

Review

Production of Nanofibers by Electrospinning as Carriers of Agrochemical

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Abstract: Agrochemicals can now be protected from harsh environments like pH, light, temperature, and more with the help of a drug-loading system. This has allowed the creation of targeted and continuous release functions for pesticides and fertilizers, as well as the precise application, reduction, and efficiency of agrochemicals. All of these benefits have been made possible by the recent advancements in the field of nanomaterials. A simple procedure known as electrospinning can be used to create nanofibers from natural and synthetic polymers. Nanofibers have come to be recognized as one of the sustainable routes with enormous applicability in different fields. In agriculture, a promising strategy may entail plant protection and growth through the encapsulating of numerous bio-active molecules as pesticides and fertilizers for intelligent administration at the desired places. Owing to their permeability, tiny dimensions, and large surface area, nanofibers can regulate the rate at which agrochemicals are released. This slows down the rate at which the fertilizer dissolves and permits the release of coated fertilizer gradually over time, which is more effectively absorbed by plant roots, as well as the efficiency of pesticides. Thus, modern agriculture requires products and formulations that are more efficient and environmentally friendly than traditional agrochemicals. In addition to highlighting the significance and originality of using nanofibers and offering a brief explanation of the electrospinning technology, the review article's main goal is to provide a thorough summary of the research leading to breakthroughs in the nanoencapsulation of fertilizers and pesticides.

Keywords: agrochemicals; nanofibers; electrospinning



Citation: Colín-Orozco, J.; Colín-Orozco, E.; Valdivia-Barrientos, R. Production of Nanofibers by Electrospinning as Carriers of Agrochemical. *Fibers* **2024**, *12*, 64. <https://doi.org/10.3390/fib12080064>

Academic Editor: Shingo Yokota

Received: 29 May 2024

Revised: 20 July 2024

Accepted: 27 July 2024

Published: 5 August 2024



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1. Introduction

In a world of dwindling resources and a steadily growing global population, agriculture as a food source is becoming increasingly important [1]. Fertilizers are crucial in achieving the crop yields required to feed the world's rising population [2]. Nevertheless, the ineffective application of pesticides and fertilizers in agri-food systems is endangering the safety, security, and quality of food as well as wasting energy and water and having detrimental effects on the environment. More precisely, evaporation, deterioration, and environmental run-off are said to be the main causes of 60–90% of applied fertilizers and pesticides. The incapacity to deliver the active ingredient at the appropriate amount and time to the target site accounts for a large portion of this inefficiency. According to projections, food production will need to rise by 70–100% by 2050 in order to keep up with the current rate of population growth. With the pressures of a changing climate and a net loss of arable soil, reaching this level of productivity becomes increasingly difficult [2–5]. To address the mounting issues of sustainable production and food security, major technological advancements and innovations have been developed in agriculture in recent years [5]. Sustainable agriculture uses fewer agrochemicals, which helps safeguard the ecosystem and prevent the extinction of various species [6].

Numerous agricultural-related issues may find practical answers thanks to nanotechnology. Nanoformulations are of tremendous scientific interest to bridge the gap between bulk materials and atomic or molecular structures [6]. Research into sustainable nano-enabled agriculture has recently increased in response to efforts to reduce the inefficiencies of fertilizers and pesticides; in this regard, nanotechnology can be very helpful in this endeavor. It is, therefore, necessary to develop a coating platform in order to address the above highlighted inefficiencies. Materials for porous, tunable coatings that serve as a vehicle for the targeted release and regulated distribution of agrochemicals must be made using non-toxic, biodegradable biopolymers derived from nature [3]. Nanostructure materials are composed of one or more materials and are classified as nanomaterials (NMs) with one dimension in the nanoscale range (<100 nm). By contrast with their counterparts in bulk, they offer greater mechanical performance, variable porosity, a high surface area, and the potential for surface functionalization. Because of these extraordinary qualities, nanoparticles are the best options available in the biomedical industry for the creation of tissue-engineered scaffolds, chemical sensors, biosensors, and drug delivery systems [7].

NMs have been reported to boost crop yield by increasing the efficiency of agricultural input and permitting the regulated delivery of nutrients to specific consumption of agricultural inputs. In order to temporarily stop nutrient release, conventional soluble fertilizers and pesticides are encapsulated within protective nanoparticle shells to create nanocoated agrochemicals [2]. In addition to offering passive release mechanisms designed to address problems with excessive nutrient loss pathways, coatings act as a physical barrier to regulate solubilization until environmental triggers, such as moisture and temperature, cause shell disintegration or swelling [8].

One of the most significant methods for creating nanomaterial is electrospinning, a sophisticated technique that creates continuous and tiny fibers at both the nano and microscales; the method is highly adaptable, cost-effective, and readily available. Electrospun nanofibers can be produced using a variety of materials, including both natural and synthetic polymers [9]. Numerous fields have made use of electrospun nanofibers for a variety of purposes. Due to their highly interconnected ultrafine fiber structure, high surface-to-volume ratio, tortuosity, permeability, and ability to be downsized, they are extensively used in numerous research disciplines. They also benefit from their lightweight, porous nanofibrous structure [10]. The idea of adding active ingredients to nanofibers is becoming more and more popular these days. Using nanofibers as carriers of various compounds gives agriculture a revolutionary edge by guaranteeing accurate delivery of active agents like fertilizers and pesticides. With strategic use, this innovation maximizes resource efficiency, reduces environmental pollution, and increases crop output [11]. The main goal of this review is to provide a comprehensive overview of the scientific advancements in the electrospinning technology for fertilizer and pesticide nanoencapsulation.

