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Nanotechnology Applications of Pesticide Formulations

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Abstract

In the last few years, the application of nanotechnology in agriculture has created new opportunities for developing nanosized agrochemicals that have the potential to improve efficiency, enhance stability, prolong the effective duration and at the same time reduce environmental loads [1,4]. One of the critical challenges in the agricultural industry is the need to address issues associated with the pesticide's use as environmental contamination, bioaccumulation, and increases in pest resistance, which demands a reduction in the quantity of pesticide applied for crop and stored product protection. Nanotechnology is emerging as a highly attractive tool to achieve this goal by offering new methods for the formulation and delivery of active pesticide ingredients, as well as novel active ingredients, collectively referred to as nanopesticides [5].

Pesticides may have a negative impact on environmental biodiversity and potentially induce physiological effects on non-target species. Advances in technology and nanocarrier systems for agrochemicals led to new alternatives to minimize these impacts, such as nanopesticides, considered more efficient, safe and sustainable. However, it is essential to evaluate the risk potential, action, and toxicity of nanopesticides in aquatic and terrestrial organisms [6].

Regulations for the registration and introduction of nanoagrochemicals into the market are still missing. Uniform worldwide rules for defining nanoagrochemicals and for harmonizing the methods of risk assessment are needed [7].

Introduction and significance

Nanomaterials held great promise regarding their application in nano-based pesticide formulation due to their small size, big surface area, and target modified properties. The nano-based formulation may bring beneficial improvements in properties and behaviors of pesticides, such as solubility, dispersion, stability, mobility, and targeting delivery [8].

The term *nano pesticides* is used to describe any pesticide formulation that (a) intentionally includes entities in the nanometer size range (here we include entities up to 1000 nm), (b) is designated with a "nano prefix (e.g., nanohybrid, nanocomposite), and/or (c) is claimed to have novel properties associated with the small size. On this basis, nano pesticides include a wide

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variety of products. The aims of nanopesticide formulations are generally similar to those of other pesticide formulations, these being (a) to increase the apparent solubility of poorly soluble active ingredients or (b) to release the active ingredient (a.i.) in a slow/targeted manner and/or protect the a.i. against premature degradation [9].

Is it safe or more toxic?

Conventional pesticide disadvantages

Inefficient use of pesticides causes a series of ecological, environmental problems. They include the pathogen and pest resistance, non-point pollution, water eutrophication, soil degradation, bioaccumulation in the food chain, and loss of biodiversity, (**Figure 1).** Wettable powder (WP) and Emulsifiable Concentrate (EC) are two major conventional pesticide formulations. WP is a crushed powder pesticide formulation composed of active pesticide ingredients (AIs), inert fillers, and other additives. The inorganic fillers in WP easily drift and run off into the environment, and the loaded AIs cannot be completely released. Besides, the residual pesticides are difficult to be degraded, (**Figure 2).** EC is a liquid pesticide formulation. Pesticide AIs are dissolved in the solvent, added with an emulsifier, and then diluted into water to form a stable emulsion. The organic solvents and toxic ingredients directly leach and leak into the environment while pesticide spraying, resulting in serious pollutants in soil and water system, chemical residues in crops and food products, and a potential threat to human health [5].

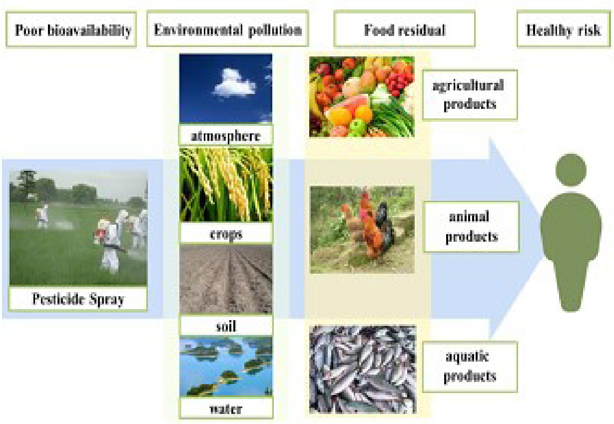

Figure 1: Potential environmental impacts induced by inefficient pesticides.

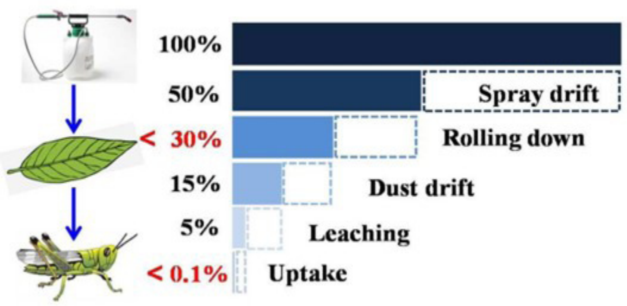

Figure 2: Low efficiency of convential pesticides.

Nanopesticide advantages

Developing new advanced nano-based formulations that remain stable and active in the spray condition (sun, heat, rain), penetrate and deliver to the target, prolong the effective duration and reduce the run-off in the environment. It is one of the hotspots in the field of nano-technical agriculture applications [10].

Nanomaterials held great promise regarding their application in nano-based pesticide formulation due to their small size, big surface area, and target modified properties (**Figure 3).** Nano-based formulation may bring beneficial improvements in features and behaviors of pesticides, such as solubility, dispersion, stability, mobility, and targeted delivery. Furthermore, it might significantly improve the efficacy, safety, and economic effects of traditional pesticides. It is by increasing efficiency, extending effect duration, reducing the dose required, providing the capability to a controlled release of active ingredients, and improving the stability of payloads from the environment, subsequently diminishing run-off and environmental residuals [8].

