Physicochemical Properties of Inorganic Nanopesticides/Nanofertilizers in Aqueous Media and Tank Mixtures

Rafael Augusto Alves Ferreira, Marta Simão Kfouri, Rafael Pires-Oliveira, Augusto Cesar Gonçalves, and Poliana Cardoso-Gustavson

Abstract Nanotechnology is still pointed out as a promising technology in the crop protection market, mainly in a sustainable scenario of reducing the amount of active ingredient (AI) applied in the field. Although the benefits of this technology in terms of safety, efficiency, sustainability, and performance in the field are undeniable, a huge regulatory issue remains to be overcome. Apart from the several promises and challenges in the development, scale up, and use of the nanoformulations in the field, the global market shows a stable growth of this technology and a movement toward innovation by using sustainable components and new application models. All the known nanosystems' advantages are thoroughly explained by the physicochemistry of colloids. This technology might provide more stable formulations in terms of shelf-life, a higher field performance with a lower applied dose of the AI, and less issues in the tank mixtures. Indeed, a rising technology in precision agriculture is the application of nanoformulations through drones, which can finally overspread their use in the field. In this chapter, we provide an overview of the global market for nanofertilizers, besides deepening on the main physicochemical properties linked to the higher stability of nanoformulations over conventional ones, as well as their expected performance in the tank mix applications in the field.

Keywords Nanotechnology · Nanoparticles · Formulation · Fertilizer market · Pesticide market · Nanoparticle uptake · Tank mix compatibility

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1 Introduction

Agriculture is responsible for the production of food crops (cereals, vegetables, fruits, and edible oils) and non-food crops, also known as industrial crops. Industrial crops include the production of flowers, first- and second-generation biofuels (bioethanol, biodiesel, and biomass), natural fibers (such as cotton, linen, and industrial hemp, commonly used to produce paper, cloth, fabric, and rope), and sustainable raw materials (such as biopolymers, rubber, and building materials). The demand for these products is increasing with the global population growth, estimated to achieve over 9 billion in 2050 (United Nations, 2019). In order to ensure high productivity to supply the world needs, it is crucial to supply all macro- and micronutrients particularly required by each crop and to protect the plants against pest attack. In addition, some mineral nutrients, such as phosphate and potash, are facing a global source scarcity, leading to a disproportion in the supply/demand balance and hence affecting the fertilizers price (Scholz et al., 2013; Jung, 2021). Nanotechnologies enable more effective production of inorganic fertilizers and pesticides, safely reducing the dosage applied and preventing material loss or undesired residues in terms of environmental pollution, addressing the nutrients shortage as well. In this chapter, we examine the technological status of this sort of products, the patent's overall status, and a physicochemical overview to understand the formulation stability of nanosystems focused on shelf life and their behavior in tank mixtures.

2 Market, Intellectual Property, and Technology Analyses

A conceptual issue that has received attention from the market is the debate about the use of the term "nano" for nanopesticides, including nanofertilizers. This use is problematic because the definition based on size alone excludes the recently named nanofertilizer formulations and includes products that have been available in the market since a long time ago without posing clearly as a formulation based on nanosize scale, such as microemulsions[1]. So, to avoid customer confusions by including ingredients which were not characterized as nano, it is more useful to discuss nano-enabled or formulation technology instead focus on nanoparticles and their definitions. In addition, the absence of comprehensive studies in the literature that evaluates efficacy and environmental impact of nanofertilizers under field conditions and comparison with conventional fertilizers to assess economics limit a higher use and acceptance of nanotechnologies. This is a crucial knowledge gap and

[1] Microemulsion is defined as a "dispersion made of water, oil, and surfactant(s) that is an isotropic and thermodynamically stable system with dispersed domain diameter varying approximately from 1 to 100 nm, usually 10 to 50 nm". (Slomkowski et al., 2011)

therefore more work will be necessary for a solid evaluation of the benefits that nanofertilizers represent in relation to existing products.

The fertilizers market has been virtually static in the last few years, and in this section, we analyze some figures from this market. The general fertilizer industry made a global production revenue of USD 250 billion in 2018, reaching 252 Mt. nutrients (International Fertilizer Association (IFA) Fertilizer Outlook 2019–2023 IFA Annual Conference 11–13 June 2019 Montreal (Canada)). The COVID-19 pandemic[2] is adversely affecting this market in conjunction with several global supply chain disruptions and severe macroeconomic turbulence, and it was expected to reach in 2020 a reduction of total sales to 247 Mt. (Fertilizer Outlook, 2020–2024 Market Intelligence and Agriculture Services). On the other hand, the controlled-release fertilizers global market, a portion of which may comprise nanofertilizers, is projected to grow at a compound annual growth rate (CAGR) of 6.3% in the forecast period (2020–2025) reaching USD 3.2 billion by the end of 2025 (Gupta, 2020). The drivers for this expectation are the increase in global population and economic growth. Indeed, the market of the emerging nations is growing with the support of the government in terms of incentives, loans, and tax waives in agricultural fertilizers, thus boosting the overall industry.