2. Nanotechnology Applied to Agriculture

Creating materials and technologies with nanoscale-engineered size and shape is known as nanotechnology, and it involves design, synthesis, and application. When matter is arranged at the nanoscale, special, physical, electrical, and mechanical properties emerge [12–16]. Nanotechnology is about controlling really tiny things and using new properties of them [17]. Hence, progress in studying very small things has helped make new and interesting possibilities for a lot of different areas that affect people's lives, like electronics, energy, cleaning up pollution, cars, space technology, and medical science. It can be used in many ways for medicine and biology, like delivering genes and drugs, biosensing, and tissue engineering [17,18].

Currently, research into nanotechnology for agricultural applications is growing [19]. Food production and distribution are under great strain from a variety of sources, including sudden climate change, population expansion, water scarcity, and soil contamination. The loss of arable land and inefficient use of agrochemicals exacerbate the situation, making food security the century's most pressing challenge [20,21]. As a result, increasing food

production is an urgent concern; new technologies or approaches that protect plants from stress and improve pesticide efficiency are required to attain food security safely and sustainably [21]. Therefore, increased use of nanotechnology could provide innovative solutions to improve sustainable agriculture that also meets food needs [19].

Agriculture is one of nanotechnology's many applications; this field is becoming increasingly important in modern precision agriculture [15,22]. Applications for this technology in agriculture include seed treatment, germination, plant growth and development, insect control, pesticide and fertilizer delivery, genetic material delivery, pathogen and toxic agrochemical detection, and more. Agrochemical effectiveness can be increased, and the delivery system can become more intelligent thanks to the special properties of nanoscale particles. With a clever delivery system, chemicals can be delivered in a targeted and regulated manner [23].

The development of nanotechnology has made it possible for researchers to create a wide range of nanomaterials (NMs) or materials that are extremely small (1–100 nm) [24]. Many NMs have been developed to boost food safety and agricultural output. Nanorods, nanofilms, nanotubes, nanofibers, nanolayers, and nanosheets are a few of them. These materials are used to make nanopesticides, nanofertilizers, and nanomaterials that stimulate plant growth, genome modification, and transgenic expression in plants [25]. Because of their unique and beneficial chemical, physiological, and mechanical features, NMs are extraordinary objects. Numerous industries, including energy, environmental research, information technology, food safety, national security, transportation, and medical, have found applications for these qualities [24,26]. Inorganic NMs are mainly divided into two categories: carbon-based and metal-based. Carbon-based NMs include single and multi-walled carbon nanotubes, which are used as nanosensors to promote better plant development. On the other hand, metal-based NMs comprise a variety of metals such as aluminum (Al), cadmium (Cd), cobalt (Co), copper (Cu), gold (Au), iron (Fe), lead (Pb), silver (Ag), and zinc (Zn); and metal oxides as zinc oxide (ZnO), titanium dioxide (TiO₂), and aluminum oxide (Al₂O₃) [14,27]. NMs copper oxide (Cu₂O) or copper hydroxide (Cu(OH)₂), copper sulfide (CuS), Fe-Zero-valent, selenium (Se), manganese oxide (Mn₂O₃), hydroxyapatite Ca₅(PO₄)₃OH, and zinc oxide (ZnO), can be used directly as agrochemicals [28]. For example, Ag nanoparticles play a role in protecting agricultural crops and properly regulating plant nutrition by acting as antifungal and antibacterial agents. On the other hand, ZnO nanoparticles have been shown to be useful in stimulating stem and root growth in peanuts, as well as promoting seed germination, seedling vigor, and plant growth. Furthermore, both MgO and ZnO in the form of nanoparticles have a strong antimicrobial impact [29].

NMs' fabrication methods can be divided into groups according to how they are assembled. Top-down and bottom-up are the two main categories. According to a natural physical principle or an external driving force, smaller atomic or molecular components self-assemble together to form larger, more ordered structures. This is known as the bottom-up method approach. Chemical techniques such as hydrothermal, sonochemical, electrochemical, photochemical, microwave, microemulsion, pyrolysis, redox, co-precipitation, and sol-gel are examples of bottom-up approaches [24,30]. On the other hand, the top-down strategy involves starting with a large component and then using finer and finer tools to create smaller pieces. Top-down approaches employ physical techniques such as lithography, ball milling, vapor and gas phase, evaporation-condensation, electrodeposition, pulsed laser ablation, arc discharge, sonication, and spray pyrolysis. Additionally, the bottom-up biological strategy uses biopolymers, biomolecules, viruses, bacteria, yeasts, plants, and fungi to create NMs [24,30,31]. NMs can help crops grow better by making agricultural inputs work better and by delivering nutrients directly to where they are needed. This means farmers can use less agricultural inputs while still getting good results. Furthermore, engineering nanomaterials (ENMs) is a new and advanced area of research that helps to improve high-tech farming by creating surfaces that are important for sustainable agricultural growth [6]. Another feature of NMs is that they are sufficiently used to carrying things

to have good qualities like stiffness, permeability, having a crystal-like structure, staying stable in heat, and breaking down naturally [23].

Nanocarrier materials help to keep the active ingredients (AIs) safe from breaking down too early and allow them to be released in a controlled manner. Nanoencapsulation technology is the most promising as it is much more efficient than other techniques. Compared to microencapsulation, nanoencapsulation has a number of advantages. A thin encapsulating layer, in particular, ought to considerably increase the mass transport of active chemicals to the intended location and decrease the overall volume of compounds that are not active substances that are transported. Furthermore, the tiny size of the capsules, especially when it comes to nanoencapsulation of pesticides, will guarantee simple entry into alternate areas for efficient pesticide action [32]. Nanoencapsulation is the coating of different substances with different materials and sizes in the nanorange. The encapsulated material is commonly referred to as the internal phase, core material, or filler, and the encapsulating material or covering is called the outer phase, shell, coating, or membrane. Attempts have been made to encapsulate commercially available agrochemicals using nanomaterials to improve their physical properties and to control the amount used [23]. There is an enormous interest in developing nanoformulations of traditional fertilizers and pesticides to minimize losses and improve utilization efficiency [28]. Nanoagrochemicals like nanofertilizers and nanopesticides use different nanoformulations that combine multiple surfactants, polymers, and metal nanoparticles. Nanoformulations have goals that include making it easier for active ingredients to dissolve, releasing the active ingredient slowly or in a targeted way, and protecting the active ingredient from breaking down too quickly [33].

