophytes, benthic invertebrates, zooplankton, and fish (Solomon et al., 1996).

Studies have demonstrated that atrazine has the potential to reduce cellular metabolism and to influence the formation of reactive oxygen species (ROS), altering the antioxidant activity in fish (Nwani et al., 2010; Owolabi and Omotosho, 2017; Santos and Martinez, 2012), crustaceans (Schmidt et al., 2017; Stara et al., 2018), and chironomid larvae (Londoño et al., 2004).

Some European countries had already banned the use of atrazine before the decision of the European Union (Ackerman, 2007). At the same time when this herbicide was banned by the European Union, the United States renewed authorization of its usage, rejecting the allegations that atrazine may cause serious risks to the environment and human health (Ackerman, 2007; Sass and Colangelo, 2006).

Before atrazine was banned by the European Union, a uniform limit of 0.1 µg.L^{-1} of the pesticide residue was established for drinking water and groundwater (Ackerman, 2007). The World Health Organization allows a maximum concentration of 100 µg.L^{-1} for atrazine and its chloro-s-triazine metabolites in drinking water (WHO, 2017). In Australia is allowed 20 µg.L^{-1} of atrazine (NHMRC/NRMMC, 2011), in the United States 3 µg.L^{-1} (USEPA, 2009) and in the Brazil 2 µg.L^{-1} for freshwater, considering the use of the water for human consumption and the protection of aquatic life (CONAMA, 2005).

A review of the literature, considering articles published in the last five years, provides ample evidence that atrazine at different concentrations, including those that are environmentally relevant, can affect the development, behavior, and reproduction of many species present in the aquatic environment (Table 1; Fig. 2).

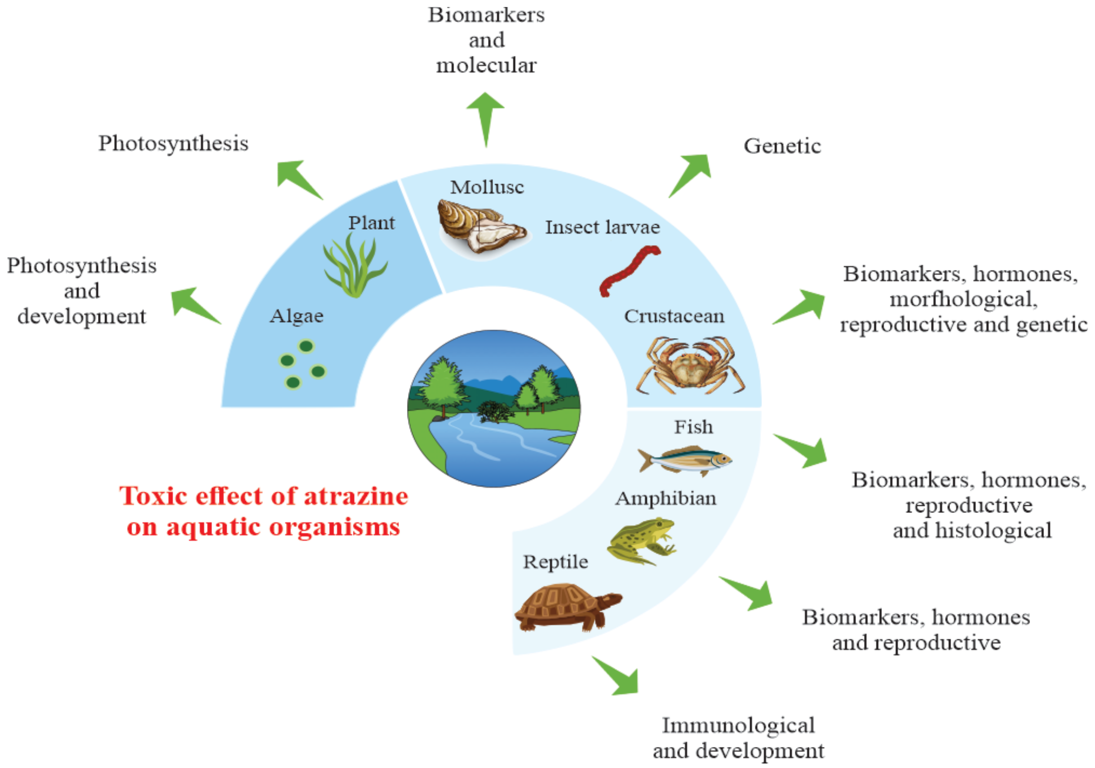

Fig. 2. The presence of atrazine in aquatic environments causes toxic effects on organisms representative this ecosystem. Each group represents different species that were exposed to atrazine, together with the corresponding toxic effects. Illustration adapted from Table 1.

Despite having the potential to cause toxic effects presenting toxic effects towards aquatic species, atrazine continues to be used in several countries, indicating the need to search for solutions and technologies that can reduce its impact (Singh et al., 2018), especially because agricultural activity is an important source of contamination of the environment with this herbicide (Sun et al., 2017).