The restrictions of this market are linked to the environmental and health concerns, such as soil and water pollution, and fate of microplastics. The increasing use of biofertilizers and trend of organic food, besides the issues about government regulations and the political-economic scenario of the reduction of free trade, have also constrained the market for fertilizers – conventional and nano-enabled ones.

The sustainability claim for nanofertilizers has affected the market positively, acting as an incentive to this technology. Indeed, a more widespread adoption of nanofertilizers would reduce environmental risks, such as atmospheric and groundwater pollution, soil acidification, eutrophication, the decline of the level of soil fertility, and loss of biodiversity. Compared to other fertilizer technologies such as chemical or biofertilizers, nanofertilizers help in supplying nutrients in a more effective way, offering controlled release of active ingredients onto the soil, which in turn improves the crop yield. These are the main reasons for the rising demand for nanofertilizers in the next years, although this market seems not to forecast an aggressive increase, but a slower one following the establishment of the technologies to their production. Looking forward, the global nanofertilizers market is expected to continue its moderate but consistent growth during the next decade (IMARC Group, 2021).

From a global market point of view, the continuing driver for research and investment into nanofertilizers is the urgent need to increase nutrient uptake efficiency in order to decrease environmental harms from synthetic fertilizers. Advancements in nanotechnology have paved the way for large-scale production of nanoparticles that are used in the manufacture of nanofertilizer formulations. The market benefits of nanofertilizers are mainly linked to the slow/controlled release of nutrients,

[2] The COVID-19 pandemic was declared in March 2020 by the World Health Organization.

reducing nutrient loss and increasing their bioavailability, and the specificity to be synthesized according to the objective, creating highly nutrient efficient crops. However, the lowlights of this technology include the high reactivity and variability, the environmental impacts of microplastics, and safety concerns for farm workers and consumers (Kah, 2015, Kah et al., 2018, Zulfiqar et al. 2019). The market for surfactants, and monomers/polymers to be applied in the formulations may follow a similar forecast compared to nanofertilizers, presumably due to the benefits of improving physicochemical aspects of the nanofertilizers' formulation. This forecast is expected to be even more positive for sustainable and low carbon footprint components. In addition, these components must be suitable for registration by regulatory agencies from the USA and EU to be applied in crop and even in organic markets, being convenient for customers of the surfactant industry to have at least one registration.

Key agrochemical companies figure as key players in the global pesticides and fertilizers market, such as Syngenta, Nanosolutions, Smart Agri-Tech Co. Ltd., Richfield Fertilizers Pvt. Ltd., Alert Biotech, Prathista Industries Limited, Lazuriton Nano Biotechnology Co., Sonic Essentials, Jinzhou City Jinchangsheng Chemical Co., UNO Fortunate Inc., Florikan, Bayer, BASF, Nutrien, Yara International, ICL, Haifa, and Mosaic, among others (Dimkpa & Bindraban, 2018; Pires-Oliveira et al., 2020a), but when nanosized products are taken into consideration, small companies also stand out. Nanotechnology is still not widespread in agricultural products nor clearly positioned by big players of the market. The main reasons are the lack of robust studies showing the environmental safety and benefits of nano-sized products in comparison to the conventional ones, and the challenge for a large-scale production in a competitive cost (Dimkpa & Bindraban, 2018; Kah et al., 2018). The same behavior is observed by patent landscape analysis (Figs. 1 and 2), which allows the understanding of the maturity, players, and most promising regions for commercialization of this technology.

The intellectual property analysis was performed using PatSnap IP Platform searched from 116 databases. We performed searches using different queries, adjusting the terms searched in the Title/Abstract/Claims/Description (original and machine translation) (TACD_ALL) and selecting the International Patent Classification (IPC) to recover the best results according to the objectives – for example, using the term "nano*" resulted in documents not related to nanotechnological products that only appeared due to terms "nanoseconds", "[wavelength] nanometer" (as a unit of UV-Vis measurements), etc. On the other hand, when the IPC B82 (Nanotechnology) was searched no relevant results were obtained. Therefore, the searches were performed using the search terms described in Table 1, and queries F1 and F4 recovered the best results for conventional and nano-enabled fertilizers, respectively. A similar analysis was performed separated for inorganic nanopesticides, using the queries shown in Table 2 and, in this case, most reliable results were recovered using queries P4 and P5 for conventional and nano-based inorganic pesticides, respectively.

Fertilizer is an old technology, with a significant number of patent applications per year since 1922 showing an expressive growth of patent application in 2000