On another hand, nanosensors constitute a modern stage for observing plant development and advancement, which accomplishes nondestructive and exact observing and can be connected to person plants in genuine time. Nanosensors for plant malady conclusion are noteworthy for observing plant wellbeing and taking prompt protective activities. Versatile, conservative, and exact nanosensors help analysts recognize plant pathogens, aiding in precision farming practices and optimizing resource usage [19,34]. Reportedly, nanoparticles (NPs) can be loaded or encapsulated with conventional pesticides or active ingredients to achieve slow, controlled, and targeted release. Progress in the use of NPs applied as foliar sprays, hydroponics, or soil roots to promote plant growth and stress tolerance. There are three groups of NPs that hold promise as representing new types of agrochemicals that can address the simultaneous challenges of food availability and environmental protection [21].

The first group, the NPs as nanoregulators, can improve plant tolerance to abiotic stresses. Abiotic stress can be defined as that which is caused by external non-biological factors, such as rain, high or low temperatures, drought, wind, salinity, soil problems, chemicals, or oxidative stress; these are the main causes of loss of crops and cause morphological, physiological, biochemical, and molecular changes in plants; therefore, it is directly related to crop productivity [21,35]. The production of oxygen, the control of climate, and the energy source for biological processes like agricultural productivity all depend on photosynthesis. Abiotic stress, on the other hand, inhibits photosynthetic processes and reduces physiological responses, making it the biggest barrier to plant growth. When plants are stressed, they release reactive oxygen species (ROS), which set off a series of coordinated oxidative events within the cell that lead to membrane disintegration, protein instability, structural denaturation, and disruption of the metabolism. Various NPs have been demonstrated to reduce stress and mitigate stress-induced negative effects at the chloroplast, leaf, and different phases of crop production when applied as a supplement through seed priming, soil, or foliar application [21,35,36].

In the second group, nanopesticides are mentioned. They are described as pesticide formulations or products that contain nanomaterial as active ingredients with biocidal capabilities. These can strengthen a plant's defenses against biotic stressors, including pathogen invasion and herbivore assault. However, rather than using these small particles,

which are intended to be used as nanopesticides, it has already been chosen to encapsulate pesticides in polymers [21,37]. Using ENM pesticides in lower amounts would decrease the amount that gets onto the ground and into the environment, which would help prevent pollution. These benefits also include using less energy and water to make materials. It will also help reduce the economic cost of pesticide use by farmers [37].

Regarding the third group, nanofertilizers promote stress tolerance by giving plants important nutrients [21]. Micronutrient insufficiency is a major challenge in developing countries; however, the use of nanofertilizers has the potential to solve this problem and improve plant growth and soil quality [38]. The impact of three essential nanomicro-nutrient fertilizers (Zn, Fe, and Mn) on the yield and associated characteristics of chickpeas grown in semi-arid environments is discussed in the study by Sabaghnia et al. (2023). According to their research, using zinc nanofertilizer enhances a variety of chickpea characteristics, including yield components and seed yield when grown under regular watering. Iron nanofertilizer played a more distinguishing role in semi-rain-fed and rain-fed environments. Manganese nanofertilizers had less of an effect on chickpea output than zinc and iron nanofertilizers did [39]. New types of plant-protection nanoformulations are being made using biodegradable materials and natural ingredients to be less harmful to the environment. The use of biodegradable materials made from plants has increased, and it is possible that these materials, when combined with active ingredients (AIs) of natural origin, could be used in organic farming [23,40].

Organic nanomaterials such as nanospheres, nanogels, nanoliposomes, nanocapsules, and nanofibers are shapes of polymer-based nanoformulation [37,41,42], which allude to the improvement of agrochemicals, such as fertilizers and pesticides, in nanosized definitions with changing degrees of biodegradability. They improve the productivity of the dynamic fixings, permitting for lower dosages, whereas keeping up adequacy, which diminishes natural contamination and limits the potential negative impacts on useful living beings. Nanoformulations, moreover, make strides in focus on the conveyance of agrochemicals, guaranteeing that they reach the expected plant tissues or bugs more viably and diminish harm to non-targeted destinations of plants, controlling the negative impacts of chemicals on the environment [34]. Nanospheres are made up of a polymeric matrix that contains the drug of interest, which must be mainly hydrophobic in order to load optimally [43], and nanogels are small networks of biopolymer with pores filled with compounds like pheromones, essential oils, or Cu [23,37]. Nanogels are composed of natural or synthetic polymers that are both nano-sized ionic and non-ionic hydrogels. Because of their excellent physicochemical properties, bioconjugation, colloidal stability, and sensitivity to pH and temperature changes, the nanogels are garnering increased interest. Moreover, nanogels are highly porous and have a high water content (70–90%) of the entire structure with a high loading capacity [44].

In the same way, lipid-based nanomaterials are considered potential carrier systems for bioactive substances with better encapsulation efficiency and lower toxicity. Nanoliposomes are spherical amphiphilic structures made from lipids nanosized and used for the delivery of biologically active agents or agrochemicals [4]. The primary components of these carriers are phospholipids and lipids, but in their structure, some include other components, such as proteins, sterols, antioxidants, or carbohydrates. Because of their amphiphilic character, they can concurrently entrap and release a wide variety of hydrophilic and hydrophobic chemicals, which will be beneficial to both parties. This benefit, along with biocompatibility and biodegradability, makes using nanoliposomes as smart drug delivery systems very interesting [45].