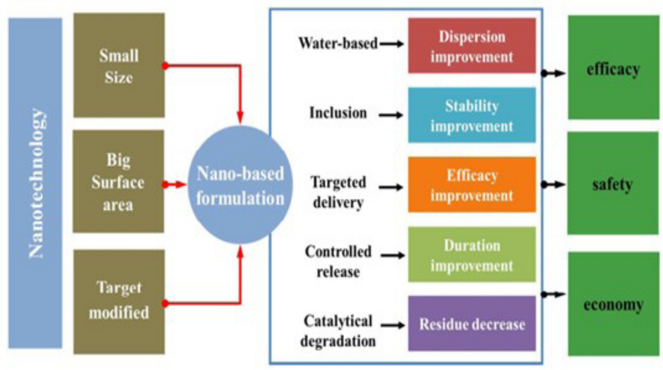

Figure 3: Nano- based formulation brings beneficial improvements in pesticide properties.

Categories of nanopesticides

A broad variety of natural or synthesized materials are used in the construction of pesticide nano formulations, such as metal, metal oxides, non-metal oxides, carbon, silicates, ceramics, clays, layered double hydroxides, polymers, lipids, dendrimers, proteins, quantum dots, and so on [11,12].

Varieties of Nano formulation types, (**Figure 4),** have been developed. They include nanoemulsions, nanocapsules, nanospheres, nanosuspensions, solid lipid nanoparticles, mesoporous nanoparticles, and nanoclays.

These formulations show high potential for improving formulation properties, such as water-dispersion, chemical stability, targeting adhesion, permeability, and controlled release [13-15],

1. *Aqueous nanoemulsion and nanosuspension* of pesticides could increase the solubility of water-insoluble AIs and eliminate the toxic organic solvents. And, they would gradually substitute the conventionally EC products [16,17].

2. *Nanocapsule and nanosphere* are suggested as vehicles for the environmentally sensitive pesticides, due to their capability to slow release of AIs, improve stability of the formulation, prevent early degradation, and extend the longevity of pesticides [18,19].

3. *Mesoporous nanoparticles***,** include nanoclay, activated carbon, and porous hollow silica are also verified to be suitable for the controlled release and delivery systems for the water-soluble and fat-dispersible pesticides. They possess high drug-loading capacity, excellent biocompatibility, low toxicity, and multistage release pattern [20,21].

4. *Water-based dispersion pesticide nanoformulations* improve the solubility and dispersion in water, uniform leaf coverage, biological efficacy, and environmental compatibility, due to the small particle size, high surface area and elimination of organic solvents in comparison to conventionally formulations [22-24].

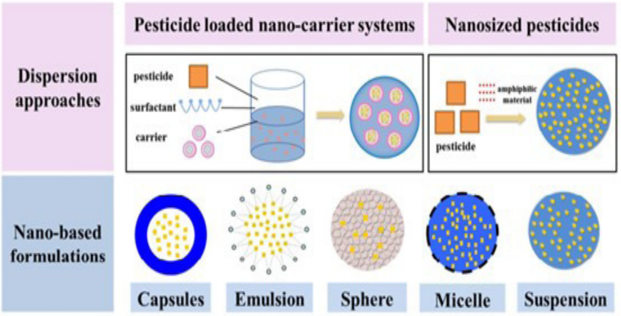

Figure 4: The nano-formulation of water- dispersed pesticide.

Synthesis of nano-based formulations

Nano-pesticides may be developed by two pathways, directly processing into nanoparticles (nanosized pesticides), and loading pesticides with nano-carriers in delivery systems. In nanocarrier systems, pesticides are loaded through encapsulation inside the nanoparticulate polymeric shell, absorption onto the nanoparticle surface, attachment on the nanoparticle core via ligands, or entrapment within the polymeric matrix. It involved size reduction by top-down methods as milling, high-pressure homogenization, and sonication. In contrast, the bottom-up processes involve melt dispersion, solvent displacement, complex coacervation, interfacial polymerization, and emulsion diffusion [25].

Nanocapsules, nanoemulsions, nanospheres, nanomicelles, and nanosuspensions show high potential for improving formulation properties, such as water-dispersion, chemical stability, targeting adhesion, permeability, and controlled release (**Figure 5).**

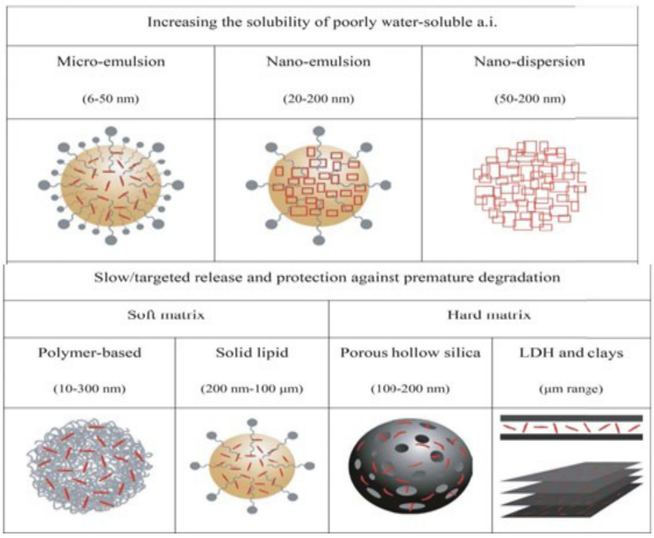

Figure 5: Formulations aiming to increase the solubility of poorly water- soluble compounds. a.i.: Active Ingredient; LDH: Layered Double Hydroxides (Kah et al. [9]).

Nanocapsules are core-shell structural vesicular systems, encapsulating the pesticide AIs in the inner core. The shell is usually composed of biodegradable polymeric, including poly-ε-caprolactone (PCL), polylactic acid (PLA), polyglycolic acid (PGA), poly (lactic-co-glycolic) acid (PLGA), polyethylene Glycol (PEG), chitosan, and etc [26-28]. The polymeric shell degrades slowly in the environment, thus improves chemical stability for environment-sensitive compounds (i.e., UV degradation and soil degradation). Besides, nanocapsules can increase the targeting delivery efficiency with membranal polymeric leaf-affinity modification, improving the behaviors of wetting, spreading and absorbing of droplets on leaves [29-31].