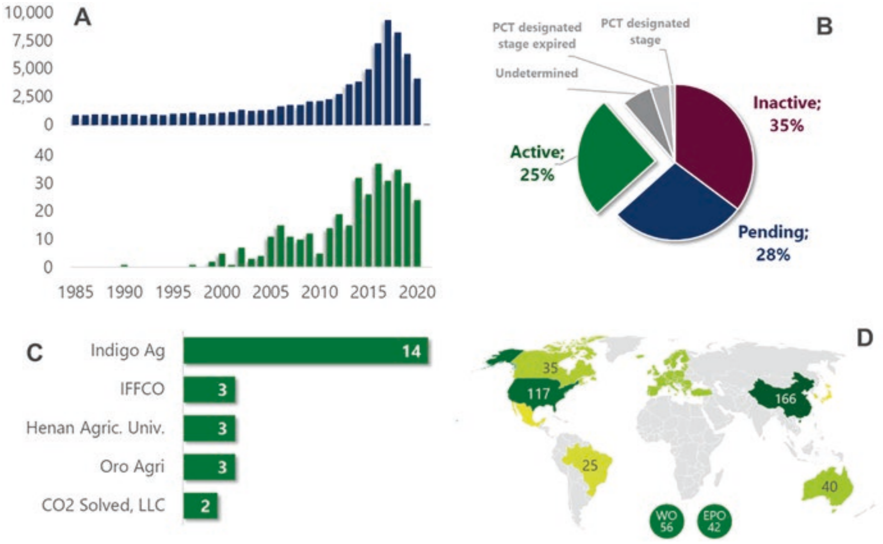

Fig. 1 Patent landscape analysis for nano-enabled fertilizers using query F4. (**a**) Patent application per year of nano fertilizers (green bars, query F4) in comparison to conventional fertilizers (blue bars, query F1). (**b**) Simple legal status breakdown of the technology field. (**c**) Highlight of the top 5 assignees with the largest patent portfolios in the technology field. (**d**) Geographic coverage of where patent applications have been filed

(Fig. 1a). Similarly, inorganic pesticides also display a constant patent applications per year until mid-1960s, when it grew reaching a plateau up until mid-2000s, when started to grow at a faster rate (Fig. 2a). This may be due to the development of more effective organic active ingredients replacing old inorganic compounds. Nanotechnology is a recent development and first patent applications in both technological fields were filed relative recently, around mid-2000s. From the patent applications, only about one-fourth are currently active (granted and alive) assuring the exclusivity of commercialization of that technology in a specific region for the assignee and in both nanotechnological fields the patent application is widespread all over the world and filed by multiple assignees.

According to the Nanotechnology Products Database, (2021), there are around 9000 nano-enabled products available for different market segments, but only a few are agricultural products (231 products from 75 companies, against 850 products from 244 companies available in the cosmetics market, for example). Nano-based products and technologies comprise mainly nanoparticles, such as metals, metal oxides, clays, nutrient or active ingredient impregnated in a polymeric or inorganic nano-sized matrix acting as a nanocarrier. Some products claimed as nanotechnological are also prepared by emulsification using surfactants or polymers as emulsifiers and stabilizers (Nuruzzaman et al., 2016; Mustafa & Hussein, 2020; Sikder et al., 2021), which can also be coacervated or polymerized in situ to form, respectively, a soft or a hard shell (Pires-Oliveira et al., 2020a). Fertilizers (102) account

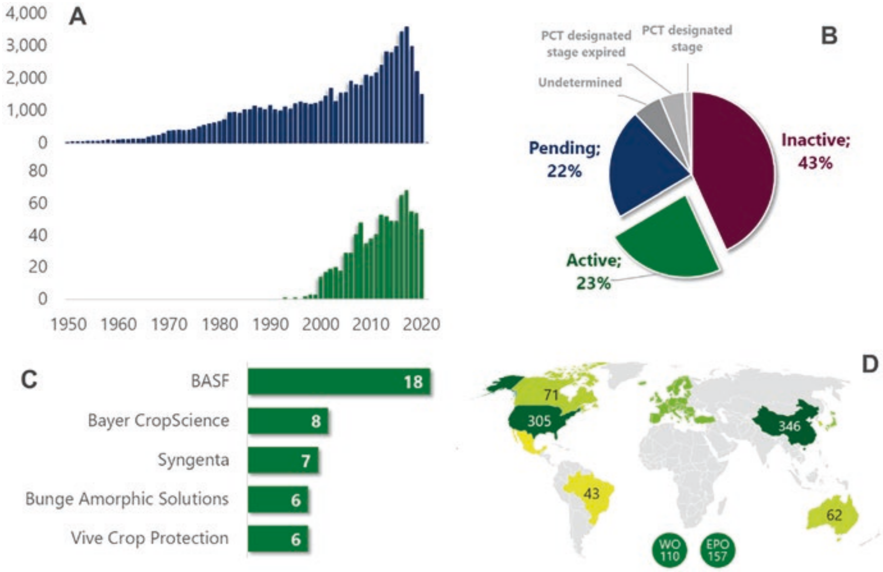

Fig. 2 Patent landscape analysis for nano-enabled inorganic pesticides using query P5. (**a**) Patent application per year of nanofertilizers (green bars, query P5) in comparison to conventional fertilizers (blue bars, query P4). (**b**) Simple legal status breakdown of the technology field. (**c**) Highlight of the top 5 assignees with the largest patent portfolios in the technology field. (**d**) Geographic coverage of where patent applications have been filed

for the main nanoagricultural products available with formulations, being divided mainly into the application mode (aeroponics, hydroponics, soil, or foliar applications) and type of nutrient, such as macronutrients (NPK), secondary macronutrients (calcium, Ca), and micronutrients, such as copper (Cu), iron (Fe), and zinc (Zn). Nanotechnological plant protection products comprise silver (Ag) and copper (Cu) nanoparticles and the landscape tends to focus more on technical challenges, mainly the scale up.