Nanofibers are nanostructures that can be made using a variety of processes, including template method, drawing method, thermal-induced phase separation method, self-assembly, and electrospinning [46,47]. Nanofibers, as nanoproducts, have been applied in a variety of industries, including agriculture, biomedicine, pharmaceutical, and industrial fields. Numerous benefits come with these nanomaterials, including high porosity, large specific surface area, and great size homogeneity. A viable strategy for the sustainable

use of nanofibers in the agricultural sector is to encapsulate several bioactive molecules or agrochemicals for intelligent delivery at the appropriate locations, thereby protecting and promoting plant growth [47], as described later.

3. Nanofertilizers

Current farming practices cannot meet the growing food demand without the substantial use of fertilizers. However, traditional fertilizers are fundamentally limited due to their low nutrient use efficiency (NUE). It is defined as plants' ability to collect a nutrient, transport it through their roots and shoots, and then remobilize it in other areas of the plant [48,49].

Fertilizers have a very low NUE because there are several ways that fertilizer loses nitrogen, including leaching, mineralization, NH_3 volatilization, gas emissions, soil erosion, and denitrification processes, which account for 40–70% of total nitrogen content loss. Whereas 50–70% of the potassium is primarily lost by leaching connected to water movement in the soil and surface run-off, 80–90% of the phosphorus is lost as a result of mineralization and surface run-off [50–52]. A low NUE is frequently the consequence of fertilizer release rates greater than plant absorption, as well as fertilizer/nutrient transformation into form not bioavailable to plants, which not only depletes resources and causes economic losses but also seriously pollutes the environment [52,53]. Consequently, the optimal fertilizer is one that provides a practical means of enhancing nutrient efficiency, minimizing fertilizer leaching and volatilization losses, and lowering environmental dangers. For these reasons, new fertilizer types have had to be developed in order to increase nutrient use efficiency; these may be based on the application of nanofertilizers [52]. The act of converting macronutrients like nitrogen, phosphorous, and potassium into a nanoscale form may alter both the crop's absorption mechanism and its bio-effectiveness. This is because nanofertilizers are emerging from advances in nanotechnology, and they have a variety of characteristics that meet targeted nutrient requirements. When it comes to nutrient elements, they are primarily separated into two categories: macro and micronutrients nanofertilizers [5].

In order to meet the essential nutrient needs of plants, one or more nutrients can be controlled and delivered gradually with the use of nanofertilizers, which are nutrients encapsulated or coated with NMs [49,54]. Nanofertilizers, as compared to conventional fertilizers, are projected to greatly boost crop growth and output, improve fertilizer efficiency, reduce nutrient loss, and/or limit negative environmental implications [55]. Nanofertilizers can be produced by applying nutrients alone or in combination with nano-sized adsorbents [56]. Nanofertilizers can be created in three forms based on the nutritional requirements for plant grows and development: nanoscale fertilizers, nanoscale additives, and nanoscale coating or host materials [57]. In the first way, nanoscale fertilizer, the fertilizer is reduced in size using mechanical or chemical methods, for example, phosphorus (P), nitrogen (N), or potassium (K) in nanoparticle form. When applying the NPs, these undergo a gradual destruction, releasing the nutrient, and later, it is absorbed through the roots or leaves of the plant and is distributed to the area that is needed. Secondly, nanoscale additives, which is to say, bulk products with nanoscale additives, act as a nanocarrier; the nutrients are loaded inside and/or on the surface of the nanomaterial, protecting them against degradation. Then, the nutrients can be released gradually within of crop or by diffusion. Lastly, the category of nanoscale coating or host materials refers to materials that are either nanoporous or nanothin films that are utilized to release inputs under controlled conditions. Additionally, there is a combination, wherein a nanoporous host material and a nanoscale fertilizers particle are combined to provide a final product with two mechanisms for release [52,57]. Stated differently, the mineral nutrients needed for plant sustenance can be contained inside nanoscale particles, protective polymer films, nanotubes, or nanoporous materials, and depending on the application, synthetic or natural nanoparticles derived from plants, soils, and microorganisms may be used [52]. Thus, bioactive chemicals that would otherwise be vulnerable to unfavorable circumstances like

heat, UV light, and oxidation are stabilized by nanoencapsulation systems, which also control the release of integrated compounds and greatly lower the rate of nutrient loss. The solubility and dispersion of mineral micronutrients can be advantageous aspects of nanofertilizers. Because of their reduced particle size and ease of penetration into the root and leaf cuticular cells through foliar and soil sprays, nanofertilizers contribute to increased NUE and uptake ratios. Fertilizers with a higher nutrient content in oxide form can be changed into a soluble form by thinking about their size, shape, and solubility [52,58]. Furthermore, as the growth cycle progresses, more nutrients become available, which helps to stop nitrogen from being lost through denitrification, volatilization, leaching, and fixation in the soil, especially in the form of nitrate (NO_3) [58], as well as gaseous nitrogen release [59,60].