Nanoemulsions are oil-in-water (O/W) emulsions where the pesticides are dispersed as nanosized droplets in water, and the surfactant molecules localized at the pesticide-water interface [32,33]. Nanoemulsions improve the efficacy and safety effects of traditional pesticides, due to the small size effect, high dissolution rate, and elimination of toxic organic solvents [34].

Nanospheres are solid sphere vesicular systems where the pesticides are uniformly distributed through adsorption or entrapment inside the nano-matrix [35-37]. Nanospheres are composed of organic polymer materials or inorganic mesoporous materials, such as activated carbon, non-metal oxides, and porous hollow silica. Nanospheres possess high drug-loading capacity, good biocompatibility, and slow/controlled release pattern, showing great potential in soil infection disease and soil pest control [38-40].

Nanomicelles are ideal bioactive smart nano delivery systems for encapsulating pesticides. Nanomicelles can be induced by the external environment, and thus make the corresponding changes in physical and chemical properties. For example, based on the hydrogen bonding cross-linked nanomicelle, an environment-responsive controlled release system was constructed. Under high temperature and high humidity conditions, the hydrogen bonding fractured, the nanomicelle swelled, and the pesticides were released. The pesticides were blocked under low temperature and low humidity conditions the other way round [41].

Naonosuspensions are pesticide nanoparticles uniformly suspended in water. The aqueous colloid dispersion systems render higher solubility and dispersion for insoluble or fat-dispersible compounds in solution, improve the pesticide bioavailability, and reduce the costs due to the ease of large-scale manufacture.

Technology of nanosuspension

For manufacturing nanosuspensions, there are two converse methods “bottom-up” and the “top-down” techniques [42].

Bottom-up methodology

Antisolvent precipitation

Antisolvent precipitation is an effective way to prepare micro- or nano-sized drug particles. In this precipitation method, first, the drug was dissolved in the solvent, and then, the solution containing drugs was quickly added into the antisolvent. Crystal precipitation occurs under the condition of drug concentration supersaturation. To ensure better stability of the nanosuspension; the used stabilizer should have enough affinity for the particle surface. And have a high diffusivity that can quickly cover the generated surface. Besides that, the quantity of stabilizer should be able to completely cover the surface of particles [43].

All-Trans retinoic acid nanosuspensions were prepared with a precipitation method. The use of simple and low-cost equipment and also benefit for higher saturation solubility is the advantage for precipitation technique compared to other methods of nanosuspension preparation. Precipitation technique is not applicable to drugs that are poorly soluble in aqueous and non-aqueous media. In this technique, the drug needs to be soluble in at least one solvent, which is miscible with non-solvent [44].

Top-down technologies

Media milling (nanocrystals or nanosystems)

In this method, the nanosuspensions are produced using high-shear media mills or pearl mills. The media mill consists of a milling chamber, a milling shaft, and a recirculation chamber. The milling medium is framed of glass, zirconium oxide, or highly cross-linked polystyrene resin. The milling chamber is charged with the milling media, water, drug, and stabilizer, and the milling media or pearls are then rotated at a very high shear rate.

The milling process is performed under controlled temperatures. The high energy and shear forces generated as a result of the impaction of the milling media. The drug provided the energy input to break the microparticulate drug into nanosized particles. The unimodal distribution profile and mean diameter of <200 require a time profile of 30–60 min. Once the formulation and the process are optimized, very slight batch-to-batch variation is observed in the quality of the dispersion. A nanosuspension of Naproxen with a mean particle size of 300–600 nm was prepared using pearl milling technique [45].

High-pressure homogenization (Disso Cubes)

The main principle is high pressure, i.e., 100–1500 bars. By this pressure, we can easily convert the micron size particle into nanosize particle. Moreover, it initially needs the micron range particle, i.e., <25 µm, so that we have to get the sample from the jet mill because using a jet mill, we can reduce the particle size up to <25 µm. Moreover, we can use this equipment for both batch and continuous operations. Capacity is also 40 mL–1000 L. Here, first, we have to convert the particles into pre-suspension form (after jet milling) [46].

Yang et al. [47] prepared nanosuspension and microsuspension by high-pressure homogenization. Their crystalline state was evaluated by differential scanning calorimetry and powder X-ray diffraction. Both evaluations indicated that the lattice energy of drug particles decreased with the decrease of particle size; *et al*. Shown that particle size reduction could increase the solubility and *in vitro* dissolution rate. The smaller the particle size, the higher the dissolution rate.

Emulsion

These emulsions are also useful for the preparation of nanosuspensions. The drugs which were insoluble in volatile organic solvents or partially soluble in water are prepared by this method. Initially, organic solvents, such as methylene chloride and chloroform, were used. However, environmental hazards and human safety concerns about residual solvents have limited their use in routine manufacturing processes. Relatively safer solvents such as ethyl acetate and ethyl formate can still be considered for use [48].

Microemulsion

Microemulsions are thermodynamically stable and isotropically transparent dispersions of two immiscible liquids, such as oil and water stabilized by an interfacial film of surfactant and co-surfactant. The drug can be either loaded into the internal phase, or the pre-formed microemulsion can be saturated with the drug by intimate mixing. Suitable dilution of the microemulsion yields the drug nanosuspension. An example of this technique is the griseofulvin nanosuspension, which is prepared by the microemulsion technique using water, butyl lactate, lecithin, and the sodium salt of aurodeoxycholate [48].