Inorganic matrices, such as nanoclays (Chevillard et al., 2012; Zhang et al., 2020), mesoporous silica nanoparticles (Plohl et al., 2021; Xu et al., 2021), and other nanocomposites (Pancera & Wengeler, 2015; Kottegoda et al., 2017; Zhang et al., 2019; Eldridge & Rosa, 2020) are often used to produce a nanocarrier for pesticides and nutrients. Polymers, dendrimers, and surfactants are classes of organic compounds able to encapsulate and/or deliver nano-sized inorganic pesticides or fertilizers. In addition to a controlled release, these nanomaterials may also display further benefits: be a nutrient source providing N, P, and Si when decomposing. Moreover, smart nanomaterials can be generated by coating the nanoparticles, leading to a nanopesticide or a nanofertilizer responsive to light (Chen et al., 2018), pH (Hao et al., 2020), temperature (Yao et al., 2021), or even to a plant enzyme (Abdelrahman et al., 2021), releasing the active ingredient in a specific target or at a desired time. Another advantage of polymer coating is to provide adhesion of the nanoparticle onto the leaves' surface, guaranteeing the uptake of nutrients (Read et al., 2020).

Table 1 Searched terms used for queries related to conventional and nano-enabled fertilizers. TACD_ALL = search in Title/Abstract/Claims/Description (original and machine translation). IPC: A01N is related to pesticides, and A01C is related to fertilizers

Query	Search terms	Total	Simple families
F1	TACD_ALL:((leaf OR foliar OR foliage OR root) AND (fertiliz*)) AND IPC:(A01N OR A01C)	230,573	94,261
F2	TACD_ALL:((leaf OR foliar OR foliage OR root) AND fertiliz*) AND IPC:(A01C)	54,156	40,579
F3	TACD_ALL:((leaf OR foliar OR foliage OR root) AND (fertiliz*) AND (nano*)) AND IPC:(A01C)	1597	1007
F4	TACD_ALL:((leaf OR foliar OR foliage OR root) AND (fertiliz*)) AND TACD_ALL:("nanoscale" OR "nano-scale" OR "nanosize*" OR "nanomater*" OR "nanopar-tic*" OR "nano-particle" OR "nano-level" OR "nanosphere" OR "nano-powder" OR "nano-sphere" OR "nano-material" OR "nanotech*" OR "nanocaps*" OR "nanostruct*" OR "nano-tech*") AND IPC:(A01N OR A01C)	865	351
F5	(TACD_ALL:((leaf OR foliar OR foliage OR root) AND (fertiliz*) AND (("nanoscale" OR "nano-scale" OR "nanosiz*" OR "nanomat*" OR "nanoparticle" OR "nano-particle" OR "nano-level" OR "nanosphere" OR "nano-powder" OR "nano-sphere" OR "nano-material" OR "nanometer" OR "nano-copper" OR "nanotech*" OR "nanocaps*" OR "nanostruct*"))) AND IPC:(A01C))	442	253

Metal and metal oxide nanoparticles with potential application as pesticide or fertilizer can also be produced by the sol-gel method, which generates solid materials (*gel*) from small molecules in colloidal solution (*sol*) (Parashar et al., 2020), as described in several embodiments of patent documents from industries of the two different segments, for instance, BASF (Dreher et al., 2013) and Bunge Amorphic Solutions LLC (Foscante, 2018), besides universities (Duan et al., 2005; Santra, 2018; Santra et al., 2018). A composite of titanium dioxide (TiO_2) and calcium carbonate ($CaCO_3$) nanoparticles (Baker et al., 2020) applied to agricultural plants was developed to enhance CO_2 trapping from the air, as an attempt to reduce the concentration of greenhouse gases. Micronutrients, such as copper (Cu), iron (Fe), zinc (Zn), manganese (Mn), boron (B), silicon (Si), and titanium (Ti), were combined with coordinating anions to produce 2D nanostructured compounds that can be used as nanofertilizers or nanopesticides showing an enhanced performance (Hamers & Borgatta, 2020). A similar system was produced neutralizing a water-soluble polyelectrolyte using an oppositely charged species, forming a collapsed polymer nanoparticle that entraps the active ingredient in its interior producing a controlled release (Li et al., 2020).

Amphiphilic copolymers have been widely used to produce nanocapsules of pesticides and fertilizers. Mulqueen et al. (2014) described a method for coating crystalline nanoparticle of an active ingredient using block copolymer micelles. The fungicide mancozeb was prepared in a nanoformulation comprising micelles of a poly(ethylene glycol)-based functionalized amphiphilic copolymers for targeted

Table 2 Searched terms used for queries related to conventional and nano-enabled inorganic pesticides. TACD_ALL = search in Title/Abstract/Claims/Description (original and machine translation). IPC: A01N is related to pesticides, B82 is related to nanotechnology, and C01 is related to inorganic chemistry