4. Nanopesticides

Research on creating novel crop protection formulations has long been intense due to the need to address issues with commercially existing insecticides. Using the advantages of materials at the nanoscale, research is currently creating formulations that are comparable to conventional formulations but have better qualities, such as being more soluble, releasing more slowly, and not degrading too quickly [23]. Pesticides, which are chemical or biological agents, can be used to protect plants from a different kind of pest. Insecticides, herbicides, acaricides, molluscicides, rodenticides, bactericides, and fungicides are some of the main classes into which pesticides can be divided [61]. They are further divided into fumigants, defoliant, desiccants, and plant growth regulators based on their intended use [62]. Commonly used pesticides have very limited uses; careless use of inorganic chemical pesticides has caused negative impacts such as the progressive increment in pesticide levels (biomagnification) leading to soil and water pollution, interference of pesticides within the nourishment chain environments, the impacts hurtful impacts of pesticides on people, as well as an increment in generation costs [61,63]. Another point to consider is that over 90% of pesticides that are employed either fail to reach the target areas required for successful pest management or are lost to the environment [64]. Between 20–50% of pesticides are lost due to emissions; the amount of loss is influenced by wind speed, humidity, temperature, and the physicochemical qualities of the pesticides, as well as the application technique. Leaching, evaporation, washing away, deposition, and degradation by photolysis, hydrolysis, and microbiological activity account for the remaining losses [23,62].

Despite these effects, their use is essential to maximize agricultural productivity. The increasing demand for food and today's challenges in agriculture require a scientific approach to the development of organic pesticides [61]. Hence, precise amounts are required to achieve the desired biological response in terms of pest control within a certain period of time, which influences the non-specific and regular application of the active ingredient [23]. The use of a new pesticide concept based on nanotechnology, referred to as nanopesticides, is intended to solve these problems by increasing the effectiveness of pesticides, reducing the required dose, and improving the stability of active compounds. This reduces run-off and mitigates environmental problems [64]. Compounds known as nanopesticides are made at the nanoscale using physical, physicochemical, and chemical techniques to eradicate weeds, bacteria, and insects. New pesticide nanocarriers are intended to be inexpensive, easily degradable, and have low contamination. Additionally, with a regulated amount of pesticide and its potential harm, it enables you to control and predict the intelligent release and effective targeted delivery of active ingredients. Nanoparticles' small size can improve pesticide saturation and solubility in water, increasing their stability and dispersibility in water and so boosting control effectiveness and usage rates [65]. Modifiability of nanopesticides can improve pesticide uptake, especially of hydrophobic compounds, by encouraging plant uptake and transport. Plants are primarily affected by pesticides that are sprayed on the leaves or applied to the roots. Plants absorb nanoparticles, which subsequently pass through the cuticle and epidermis, enter the vascular tissue through plastids

or exoplasts, and travel to different areas of the plant via vascular tissues. Because the fine structure of plant leaves gives the surface of the leaves a certain degree of hydrophobicity, pesticides find it difficult to adhere to them, resulting in a waste of pesticides; however, the surface of the nanocarriers allows the association of different active groups that can increase or change the charge on pesticides improve their adhesion to leaves. When compared to conventional pesticides, nanopesticides stick to plant leaves and stems more readily, increasing the plants' resilience to erosion caused by rainfall. This increases the pesticide's effective contact duration and rate of usage [65].

There are two types of nanopesticides depending on the delivery of the AI. Type 1 comprises metal-based nanopesticides that act directly as AIs. In contrast, Type 2 includes materials in which AIs are encapsulated by nanocarriers, such as polymers and clays, to facilitate their controlled release and application [66]. The basis for grouping and categorizing nanopesticides is according to the type of nanocarriers used, the route of administration, the origin of bioactive compounds, or the conjugate used in nanoform [61,64]. The advantages of the nanoformulations offered by this new technology include greater effectiveness, durability, and reduction in the amount of active ingredients required. These products can be used to intensify the efficiency of the pesticide operational components, leading to the improvement of environmental safety profiles or both [61,64].

5. Mechanism of Controlled Agrochemical Delivery

5.1. Slow Release Fertilizers (SRFs)

Because of nanotechnology, fertilizers are made to release their nutrients gradually and in accordance with a plant's nutrient needs [59]. Several factors affect the efficiency of nanofertilizers. Crop uptake, dispersion, and accumulation of nanofertilizers will be heavily influenced by exposure routes and extrinsic and intrinsic factors. The most significant extrinsic factors affecting the potential application of nanoparticles are soil, pH, organic matter, and soil texture, and the significant intrinsic factors are particle size and surface coatings. Furthermore, because nanofertilizers can be taken by the roots and leaves of plants, their behavior, bioavailability, and uptake in crops are greatly influenced by the exposure route and application method [54]. The permeation-regulated transfer of an active component from a reservoir to a targeted surface is known as controlled release (CR), and it is used to maintain a predefined concentration level for a given amount of time [67]. Agrochemical controlled release delivery systems can be divided into two types: physical and chemical. In the first group, the bioactive ingredient is simply admixed with some entity that will slow its loss via volatilization and leaching, by chemical breakdown caused by the action of water, air, and sunshine, or microbial destruction [68]. An alternative to improve the efficiency of agrochemicals is the use of systems that could present a lower or controlled release. Compared to traditional methods, slow-release fertilizers (SRFs) and controlled-release fertilizers (CRFs) offer a safer and more innovative means of supplying agrochemicals to crops [51]. Although the rate, pattern, and duration of nutrient release are not well controlled, the SRFs exhibit a slower-than-usual rate of release. Soil conditions, including moisture content, wetting and drying, thawing and freezing, and biological activity, as well as handling conditions, such as storage, transportation, and field distribution, may have a major influence. The pattern of nutrient release in the SRFs is entirely determined by the soil and climate, which is why nutrient release cannot be anticipated [50,52,69,70]. Instead, the CRFs refer to fertilizers where the dominant elements in terms of release rate, pattern, and duration are known and controllable before preparation; within specific bounds, the pattern, quantity, and time of release can be predicted [69]. Also, the CRFs are generally related to agrochemicals coated or encapsulated with inorganic or organic matter, which allow a much more controlled rate and duration of nutrient or pest release with semi-permeable coatings [50,52]. In fact, the physical and chemical interactions between the polymer material and fertilizer, as well as the homogeneity of the resulting polymer shell, have a major impact on the polymer coating's efficiency [71]. The process by which the nutrients are released is as follows: water is