Nano versus conventional pesticides

Water-dispersion, leaf-affinity, bio-availability, and residues degradation are the most critical factors regarding the development of nano-based pesticide formulations. Four key scientific issues for improvement of pesticide efficacy and safety are proposed: **(i)** Construction of water-based dispersion pesticide nanoformulation; **(ii)** Mechanism on leaf-targeted deposition and dose transfer of pesticide nano-delivery system; **(iii)** Mechanism on increased bioavailability of nano-based pesticide formulation; and **(iv)** Impacts of nanoformulation on natural degradation and bio-safety of pesticide residues **(Figure 6,7).**

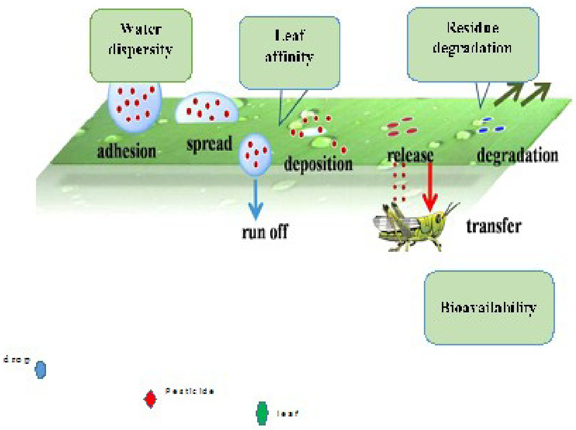

Figure 6: The critical factors related to the development of nano-pesticide.

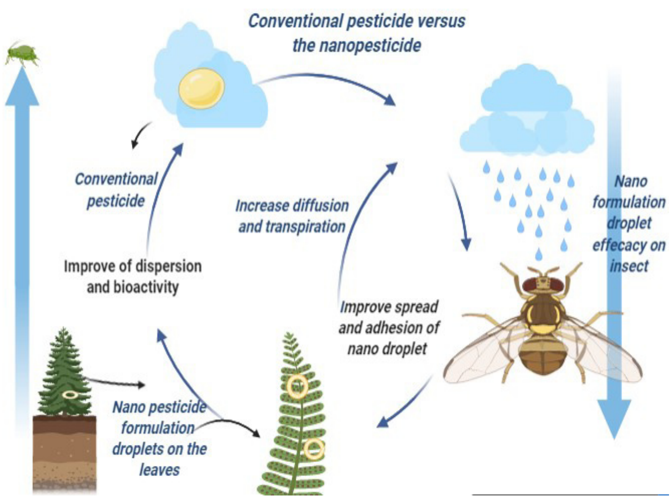

Figure 7: Size- down of pesticides increase bioavailability and efficiency.

The characterization of nano- pesticide

Solubility and dissolution velocity related to the particle size distribution

The most appropriate characterization parameter for the nanosuspension is the mean particle size and width of particle size distribution. It can determine the physicochemical properties such as saturation solubility, dissolution velocity, physical stability, and even biological performance. A change in particle size changes saturated solubility and dissolution velocity. Smaller the particle size more will be the saturated solubility and dissolution [49].

The particle size and zeta potential_

Zeta potential determines the physical stability of nanosuspension. The particle size, polydispersity index (PDI), and zeta potential **(Figure 8)** are an indirect measurement of the thickness of the diffusion layer that can be used to predict long-term stability. A minimum zeta potential of ±30 mv is required for obtaining a nanosuspension exhibits a good stability, and electrostatically stabilized structure. In the case of a combined electrostatic and steric stabilization, a minimum zeta potential of ±20 mV is desirable [25,42].

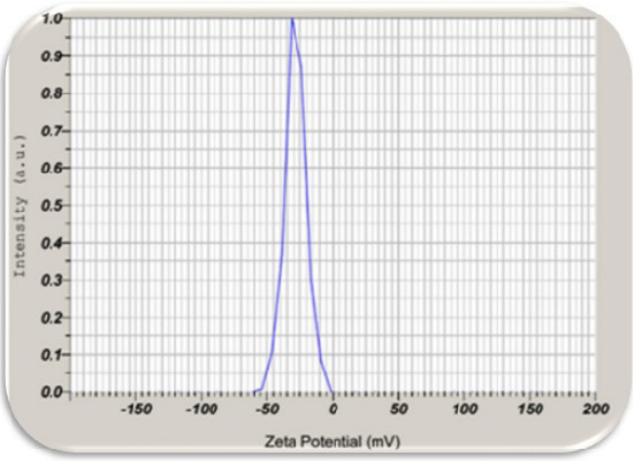

Figure 8: Zeta potential pattern of nano-particles.

Droplet size for Nanoemulsions has been considered useful for improving water delivery of insoluble compounds or active compounds [33,50]. The average size of a drop of oil-in-waterer type nanoemulsions usually falls within the range of 20 to 200 nm [51]. The particle size and PDI of prepared nanoemulsions produced by a Dynamic Light Scattering (DLS), showed droplet size values of 18.35, 177.2, 84.99, 24.42, and 79.05 nm for chlorpyrifos, malathion, cypermethrin, deltamethrin, and lambda-cyhalothrin, respectively with their respective PDI values of 0.300, 0.235, 0.121, 0.377 and 0.162 [52]. Understanding the physics of the formation of nanoemulsions is critical to controlling the volume of droplets [53]. It should be noted that significant effects of surface concentration, type of oil, ultrasonic energy, time on drop diameter, and PDI, as reported in previous studies [54,55].

Crystal imaging of the nanoparticle

X-ray diffraction (XRD) **(Figure 9)** is used to assess the degree of crystallinity of the nanoparticles. X-ray diffraction analysis is used to determine the polymorphic changes due to the impact of high-pressure homogenization in the crystalline structure of the new compound. Nanosuspension can undergo a difference in the crystalline structure, which may be to an amorphous form or other polymorphic forms because of high-pressure homogenization. An increased amount of amorphous d compound fraction could induce higher saturation solubility [56,42].

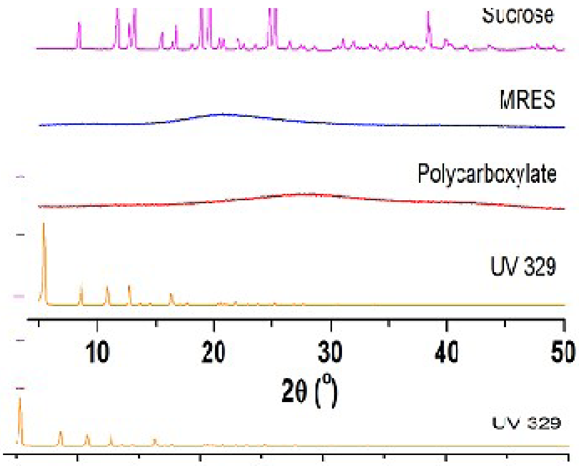

Figure 9: XRD pattern of nano-particles.