Query	Search terms	Total	Simple families
P1	TACD_ALL:((herbicid*) OR (pesticid*) OR (insecticid*) OR (fungicid*)) AND IPC:((A01N) AND (C01))	3045	1073
P2	TACD_ALL:((herbicid*) OR (pesticid*) OR (insecticid*) OR (fungicid*)) AND IPC:((A01N) AND (C01) AND (B82))	74	36
P3	TACD_ALL:((herbicid*) OR (pesticid*) OR (insecticid*) OR (fungicid*)) AND IPC:((A01N) AND (C01)) AND TACD_ALL:((“nanoscale” OR “nano” OR “nano-particle” OR “nano-scale” OR “nano-level” OR “nanosphere” OR “nano-powder” OR “nanomaterial” OR “nano-sphere” OR “nano-material” OR “nanometer” OR “nano-copper”))	347	131
P4	TACD_ALL:(((herbicid*) OR (pesticid*) OR (insecticid*) OR (fungicid*))) AND TACD_ALL:(“silver” OR “copper” OR “cupper” OR “zinc” OR “zinc-copper” OR “titanium” OR “silicon” OR “silicon oxide” OR “aluminium” OR “SiO2” OR “TiO2” OR “ZnO” OR “Al2O3”) AND IPC:(A01N)	261,856	74,769
P5	TACD_ALL:(((herbicid*) OR (pesticid*) OR (insecticid*) OR (fungicid*))) AND TACD_ALL:(“silver” OR “copper” OR “cupper” OR “zinc” OR “zinc-copper” OR “titanium” OR “silicon” OR “silicon oxide” OR “aluminium” OR “SiO2” OR “TiO2” OR “ZnO” OR “Al2O3”) AND TACD_ALL:(“nanoscale” OR “nano-scale” OR “nanosize*” OR “nanomater*” OR “nanopartic*” OR “nano-particle” OR “nano-level” OR “nanosphere” OR “nano-powder” OR “nano-sphere” OR “nano-material” OR “nanotech*” OR “nanocaps*” OR “nanostruct*” OR “nano-tech*”) AND IPC:(A01N)	2030	848

delivery of the active ingredient (Majumder et al., 2020). Using a nanoemulsion, Berg and Pullen (2016) created a lipid nanocarrier system for delivery of nutrients or active ingredients. Other nanocarrier for fertilizer and pesticide application is highly branched dendrimers, such as poly(etherhydroxylamine) (PEHAM) (Hayes et al., 2017) or poly(aminoamide) (PAMAM) (Bunderson et al., 2020), which enhance the water solubility of active ingredients and increase their bioefficacy. In this case the active ingredient is conjugated and entrapped in the dendrimer molecule.

Different materials and approaches can be employed to produce nanomaterials with potential use in agriculture. A wise combination of inorganic particles and polymers enables a prospective system to overcome current limitations in nanocarriers for agrochemicals. It is possible to design and control the polymer architecture generating a versatile functional component that allows to tune the transition trigger tailoring the nanostructure formed (Pires-Oliveira et al., 2020b), hence enabling a controlled delivery of the active ingredient (Sikder et al., 2021). Moreover, there are a number of monomers that can be selected to produce biodegradable polymers avoiding microplastics pollution. Further, these additional outer layers may provide physical stability of the nanoparticles in aqueous suspension, as discussed in the following section, ensuring long-term stability for an appropriate time between production, transportation, storage, and application. The ionic moieties of the coating polymer grant electrostatic repulsion between nanoparticles and the non-ionic groups, such as ethylene oxide chains, provide steric hindrance; both mechanisms avoid particle agglomeration and aggregation, eventually followed by a phase separation. Finally, with all these features together and taking into consideration the best feasible process for a large-scale production using ecofriendly raw materials, nanotechnology can be used as a cost-competitive alternative to increase the sustainability of the agriculture.

3 Physicochemical Concepts and Properties of Nanosystems

As previously mentioned, the development of new vehicles to deliver actives for different systems, aiming to deliver at a specific target or time and to increase bioavailability or stability is recurrent in several areas of industry. In agriculture, nanostructured systems such as microemulsions, nanocapsules, and nanoparticles are examples of strategies that can intensify uptake, promoting a sustained release, with enhanced residual effect or bioefficacy in the field. Usually, nanoparticles cover the range 10–200 nm diameter, being included within the colloidal range, between 1 nm and 1 μm (IUPAC, 2019). These particles start presenting properties completely different from their bulk counterparts. The observations of these size-dependent properties are intriguing because the entities that make up the micro and the nanoparticles are the same. So why are the properties so different? Other than the exponentially increased surface area, the shape or assembly of the atoms is enough to modulate the properties. Before understanding the field performance, the nanosystems present highlighted features in terms of formulation stability. The destabilization of a colloidal system in liquid media can occur by two main mechanisms: gravitational force and Ostwald ripening.