transported through the coating, water molecules condense on the nutrient core's surface, osmotic pressure builds, the nutrients dissolve, the polymer-coated granule swells, and ultimately, the nutrients are released through transport through the coating film through micropores in the coating membrane (Figure 1) [8,71]. In a matter of days, the soil's moisture penetrates the covering polymer, dissolving the nutrients that were enclosed. Following that, over the course of several months, nutrients gradually permeate through the covering polymer. The soluble fertilizer then gradually seeps into the ground. After all the nutrients have been released, soil bacteria finally break down the covering polymer. The technique of controlled release is greatly influenced by variables such as the mechanical characteristics and biodegradability of the coating materials, coating thickness, nutrient density, soil physiology, and soil water content [71]. Thus, the three key phases of the release mechanism are water adsorption, nutrient dissolution, and leaching [70,71].

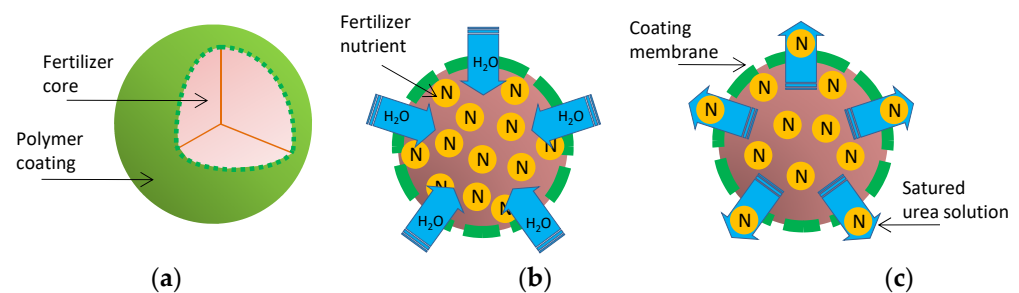


Figure 1. Process of controlled release: (a) a polymer-coated fertilizer core; (b) water seeping into the coating and core granule where fertilizer dissolution and creation of osmotic pressure occurs; and (c) a swollen coating that allows for regulated release of nutrients membrane [8].

5.2. Controlled Release Fertilizers (CRFs)

On the other hand, there are a few factors to take into account when using CRFs. For instance, it is thought that one drawback is that, because of the cost of the materials and the manufacturing process, the majority of coated or encapsulated CRFs still have manufacturing costs that are significantly higher than those of conventional mineral fertilizers. Nevertheless, labor, time, and energy savings can more than offset these costs. Since CRFs may supply all the nutrients needed by crops for a whole season with a single application, spreading expenses can be minimized, and application frequency can be lowered [50,72]. The advantages of CRFs are linked to bettering plant growth conditions, including the elimination of stress and particular toxicity brought on by an overabundance of nutrients within the root zones. It also enhances the synergistic effect of nutrients in CRFs by providing and releasing nutrients in a controlled manner in soil fixation processes. All of these factors increase the availability of nutrients [70,72]. From an environmental standpoint, CRFs increase NUE and hence lessen losses of excess nutrients to the environment. Consequently, a number of environmental issues related to the use of traditional fertilizers are reduced, including eutrophication, which results in fish mortality, O_2 depletion, an unpleasant odor in the environment, and aesthetic issues [70].

The controlled release (CR) of pesticides is critical to avoiding abusive use, increasing utilization, rejecting foreign bodies, and reducing pollution. CR formulations are designed so that just a portion of the AI is instantly available, while the majority is contained in an inert matrix and released slowly, following a specific or modified controlled release mechanism [73]. To offset dissipation losses and sustain activity for a suitable amount of time, a pesticide is sprayed at a higher rate than is initially required in a traditional formulation. The amount that is lost in a CR formulation is continuously replenished, negating the need for the first high dose and minimizing adverse effects on impacts both the environment and people's health. Furthermore, pesticide that is trapped in a matrix CR formulation is shielded from degradation by microbiological, chemical, and physical activities. It has a longer duration of effectiveness as a result. Therefore, CR formulations

have the following benefits over traditional formulations: longer effective lifetime of non-persistent insecticides, less pesticide is required for the same duration of activity, which means less waste and fewer applications, reduced environmental pollution, decreased losses due to environmental variables (evaporation, photolysis, leaching with water, and degradation due to chemical and microbiological causes), resulting in cost savings for the active ingredient, reduced toxicity to non-target plants, animals, birds, fish, and other organisms, improved pesticide efficacy through better targeting; and higher protection for users and those in contact with pesticide formulations [68,73].

A comparison of a traditional method versus a controlled release for a specific active ingredient is shown in Figure 2. The release rate of the active component of the conventional system is related to the concentration of the component found in the formulation; initially, the concentration in the environment is very high, reaching toxic levels; subsequently, it decreases to very low levels and is ineffective, adding to the fact that a greater number of applications is required. In the CR system, initially, the active component is released quickly at a high concentration, and then the release decreases. Owing to the smaller size and higher surface area of nanopesticides and nanofertilizers, they have improved deposition and prolonged their target on the surface, resulting in a more prolonged release period and reducing the application frequency, thus keeping the crop protected. The main advantage of the CR system is the use of a smaller number of active components or agrochemicals for the same period of activity. The application of the CR system depends on the needs of the crop, the physical–chemical characteristics of agrochemicals as well as the characteristics of the place where it will be applied, and the application device. In addition, the CR system must allow rapid and uniform application on large crop surfaces [74,75].