Structural characterization of the nanoparticles

The morphology of the nanoparticles was monitored by a scanning electron microscope (SEM) SEM, and Transmission electron microscopy TEM are useful tools to characterize particle morphology. In the case of solid nanodispersion [57] and also TEM technique is often useful to characterize nanoemulsions. They used as a complementary tool to have a direct observation of the lipid particles and obtain reliable data about the morphology of system [58]. TEM analyses also confirmed that the droplet diameter of the formulations falls in nanometric scale. The nanodroplet size measurements obtained have also been confirmed by several authors who reported that the microstructure and size distribution were obtained with nanoemulsions containing certain pesticides [52,59,60]. The micrograph of **(Figure 10)** demonstrates a spherical shape of the droplets representing a typical appearance of a nanoparticle under electron microscope.

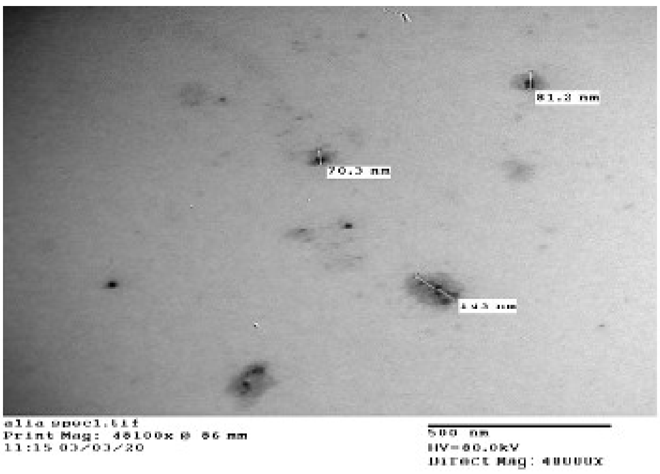

Figure 10: Structural characterization and the morphology of the nano-particles monitored by a scanning electron microscope.

Determination of nano- pesticide Content

The content of the formulation is determined by high-performance liquid chromatography (HPLC) like avermectin content as a solid nanodispersion [57]. The statement of the nano metal composition of AgNPS, AgNPS@ L-CYN nanoparticles was detected using a UV -visible spectral analysis, UV-VIS spectrophotometer, according to Ahmed et al [61].

Suspensibility test

The kinetic stability of the suspensions and the suspensibility of the pesticide formulations must be tested. It was confirmed that suspensibility was inversely proportional to particle size, mainly because brownian motion became acute with decreased particle size [17,62,63]. At the same time, surfactants also improved pesticide dissolution performance. The excellent suspensibility of the nanosuspension was attributed to particle size reduction and the formulation's composition [64].

The suspensibility of the solid nanodispersion in water was measured according to CIPAC MT 184 and calculated by the following equation **(1):**

$$\text{Suspensibility}(\%) = \frac{10}{9} \times \frac{m1 - m2}{m1} \times 100$$

Here, m1 (mg) and m2 (mg) are the pesticide contents of the original suspension and the remaining 25ml of solution at the bottom, respectively [65].

Wettability and retention Test

The wettability is a critical factor to assess the adsorption and adhesion capacity of pesticide

on leaves. It relates to the ability of the powder to be wetted or dispersed not only in liquid but also on leaves. The result of a smaller contact angle indicated that the nanosuspension was easier to spread and wet on the leaf surface [64]. The wetting time of pesticide WPs is generally longer than 50 s [66,67]. The wettability of the formulation on leaf surfaces was investigated based on contact angle measurements. As known to all, the surfactants can decrease surface tension, increase the diffusion of the solution, and further enhance the wettability on the leaves surface [68,69]. Besides, particle size reduction can increase the dissolution rate and supersaturation solubility [12,70].

The retention test was measured using an impregnation method [71,72].

The retention was calculated according to equation **(2):**

$$Rm = \frac{m1 - m0}{s}$$

The FTIR spectrometer **(Figure11a & b)** uses an interferometer to modulate the wavelength from a broadband infrared source. A detector measures the intensity of transmitted or reflected light as a function of its wavelength. The signal obtained from the sensor is an interferogram, which must be analyzed with a computer using Fourier transforms to obtain a single-beam infrared spectrum. The FTIR spectra are usually presented as plots of intensity versus wavenumber (in cm^{-1}). Wavenumber is the reciprocal of the wavelength. The intensity can be plotted as the percentage of light transmittance or absorbance at each wavenumber [61].

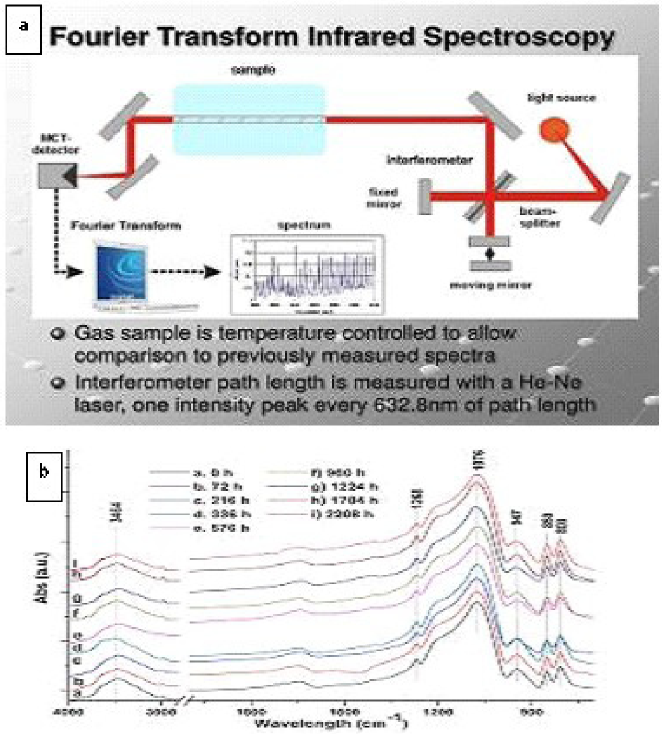

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Figure 11: (a). The FTIR spectrum and **(b)**. The pattern of the FTIR spectra.