For the sake of understanding these phenomena, it is important to consider fine particles that are dispersed in a liquid medium and undergo Brownian motion. The Brownian motion is favorable in nanosystems, since it describes their random motion and the smaller the particle size, the faster their movement and the less likely it is to sink to the bottom, resulting in no creaming or sedimentation during storage (Tadros, 2016). On the other hand, the increase of motion triggers more collisions favoring Ostwald ripening, hitting each other and changing direction of motion in solution. Therefore, the Ostwald ripening is the main mechanism for the instability of nanoformulations (Tadros et al., 2004). This phenomenon is thermodynamically driven, a spontaneous process that occurs due to the larger particles being more energetically stable than smaller ones. The molecules of the surface are interacting with less molecules than those of the bulk. As the system tends to keep the lower energy, molecules from the surface of small particles detach and diffuse into the solution. The consequence is the increase of free molecules concentration in the solution and the supersaturation leads to the aggregation of them onto the surface of larger particles (Ratke & Voorhees, 2002). Thereby, the small particles have a decrease in their sizes whereas the big particles have an increase always trying to minimize the total surface area and thus minimizing the ratio surface area by volume. Then, the Ostwald ripening describes crystal growth. By the same reason described above, a decrease of particle size leads to an increase of solubility, consequently these molecules tend to circulate in the medium and to deposit onto larger particles. The different polymorphs of the insoluble particle may also drive this phenomenon once the solubility may be different among them.

The gravitational force triggers the sedimentation, flocculation, and creaming. Regarding sedimentation, it occurs when the sedimentation velocity (v_s) is greater than the thermal velocity (v_t) of Brownian motion. Both rates can be approximated to particle size-dependent functions (McClements, 2011):

$$v_s = \frac{2a^2 g \Delta\rho}{9\eta} \tag{1}$$

$$v_t = \sqrt{\frac{kT}{m}} = \sqrt{\frac{3kT}{4\pi a^3 \rho}} \tag{2}$$

Equation 1 describes the sedimentation velocity, and it is called Stokes' law, in which "a" is the particle radius, $\Delta\rho$ is the difference between the dispersed and continuous phase densities, g is the acceleration of gravity, and η is the viscosity of the continuous phase. Eq. 2, also called the Fokker-Planck equation, describes the thermal velocity of the particles in Brownian motion, where k is the Boltzmann constant, T is the temperature, m is the mass of a particle, and ρ is the density of the dispersed phase. Generally, nanoparticles suffer less influence of this phenomenon due to their small radius, but Ostwald's ripening is predominant for the same type of particles (Tadros, 2016). Another reason for destabilization is flocculation. The driving force for flocculation is van der Waals attraction, which for spherical particles at short distances of separation is proportional to the particle or droplet radius (Hamaker, 1937). This effect is less prominent in nanosystems since the radius is much smaller when compared to suspensions and emulsions, resulting in lower van der Waals attraction between the particles or droplets. Therefore, nanoparticles do not tend to flocculate by van der Waals attraction.

Considering application as nanopesticides or nanofertilizers, some properties, such as surface area, play an important role. The surface area for a given volume of nanoparticles is much larger than the surface area for the same volume of larger particles, thus considering that the application of agrochemical formulations is usually very inefficient, the increase in surface area by volume might be an interesting strategy to improve the efficacy of these formulations. Leaf uptake can be increased by the application of nanoparticles, considering their usual sizes. The entrance routes for these nanoparticles may include the cuticle and stomata, as shown in

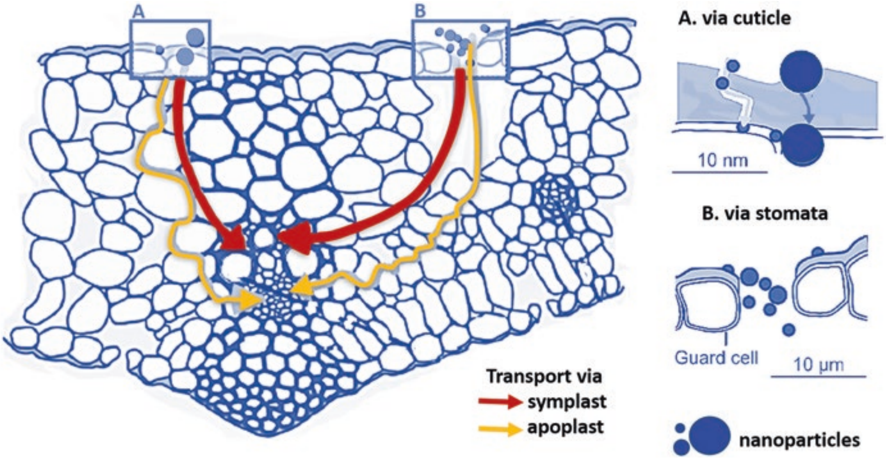

Fig. 3 Pathways for nanoparticles foliar uptake with transportation via symplast (red arrow) and apoplast (yellow arrow). Scheme depicting (**a**) the uptake via cuticle and (**b**) the uptake via stomata

Fig. 3, although these phenomena are still not fully elucidated to date (Avellan et al., 2019). It is usually assumed that the entrance through stomata seems more feasible due to the size difference between the nanoparticle and the stomata itself; however, it is more likely that nanoparticles are absorbed through the cuticle, even though cuticular pores are smaller than the nanoparticle sizes, similarly to the entrance of particulate matter from polluted environments. The entrance through stomata may occur, however alike particulate matter events, it may cause stomata clogging by nanoparticles. This clogging leads to an accumulation of reactive oxygen species at the substomatal chamber and adjacent cells, which may trigger a programmed cell death, morphologically observed as necrotic spots (phytotoxicity).