4. Use of nanotechnology in the search for less harmful formulations

In 2020, there is estimated to be an increase of half a million tons in the global production of nanomaterials developed with specific characteristics for different applications (Rocha et al., 2015). The chemical structures of nanomaterials used in agriculture can be modified according to the type of plant or soil to which they will be applied, hence offering strategies for intelligent release and delivery of active agents (Lowry et al., 2019). The application of nanotechnology and the introduction of nanomaterials in agriculture can contribute to sustainable development and maximize global food production (Fraceto et al., 2016; Kah et al., 2019).

Nanotechnology is a field of knowledge that is advancing terms of basic research, the development of new techniques, and the production of novel materials. Formulations based on nanotechnology have several objectives: i) to increase dispersibility of the active compounds; (ii) to release them slowly; iii) to protect them against premature degradation caused by environmental factors; iv) to direct delivery of the active ingredients more effectively, enabling reductions in the amounts used (Chhipa, 2019). In this way, using smaller amounts of active agents and releasing them in a controlled way, these formulations enable the agents to remain available at the target sites for extended periods, at the concentrations required for effective action. This increases efficiency, reduces toxicity, and helps to avoid environmental contamination. Furthermore, these formulations also help to reduce the level of exposure of rural workers to agrochemicals, hence decreasing undesirable health effects (He et al., 2019).

Various atrazine-loaded nanoformulations (polymeric nanocapsules, nanospheres, and solid lipid nanoparticles) have been developed with the aim of reducing both environmental impacts and the amounts of this herbicide applied in the field (Clemente et al., 2013; Grillo et al., 2012; Kah et al., 2014; Oliveira et al., 2015a, b, c; Pereira et al., 2014; Souza et al., 2012). These effects are achieved because the use of encapsulation techniques provides protection of the active agent against physico-chemical and microbiological degradation (Pereira et al., 2014).

Triazine herbicides are commonly used in combinations, in order to increase the effectiveness of weed control. For this purpose, a system consisting of nanocapsules of poly (epsilon-caprolactone) (PCL) containing atrazine, ametryn, and simazine was developed, which proved to be less toxic, compared to the free herbicides, in genotoxicity tests with human lymphocyte cells at concentration 100 $mg.mL^{-1}$ and *Allium cepa* at concentrations 1, 10 and 100 $mg.L^{-1}$ (Grillo et al., 2012). Clemente et al. (2013) also evaluated PCL nanocapsules loaded with atrazine and amethrin (amethrin (different concentrations, in a gradient employing a factor of 1.8), employing cytogenetic analyses and bioassays with the aquatic organisms *Pseudokirchneriella subcapitata* (alga) and *Daphnia similis* (microcrustacean). It was observed that the encapsulation reduced cell damage in tests with lymphocyte cultures, while use of the formulation led to lower toxicity towards the alga, but higher toxicity towards the microcrustacean, which could have been due to the presence of other compounds in the formulation, such as surfactants.

In the work of Pereira et al. (2014), it was found that in comparison to the free herbicide, atrazine contained in PCL nanoparticles presented greater efficiency in control of the target organism (*Brassica* sp.), did not cause damage to the nontarget organism (*Zea* *mays*), reduced the mobility of atrazine in the soil, and decreased the genotoxicity of this pesticide. In herbicidal activity assays and in soil column experiments was applied a formulation with the concentration of the active principle equivalent to 2.5 kg.ha^{-1}, already in *Allium cepa* chromosome aberration assays the seeds were germinated in the presence of different concentrations (0.7, 2.1, 6.3, 18, and 54 μg.mL^{-1}) (Pereira et al., 2014).

In bioassays with *Brassica juncea* (the target organism), Oliveira et al. (2015a) found that atrazine-loaded PCL nanocapsules at concentrations 2000 and 200 g.ha^{-1} decreased overall photosynthesis and the maximum quantum yield of photosystem II, induced leaf lipid peroxidation, and caused inhibition of growth of the aerial part. The development of severe symptoms demonstrated the highly effective action of this system applied post-emergence. In tests with a nontarget organism (*Zea mays*), empty and atrazine-loaded PCL nanocapsules (at concentration 2000 and 200 g.ha^{-1}) did not cause any persistent deleterious effects, indicating that this nanosystem could be used as a safe tool in weed control, without affecting the development of the crop (Oliveira et al., 2015c).

In tests using atrazine-loaded PCL nanocapsules (at concentrations of atrazine of 1, 5, 10, 50, 100 and 200 mg.kg^{-1} of dry weight soil) against the soil invertebrate *Enchytraeus crypticus*, it was observed that empty nanocapsules did not affect this species, while the atrazine-loaded nanocapsules presented effects that differed from those of the free herbicide, which could be explained by different mechanisms of absorption, differential release of atrazine following nanoencapsulation, or the combination of these two factors (Gomes et al., 2019).