Storage Stability using the Dynamic Light Scattering

The physical and chemical stability must be evaluated after storage at 54^{0}C, according to the product standard of pesticide suspension [73]. The hydrodynamic size determined by Dynamic Light Scattering (DLS) [64]. The DLS gives a hydrodynamic size, including the micelle core and the swollen corona, while SEM often gives the real particle size in a dried state [74,75]. Nanosuspensions are necessarily thermodynamically, unstable systems [48]. At a high storage temperature, the active drug particle may undergo Ostwald ripening, which caused the particles to adhere together and led to a relative increase in particle size. It may be the main reason for aggregation and particle size increase [76]. By covering the surface of the nanoparticles, the surfactant molecules could shield the inner compound, decrease the free energy of the particles, and reduce interfacial tension [77]. In addition, the polymeric structure of emulsifier 700 affords steric protection from agglomeration and prevents crystal growth [78].

Bioassays and bio-efficacy of nano pesticide

Bioassays were conducted using the larvicidal and pupicidal assays and were corroborated with the histopathological and biochemical profiles of hosts upon treatment with nanometric pesticide. Further, the biosafety studies of the nanopesticide were carried out against different non-target species like freshwater algae and *Zebrafish* [65]. The biochemical and histopathological studies of larval and pupal tissues also investigated by Mishra et al [73]. Biosafety study on non-target species as the toxicity evaluation on the algae by Cell viability assay [73]. Our group previously assessed phytotoxicity towards paddy plant and other non-target species [79-81], Toxicity study on zebra fishes, toxicity study is commenced in accordance to the OECD Guideline 203 [82,83].

Table 1 Summarized the available bioassay studies conducted until now.

Table 1: Bioassays and bio-efficacy of nano- pesticide formulations.

Bioassays and Bio-efficacy		Nanopesticide	References
Larvicidal and pupacidal effect	leaf-dip method	Lambda-cyhalothrin (Nanodispersion)	Cui et al., [65]
Biochemical studies	Biochemical and histopathological studies in larva and pupal tissues	Permethrin (Nanoemulsion)	Mishra et al., [73]
larvicide toxicity	Toxicity against *Culex quinquefasciatus*	Permethrin (Nanoemulsion)	Anjali et al., [113]
Insecticidal activity	In vivo experiment on leafworm larvae	Novaluron (Nanodispersion)	Elek et al., [114]
Toxicity study in Moth	Against moths growth in rice plant	Emamectinbenzoate (Microemulsion)	Xu et al., [115]
Efficacy against the red flour beetle	Efficacy against *T. castaneum* (*Tribolium castaneum)*	Garlic essential oil (Nanoemulsion)	Yang et al., [87]
Biocidal activity	Water system	Triclosan (Nanodispersion)	Zhang et al., [16]
Insecticidal activity	On both *Dysdercus cingulatus nymphs* and *Spodoptera littoralis* larvae	γ –cyhalothrin (Solid lipid microparticle (SLN))	Frederiksen et al., [116]
Toxicity against species of beetle	Evaluation of the toxicity toward the adult stage of *Martianus dermestoides*	Imidacloprid (Nanometal)	Guan et al., [117]
Insecticidal activity	It applied against mosquitoes at concentration ≤ 9 × 10–5 M	Deltamethrin (Nanometal)	Sooresh et al., [118]
Larvicidal activity measurements	Susceptible mosquito larvae of *Culex pipiens* strain	Lambda – cyhalothrin (Encapsulated)	Desheesh et al ., [119]
Toxicity study against larvae Mosquito	larvae were identified as *C . pipiens*	AgNPS Core Particle with Cyhalothrin gNPS@CYN (Nanometal)	Abouelkassem et al., [120]
Toxicity study against larval instars of the cotton leaf worm	Study the effect in second larval instars of the cotton leafworm Laboratory and field larvae of *S. littoralis*	AgNPS, Lambda – cyhalothrin (Nanometal)	Ahmed et al., [61]

Table 2: Biosafety study of nano- pesticide formulations against non-target species.

Biosafety study on non-target species	Nanopesticide		References
Different non-target species like freshwater algae	Algae cell viability assay	Permethrin (Nanoemulsion)	Mishra et al., [73]
Rainbow trout (Oncorhynchus mykiss)	The activity of EROD -Ethoxy-resorufin-O-deethylase was determined in liver cells as a marker of cytochrome P450 1A induction in fish.	Nano-bifenthrin (Encapsulated)	Blewett et al., [121]
Toxicity against fungal diseases	Evaluation of the fungal flavoring in vitro petri dish and growth chamber tests.	Nano-Ag (Nanometal)	Jo et al., [122]
Toxicity against the development of fungi	Tuning the rate of release to the growth of fungi	Tebuconazole (Polymer based)	Salma et al., [123]
Toxicity study on zebra fishes	Fingerling fishes of zebra fishes (*Danio rerio*)	Permethrin (Nanoemulsion)	OECD, [82]; Sahoo et al., [83]; Mishra et al., [73]
Phytotoxicity	Phytotoxicity detected in paddy plant	Permethrin (Nanoemulsion)	Kumar et al., [79]; Mishra et al., [80,81]
Toxicity toward non-target organisms	Fish *(Brachydanio rerio)* and daphnia *(Daphnia magna)*	γ -cyhalothrin (SLN)	Frederiksen et al., [116]

Environmental fate of nano pesticide formulations

Inevitably, nanoparticles will be released into the plants and the environment system. The unique physical and chemical properties of nanoparticles might cause some unpredictable adverse effects on crops, agricultural products, and ecosystems. In addition, these materials will accumulate over time in soils, and rates may vary in response to unknown parameters. The general concern is that some nanoparticles or nanostructured materials may flow into the environmental systems and food chain, which may become a new class of pollutant resources that threaten human health and ecosystem balance. However, because farmland is a complicated open system with many influencing factors of intricate functions, actual data measuring the environmental concentration of nanoformulations in various media is scarce and needs more investigation, especially on the nonspecific target [84]. The environmental fate and potential bio-safety problem of nanomaterials or nanoparticles from nanoformulations are also unclear [85]. Deliberate application of nanoparticles within agricultural practices could result in one of the rare intentionally diffuse inputs of engineered nanoparticles into the environment. The anticipated new or enhanced activity of nanopesticides will inevitably result in both new risks and unique benefits to human and environmental health. It is unclear whether the current regulatory framework is adequate for the evaluation of these new products [9].