Particles of varying sizes, including nanoparticles, can also be used for emulsion stabilization, enabling the storage and use of formulations, as well as improved tank mixtures for application in the field, in the so-called Pickering emulsion (Pickering, 1907), named after Spencer Pickering but first observed by Walter Ramsden (Ramsden, 1904). In this type of emulsion, particles adsorb on the interface between the dispersed and continuous phases preventing them from coalescing and leading to more stable emulsions (Ortiz et al., 2020). The energy of the system (ΔG_d), represented in Eq. 3, is dependent on the particle radius (r), the contact angle between the phases (θ), and the interfacial tension between the oil and water (γ_{OW}) (Zhou et al., 2020). The nature of the particle is important for the stabilization ability, being amphiphilic particles, including Janus particles (Walther & Müller, 2013), the most effective ones because they interact well with the hydrophilic phase and the oil phase.

$$\Delta G_d = \pi r^2 \gamma_{OW} \left(1 - |\cos\theta|\right)^2 \tag{3}$$

Rheological properties of nanoparticle-containing solutions can vary from Newtonian to non-Newtonian according to the power-law as represented in Eq. 4 and Eq. 5 (Saedodin et al., 2019; Kessler et al., 2019).

$$\tau = m\ddot{Y}^{n} \tag{4}$$

$$\mu = m\ddot{Y}^{n-1} \tag{5}$$

where τ is the shear stress (Pa), μ is the dynamic viscosity (Pa·s), $\ddot{Y}$ is the shear rate (s^{-1}), n is the power-law index, and m is the consistency index (Pa·s^n). When n is equal to 1, the behavior of the fluid is Newtonian (linear shear stress in terms of shear rate), whereas the fluid is non-Newtonian if n is different of 1 (having shear thinning when n is lower than 1 and shear thickening when n is greater than 1).

In terms of appearance of the nanoformulation, they can be transparent, translucent, or turbid depending on three main factors, namely the particle or droplet radius, the difference in refractive index between the dispersed phase and dispersion medium, and the volume fraction of the dispersed phase. As there are different types of formulation that apply nanotechnology, it is unspecific to list all the possible required protocols to be applied in order to evaluate the physicochemical performance. Our suggestion is that the formulator consults the FAO Guidelines and find the better kind of formulation to follow the requirements (microemulsions – ME, Capsule suspension – CS, among others). In general, the commonly recommended tests by CIPAC[3] are the following:

- Acidity and/or Alkalinity (MT 191) or pH range (MT 75.3).
- Pourability (MT 148.1).
- Spontaneity of dispersion (MT 160).
- Suspensibility (MT 184).
- Wet sieve test (MT 185).
- Persistent foaming (MT 47.2).
- Emulsion stability and re-emulsification (MT 36.3).
- Particle size distribution (MT 187).
- Accelerated storage (MT 46.3).

4 Tank Mix Compatibility

Tank mixture of two or more components is a usual and necessary practice adopted by farmers aiming to optimize resources in crop management. Time, costs, number of treatments, water, wear of agricultural implements, and energy are examples of parameters that can be optimized by combining and applying suitable products in a mixture. Furthermore, the combination of pesticides with different modes of action

[3] CIPAC: Collaborative International Pesticides Analytical Council.

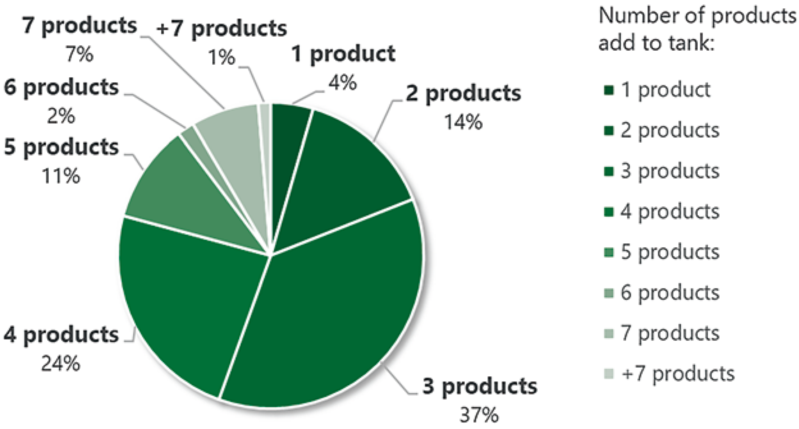

Fig. 4 Number of products added in a tank for applications in Brazil. It includes insecticides, fungicides, herbicides, foliar fertilizers, and adjuvants

can be synergistic, promoting a better result when compared to single and time elapsed application. However, although some mixtures are synergistic or neutral, it is important to pay attention to the antagonistic effect that may occur (Green, 1989). The global result of this equation is reflected in a substantial gain in profit, due to the optimized management and improved yield.

The tank mixture practice is very regionalized and customized due to obvious reasons. In Brazil, ca. 96% of the farmers apply tank mixtures, and in 86% of the cases the mixtures contain between two and five products, as shown in Fig. 4 (Gazziero, 2015). In the soybean crop, for example, 86% of the glyphosate applications are made by the combination of insecticides, fungicides, and other herbicides. The choice of the products to be mixed depends on the crop, seed germplasm, pests and diseases to be treated or prevented, weather conditions, application stage, and products available in the region. Resistant pests, weeds, and diseases are important drivers for the definition of which products will be mixed in each application.