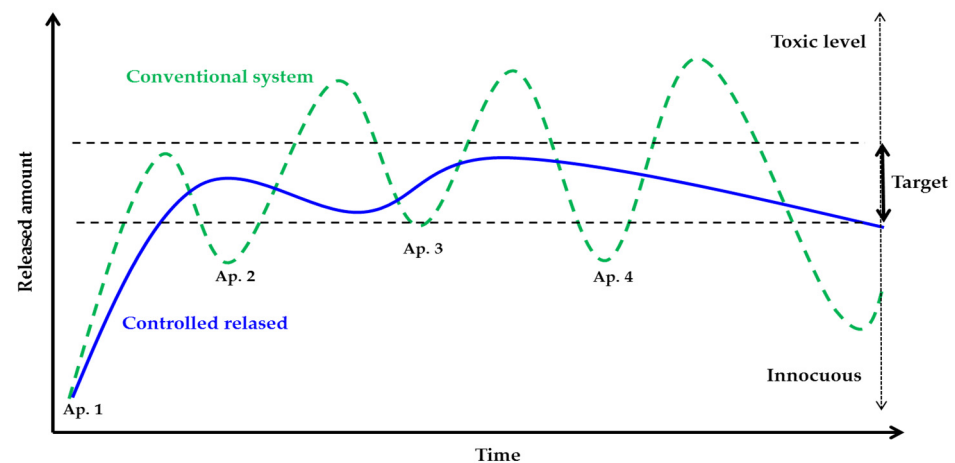


Figure 2. A comparison between release systems: controlled release and conventional [74].

6. Electrospinning Process

Electrospinning is a top-down technique for processing micro and nanometer-sized materials made from different mixes of polymer solution [76]. Figure 3 illustrates a standard setup of electrospinning equipment, which consists of an injection system that consists of a syringe pump that is responsible for pushing the polymer solution toward the needle at a constant speed and controlled flux. A plastic syringe that acts as a reservoir for the solution and a needle that acts as a positive electrode is placed in the infusion pump. High voltage generation is provided by a high voltage power supply with an operating range of 0–30 kV. Two poles emerge from this source: the anode connecting to a needle, which acts as a capillary tube through which liquid is pumped to be electrodeposited, and the cathode connecting to a collecting substrate where filamentary products are deposited [77–79].

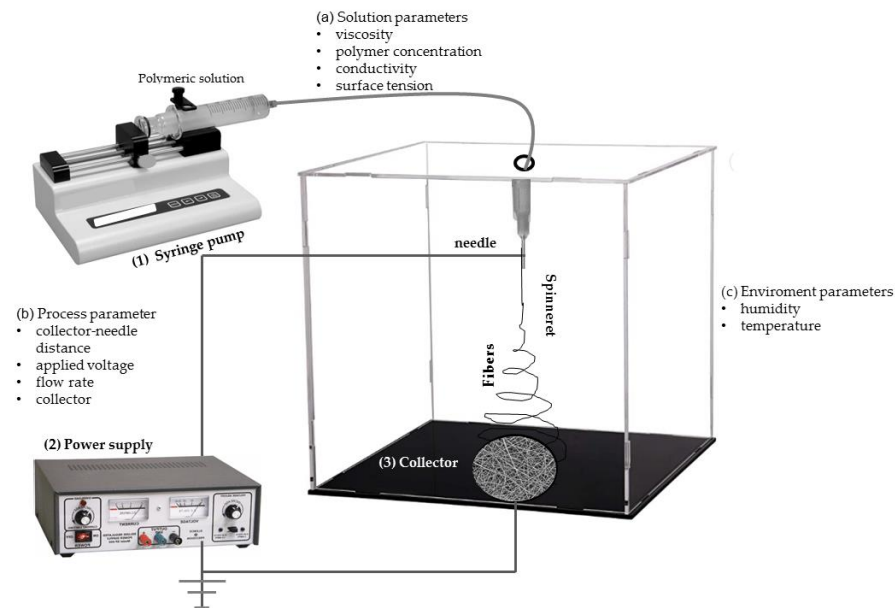


Figure 3. Scheme of electrospinning equipment: (1) syringe pump, (2) power supply, and (3) collector. Parameters are divided into three categories: (a) solution parameters, (b) process parameters, and (c) environmental parameters.

Adjusting processing parameters allows for the creation of a wide range of sizes and shapes, including flat ribbons, bent ribbons, circular beads, elongated beads, continuous and smooth fibers, and so on (Figure 4) [77]. These parameters are divided into three categories: solution, process, and ambient (Figure 3).

(a) Solution parameters: include polymer concentration, viscosity, surface tension, electrical conductivity, and evaporation rate of solvent. It has been shown that low-viscosity beads or bead fibers (Figure 4a) and a notable increase in fiber diameter are created (Figure 4c). The viscosity and polymer concentration of the solution are directly proportional to each other since fiber diameter is directly dependent on the concentration of the polymer. As the concentration increases, the average diameter of the fiber increases. Instead of fibers, mixtures of beads and fibers or only beads form at low solution polymer concentrations, while at high concentrations, the formation of continuous fiber is prevented due to the inability to keep the solution flowing at the tip of the needle, which leads to the formation of large fibers [80,81]. Therefore, each experiment should have a customized solution concentration for the electrospinning procedure [81]. Similarly, the formation of fibers, beads, and droplets is dependent on the solution surface tension; a lower solution surface tension facilitates electrospinning at a lower electric field, whereas a high solution surface tension inhibits the process due to jet instability, resulting in the generation of droplets rather than nanofibers [82,83]. Thus, the fiber diameter rises as surface tension increases [84]. On the other hand, the type of polymer, the solvent used, and the salt availability all affect the solution's electrical conductivity. The majority of polymers exhibit conductivity, and the presence of charged ions in the polymer solution greatly enhances jet production. When the electrical conductivity of the solution increases, the diameter of the nanofibers decreases, and beads are generated when the electrical conductivity of the solution is low [84]. Ionic salts, such as sodium chloride (NaCl), monopotassium phosphate (KH_2PO_4), and sodium phosphate (NaH_2PO_4), can be used to control the electrical conductivity of a solution and generate nanofibers with a very small diameter, hence decreasing the creation of beads [81,82];