The soluble portion of a pesticide has traditionally been considered to be essential for the transport and bioavailability for degradation. They are increasing the solubility of the a.i. could lead to enhanced mobility and faster degradation by soil microorganisms. Studies on the possible environmental fate of nanoformulations that aim to increase the solubility of a.i. are relatively scarce [9]. No information has been found for nanodispersions. Nanoemulsions were shown to decrease hydrolysis and volatilization of the a.i. in aqueous solutions [86,87].

Similarly, very few studies have investigated the environmental fate of microemulsions. Nevertheless, the fate of the a.i. can be expected to be mainly driven by the high content in surfactants. Katagi, [88] reviewed available literature on the possible effects of surfactants on the behavior of pesticides and showed that complex interactions are possible between several different processes, most of which have not yet been examined systematically. Surfactants may affect the physicochemical properties (solubility, dissociation, and volatilization) and fate of pesticide a.i. in the environment.

The effect that surfactants have on the sorption of an a.i. depends on both the concentration and type of surfactant. Above the surfactant's critical micelle concentration (CMC), the mobility of a.i. can be enhanced due to the formation of micelles around the a.i., which hold the pesticide in solution [89-91]. Recent field data supported a facilitated transport of dioxins in soil following an unintentional release of pesticide surfactant formulations [92] following previously found colloid-facilitated dioxin transport [93]. In the context of soil and groundwater remediation, surfactants are also added to improve the mobilization and increase the bioavailability of sorbed contaminants. It is currently unknown whether such effects can also

apply to pesticide microemulsions. It is important to stress that the CMC in soil-water systems can be much higher than in water due to the sorption of the surfactant to the soil [94].

Increased CMC can be expected for cationic and nonionic surfactants, which sorb onto the soil to a greater extent than anionic surfactants [95]. Many pesticide formulations contain concentrations of surfactants that are below the CMC. At these concentrations, surfactants may increase the sorption of a.i. through an increase in organic carbon content and by modifying of the properties of the soil surface [94]. For instance, the stronger sorption of a commercial formulation of penconazole and metalaxyl relative to the pure a.i. was attributed to the sorption of the surfactants to the soil, which in turn facilitated the adsorption of the a.i. [96,97]. It is important to note that classical batch sorption tests may not be adequate to identify the possible effects of surfactant systems on sorption in the field. In contrast to column and lysimeter experiments, the soil/solution ratio is much lower than in realistic conditions. The surfactant is thus diluted, which means that concentration falls rapidly below the CMC.

The effect of surfactants on pesticide sorption also depends on the chemical nature. For instance, the sorption of triticonazole was increased by almost 50% in the presence of a very lipophilic alkylphenol ethoxylate surfactant. In contrast, sorption was not affected by the other non-ionic and anionic surfactants tested. Soil column experiments also showed that anionic surfactants could enhance the mobility of bentazon whereas nonionic surfactants may reduce mobility [98]. As with sorption, the possible effects of surfactants on degradation rates are complex and not yet well understood. Discrepancies are to be expected, according to the degradation mechanisms (photolysis, abiotic hydrolysis, or biodegradation), the a.i., and also the concentration and type of surfactant [88]. For instance, Hernandez-Soriano et al. [99] studied the effect of surfactants on the degradation in soils of four organophosphorous insecticides (malathion, diazinon, dimethoate, and methidathion). Increasing the concentration of non-ionic surfactant (Tween 80) resulted in enhanced degradation rates for all of the pesticides except diazinon. While the addition of the anionic surfactant did not show a clear trend, a reduction in degradation occurred with high concentrations of cationic surfactant. The latter result was explained as being a result of the reduced bioavailability of the insecticides adsorbed on the surfactant-modified soil surface. The type of surfactant has been shown to affect the rate of evaporation of the a.i. in both an emulsion and a nanoemulsion [100].

Recently, Walker et al. [101] reviewed that the fate and behavior of nano-enabled pesticides in the environment are likely to be dependent upon the functional characteristics of the carrier and the durability of the a.i.–carrier complex. Both aspects should be considered in problem formulation of nano-enabled pesticides because the spatial and temporal nature of exposure to non-target organisms could change significantly when compared to conventional pesticide formulations. Durability is a measure of how long a pesticide–nanocarrier complex maintains its integrity after application in the field. The strength of pesticide–nanocarrier complexes can be categorized into three broad classes, as shown in (**Figure 12)**.

Durability is likely to be dependent upon the exposure conditions. For example, a nano-enabled pesticide may release the a.i. at different rates in the soil, they depend upon factors such as soil moisture or soil pH. These will be important considerations for the risk assessment.