In addition to the great variability presented above, there is a clear and constant trend on reducing the spray volume per hectare, which contributes to the autonomy of the agricultural to be implemented in both terrestrial and aerial applications, again impacting in the management costs. Ultra-low volume (ULV) applications through drones are a real and booming subject for both chemical and biological pesticides. In typical drone applications the spray volume varies from 5 to 10 liters/ha. The same terrestrial application would take about 100 to 300 liters/ha. There is a considerable difference in the preparation of tank mixture for terrestrial vs. drone's application.

Considering the variability of products, water quality, types of mixtures, pH of mixture, and volume/area, there is a great chance of having problems related to tank mixture compatibility. Difficulty in dissolving products, phytotoxicity on target crop, excess of foam, nozzle clogging, and precipitation of material are the most frequent problems of compatibility observed in the field. The order of addition of the products is another point of high relevance and can be determinant on the compatibility or not for a given tank mixture. As there are many variables involved and as the system becomes more and more complex by the sequential addition of products, it is a difficult (and almost impossible) task to define exactly which is the key point in a compatibility issue. For this reason, there are products in the market positioned as tank mix compatibilizers, which are in most cases water conditioners, acidifiers, buffers, chelation agents, and emulsifiers, in order to ensure compatibility and avoid problems.

When the subject of nanostructured pesticides or fertilizers is introduced, there is an additional point of attention regarding the compatibility of complex mixtures. However, there are interesting new perspectives about this incoming type of pesticides, that would help to achieve stable mixtures and new possibilities:

1. 59% of the tank mixture preparations in Brazil are made using the full dosage of the products (Gazziero, 2015).
2. Given the size range of nano-enabled pesticides, and the fact that the size impacts directly on the efficacy of the active ingredients due to better distribution and uptake, it is possible to apply reduced doses of active ingredients per hectare (De Oliveira et al., 2015);
3. As the lower the load in a tank, the lower is the risk of compatibility issues. Furthermore, lower doses of active ingredients are advantageous in terms of cost of formulation, environmentally friendly approach, and lower risks of remaining residues of pesticides on food.

The concept of nanoscale pesticides also includes hybrid micromaterials (size >200 nm) that contain substructures attached in the nanoscale. These substructures can be: (a) nanoscale coatings, (b) additives, and (c) fertilizers (Mikkelsen, 2018). Much of the tank compatibility problem comes from the surface of a given active ingredient particle that interacts with electrically charged components present in the system, giving rise to clusters of increased size, which results in aggregates that precipitate and culminate in nozzle clogging. The possibility of implementing nanocoating on the surface of a given problematic active ingredient particle can lead to a surface modification which can avoid the aggregation process and related complications. Furthermore, it can modulate the delivery kinetics of the active to the target, which can be of interest regarding residual effect, for example.

When applied in the ionic and soluble form, fertilizers or inorganic pesticides act as electrolytes in the spraying solution. The presence of charged components can result in attraction forces between ions and particles, causing instability and precipitation. Insoluble salts can be formed between ions in solution, representing another risk to the mixture. The application of formulations based on nanoparticles suggests an interesting approach to overcome issues of this nature, once they are not ions, but the particle size is of comparable dimension. As new nanopesticides and nanofertilizers emerge as product options, the results in the field practice will naturally be explored and become an alternative tool for the market toward complex mixtures. The advantages we can prospect are based on the lower doses combined with the nanosized particle that makes them more available compared to current microparticle's formulations.

5 Final Remarks

The countless benefits of nanosystems are exhaustively described in the literature for diverse fields of science. For agriculture, it is not different. In this chapter, we overviewed the main technologies used and market for this application, highlighting the physicochemical properties that ensure a relevant performance of nanopesticides and nanofertilizers in terms of formulation stability and their behavior in tank mixtures. When we refer to nanotechnology for inorganic pesticides or fertilizers the possibilities are extensive, since inorganic matrices and aggregates are formed by polymers, dendrimers, and surfactants, which can be smart and functional materials, and formulated as products classified as microemulsion (ME) or capsule suspension (CS, ZC). This approach of modern products for agriculture is growing and we expect to see an increased number of studies and patents on this technological field, followed by new products launched in the market comprising nano-enabled fertilizers and pesticides.

In this scenario, it is common to occur merges of startups with big global companies. Due to the specific technology that is currently under development, it needs a big effort to control, characterize, and scale up the process, normally the mergers are the better strategy to incorporate the technology by the big ones, once their assets scarcely can absorb the specific demand for nanosystems.

Besides that, farmers need to be convinced about the benefits of this kind of technology that probably will not deliver the load of actives nor there is a need for it, due to their nanotechnology ability to present similar performance in the field with less concentration of active ingredients or fertilizers.

Other obstacle to overcome is the regulatory issues, there are several studies proving the absence of great toxicological problems, but the regulatory agencies must position themselves about that when they carefully understand the toxicity aspects.

In contrast to several steps to overcome, the great number of studies, patents, and some products that already exist in the market prove the importance of nanotechnology for agriculture.

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