Andrade et al. (2019) used the fish *Prochilodus lineatus* to test the effect of atrazine-loaded PCL nanoparticless (at concentration of 2 and 20 μg.L^{-1}) and obtained satisfactory results, with integrated biomarker analysis demonstrating that the nanoencapsulation of the herbicide protected this fish species against the effects of the chemical.

Oliveira et al. (2015b) developed solid lipid nanoparticles (SLN) loaded with atrazine in combination with simazine, which proved to be effective against the target pest *Raphanus raphanistrum* (at concentration 3 and 0.3 kg.ha^{-1}), while presenting decreased toxicity towards nontarget organisms. Use of the system reduced both cytotoxicity towards rat 3T3 fibroblast cells (at concentrations 15.6, 31.25, and 62.5 µg.mL^{-1}) and phytotoxicity towards *Zea mays* plants (at concentration 3 and 0.3 kg.ha^{-1}). Jacques et al. (2017) evaluated the effects of these nanoparticles on the nematode *Caenorhabditis elegans* (at concentrations 0.025, 0.05, 0.1, 0.2 and 0.25 mg.mL-1) and also evaluated PCL nanocapsules loaded with atrazine (at concentrations 0.1, 0.2, 0.3, 0.4 and 0.5 mg.mL^{-1}), observing toxicity for the nanoformulations alone and loaded with atrazine and simazine, while the herbicides themselves did not cause mortality of the worms. The authors suggested that the activity could have been associated with the composition of the nanoparticles, indicating the need for further ecotoxicological studies.

In recent work by Xiao-Ting and Wang (2019), atrazine-loaded nanoparticles of poly (lactic acid-co-glycolic acid) were developed and characterized (considering morphology, size, encapsulation efficiency, and release profile). According to the authors, the herbicide delivery system developed is promising in order to reduce the impact on the environment and minimize possible damage to farmers, although more work is needed to evaluate its toxicity in different matrices.

Taverna et al. (2018) prepared lignin microspheres for the release of atrazine, with the microparticles presenting efficient release of the herbicide, as well as a lower rate of leaching in the soil, compared to free atrazine. Although this system showed potential for use, it remains necessary to carry out ecotoxicological bioassays.

The studies presented in the literature indicate that encapsulated atrazine has the potential to be used as a more environmentally friendly alternative, because it promotes a reduction in toxicity due to the characteristics of the release method. The nano/microencapsulation of active principle result in effective action against target organisms, while showing low toxicity towards nontarget species. However, despite this potential, further ecotoxicological studies with nano-formulated atrazine are needed, considering other species representative of aquatic and terrestrial environments. In addition, it is important that these nanosystems should be tested in bioassays that simulate different soil conditions, humidity, and temperature.

5. Conclusions and perspectives

The effects of atrazine are not restricted to the target organism, because the herbicide comes into contact with the wider environment and can interfere in the life cycles of many species. Atrazine is considered to be an effective herbicide in the control of target organisms, but may cause widely varying harm to nontarget species, due to its high potential to contaminate aquatic and terrestrial ecosystems. At concentrations that are environmentally relevant, this herbicide can cause sublethal effects in aquatic organisms.

Nano-formulated atrazine may potentially be an alternative that could be used to reduce the impacts of atrazine, since studies have shown that nanoformulations containing this herbicide improved the release of the active agent, allowed the application of lower doses (ten times smaller than conventional doses), and provided efficient herbicidal activity in tests with target organisms (Clemente et al., 2013; Grillo et al., 2012; Oliveira et al., 2015a, b, c; Pereira et al., 2014; Souza et al., 2012). These published results indicate the importance of performing ecotoxicological tests using these nanomaterials with different species, in order to identify formulations that do not present lethal and/or sublethal effects towards nontarget organisms.

The introduction of nanomaterials in the agricultural area can contribute to a shift towards more sustainable practices, reducing damage to human health and the environment, while ensuring more efficient utilization of pesticides and fertilizers (Damalas and Eleftherohorinos, 2011; Fraceto et al., 2016; Grillo et al., 2012; Jacques et al., 2017; Oliveira et al., 2015a).

Nanoformulations need to be studied and evaluated in terms of their efficiency, toxicity, production scale, composition, degradation behavior, and cost-benefit, preferably in comparison with the conventional analogue (Andrade et al., 2019; Fraceto et al., 2016; Jacques et al., 2017; Kah et al., 2018). These studies may contribute to the establishment of regulatory frameworks for the use of nanotechnology in agriculture. However, the successful implementation of nanotechnological interventions will require collaboration among the areas of scientific research, policy development, and industrial technology (Kah et al., 2019; Mahawar and Prasanna, 2018).

Acknowledgments

This study was financed in part by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES, Brazil, finance code 001). L.F.F. and J.L.O. would like to thank the São Paulo State Research Foundation (FAPESP, grants #2017/21004-5 and #2018/21142-1) for financial support for nanopesticide development.

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