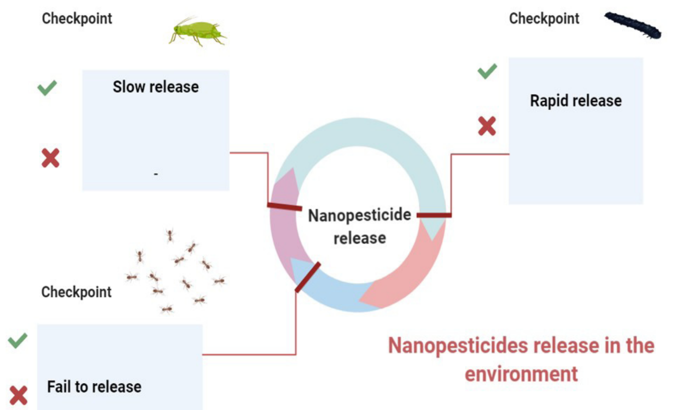

Figure 12: Durability of nano-enabled pesticide is applied in the field; environmental durability can vary widely. This variation is depicted for rapid release, slow release, and no release of the active ingredient from the complex.
*Rapidly released: within hours. € Slower release: over several days. ¥ is not released: over several weeks

The fate of nano pesticide versus the conventional analog

A frequent objective of a nanoformulation is to slowly release an otherwise too mobile or unstable AI after its application in the field. In such cases, the release of the AI from the nanocarrier system is a key process governing the environmental fate of nanopesticides [102,103]. Comparisons of release kinetics were presented in 13 papers whose results collectively demonstrate that nanoformulations can slow down the release of the AI, typically by a factor of about four (median = 3.69) [2,3]. Vast differences—several hundred-fold longer release half-life for the nanopesticide compared with the conventional formulation were also reported in a few instances for nanocarrier systems synthesized from poly (ethylene glycols) [104,105].

Published experimental data thus indicate that nanotechnology can help the design of slower release formulations. Still, comparisons with existing conventional slow-release formulations (such as those based on organoclays or zeolites) are not yet available in the open literature. There may be issues with the methodology generally applied, as release rates were most often measured in water in the laboratory (for example, using dialysis) at very high concentration levels, and over relatively short periods. Comparisons under more realistic conditions thus lack to evaluate how slow-release nanoformulations would perform in the field. Direct measurements in soil or on the plant surface are not easy to implement and indirect approaches that allow measuring release rates through other fate processes are worth considering (for example, sorption [103], degradation in soil [106], photolysis [107] or kinetics of efficacy [108].

The processes of sorption and degradation are the main determinants for assessing environmental exposure of pesticides. **(Figure 13).** Sorption was considered in ten studies measuring sorption coefficients and/or breakthrough curves, and that suggests that differences between nano and conventional formulations lie within a factor of two (median = 1.08). Nanoformulations can either decrease or increase the mobility of the AI compared with conventional formulations, which could—if adequately controlled—allow better targeting of the pest. Nanoformulations can protect the AI from various degradation processes including photolysis [107, 109-111], hydrolysis [86] or degradation in soil [14,102,106]. Separate analyses indicated that soil degradation seems to be only little affected by nanoformulations (median = 1.05), whereas the effect on photodegradation is more pronounced (median = 4.42) [2,3]. Overall, the effect of nanoformulations on the half-lives of pesticides can be considered moderate (median and mean were 1.04 and 1.43 relative to conventional formulations, respectively), when considering the variability observed in the environment for example, for a given AI, variation by a factor five in different soils from the same geographical area was observed [112]. The only one study that considered nanopesticides, a conventional product and the pure AI found that the impact of nanoformulations on the transport and degradation of an AI may be more significant than that of conventional formulations [106]. The controlled modifications of fate properties are crucial to reduce losses and achieve better targeting of the pest [2,3].

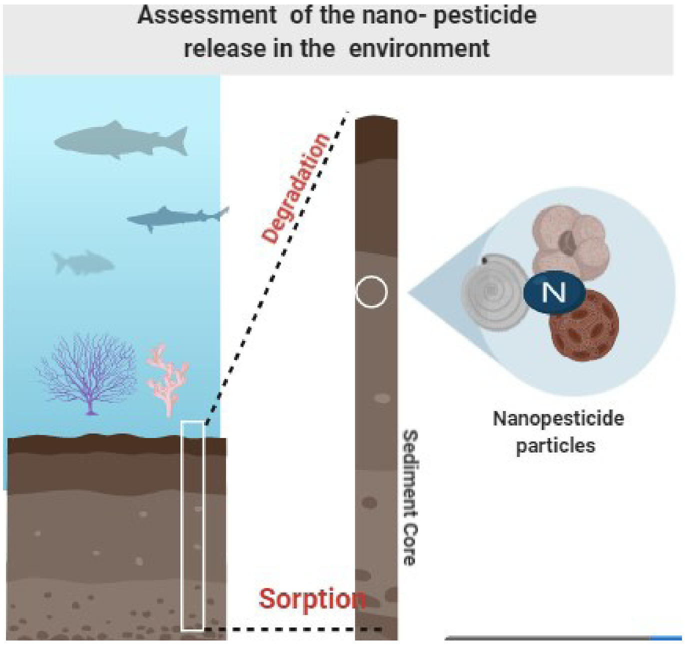

Figure 13: The processes of sorption and degradation are the main determinants for assessing environmental exposure of pesticides.

Conclusion

The nanoformulations aiming to increase the solubility of an AI are likely to affect the fate of the AI More experiments performed under realistic conditions are required to evaluate whether these effects will have a significant impact on the distribution, transport, and degradation processes of a given AI. A key question relates to the stability of nanoformulations following application. The stability of some nanoformulations is limited, and aggregation/agglomeration is likely to occur soon after they come into contact with the soil solution. In other cases, dilution may occur sufficiently rapidly for the fate of the different ingredients to be assessed separately. It is worth mentioning that these questions may also apply to more classical pesticide formulations. The only nano effect identified here may concern the nanodispersion, for which weaker sorption and faster degradation may be expected as a consequence of enhanced solubility, but no study is yet available. Thus, the risk research should be conducted on the safety and the risk assessments of nanopesticides according to the methodologies established in nanotoxicology and nanomedicine. Investigation of the toxicological effect, environmental behavior, and pharmacokinetics of nanoparticles. Besides, studying the interaction mechanism between nanoparticles and plants, and evaluating their potential impact on the quality and safety of agricultural products can provide a theoretical basis for the development of nanopesticides and the sustainable implementation of nanotechnology in agriculture.

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