(b) Process parameters: the characteristics that are considered process-specific include the applied voltage, the distance between the nozzle tip and types of collector, and the rate at which the solution is fed [81]. The electrospinning process is mostly dependent on the applied voltage; the strength of the applied electric field creation process. A sub-

optimal field strength may cause the jet formation to fail or cause bead defects in the spun fibers [82]. According to Blesson et al. (2021), applying more voltage might decrease the fiber diameter and vice versa [83]. This statement coincides with what was reported by Chowdhury and Stylios (2010) analyzed the voltage effect in the Nylon 6 solution, which used an output voltage range of 12 kV and 18 kV. They found that an increase in applied electric field slight decreases in fiber diameter [85]. Similar outcomes were found by Megelski et al. (2002) when they used polystyrene (PS); the fiber size decreased from about 20 to 10 μm with increasing spinning voltage (5–12 kV) [86]. For polyacrylonitrile (PAN) solutions, the diameter decreases as the voltage increases from 8 kV to 16 kV [87]. However, a larger voltage also increases the likelihood that beads may form [81]. However, other investigations indicated that the fiber diameter increased with increased voltage, for example, for polyacrylonitrile (PAN) [88] and poly(vinyl alcohol) (PVA) [89]. But it is contradictory to the results obtained by Gu et al. (2005); they reported that raising the applied voltage had no discernible effect on the flow rate, which meant that during the PAN electrospinning process, the diameter of the fibers did not change much [90]. The variability of polyacrylonitrile (PAN) fiber diameter was examined by Yördem et al. (2008). Specifically, it was discovered that the applied voltage was insignificant at high solution concentrations, indicating that concentration could be the main factor controlling fiber diameter on the micron scale. Distance from the collector and the concentration of the solution, along with voltage, proved to be important elements in the synthesis of nanoscale fibers [91].

It is possible to explain why different researchers made seemingly contradictory observations because the morphology and diameter are dependent on the number of processing parameters; the applied voltage provides the surface charge on the electrospinning jet [92]. Therefore, the electrospinning process is started by a charged jet when the applied voltage reaches a certain value; with respect to the opposing electrode, the liquid leaves the small diameter nozzle at a high potential. The liquid creates the so-called Taylor cone, the tip of which shoots a narrow jet or thread of liquid. The impact of altering the applied voltage on the creation of the Taylor cone was discussed by Sill and von Recum (2008) [79]. A dangling drop will develop at the capillary's tip if the voltage is relatively low. The apex of the hanging drop then forms a Taylor cone. The hanging drop volume falls with increasing applied voltage until a Taylor cone forms at the capillary tip. However, as the applied voltage is increased further, the capillary's internal fiber jets are ejected, producing flaws and the creation of beads. The drop starting shape for the electrospinning solution is significantly influenced by the spinning parameters, including viscosity, voltage, and feed rate. Thus, the concentration of the polymer solution and the distance between the collector and the tip determine the influence of applied voltage on fiber diameter [83]. The morphology of the electrospun nanofibers is determined by the flow rate of the polymer solution from the metallic needle tip. Lower flow rates are often favored because they provide the solvent and polymer solution enough time to evaporate, leaving dry fiber on the collector. Beaded fibers are generated using high flow rates due to low stretching stresses and a short drying period before reaching the collector [83,84]. The collector functions as a conductive substrate for the charged nanofibers during the electrospinning process. Typically, aluminum foil is employed as a collector, but several collectors have been developed, including pin, wire mesh, rotating rod, wheel, parallel or gridded bar, and others, all with the aim to facilitate the manipulation of the fibers of the mat. Fiber alignment is determined by the type of collector and its rotation speed [82];

(c) Environmental parameters: humidity and temperature are other solution parameters that affect the diameter and morphology of the nanofibers. Due to the humidity conditions, the polymeric solution's solidification process slows down, resulting in thicker fibers and beads. Faster solvent evaporation accelerates solidification at lower humidity levels, increasing fiber diameter. The higher temperatures produce fibers with thinner diameters, a faster rate of evaporation, and a general drop in solution viscosity as temperature rises [82,83,93]. Finally, the entire equipment setup is placed in a cabinet, where

temperature and humidity are controlled for better manufacturing and reproducibility. Some solvents used to dissolve the polymers tend to be toxic, so the cabinet is exhausted, and all equipment can be placed in a fume hood to reduce solvent exposure (Figure 3) [94]. The primary effects of these parameters on the morphology of the fibers are presented in Table 1.

Table 1. Electrospinning parameters and their impact on fiber morphology [95].

Electrospinning Parameters								
Solution			Process			Ambient		
Cause	Effect	Reference	Cause	Effect	Reference	Cause	Effect	Reference
Increase concentration	Higher diameter and no beads	[96,97]	Increase voltage	Lower fiber diameter	[85,86]	Increase temperature	Lower fiber diameter	[98]
Increase viscosity		[89,99]	Increase gap ¹	Lower diameter and no beads	[85,100]	Increase humidity	² No defined	[101,102]
Increase molecular weight	No beads	[103,104]	Increase flow rate	Higher fiber diameter	[85,105]			
Decrease surface tension	Fiber formation	[81,106]						
Increase conductivity	Lower diameter and no beads	[107,108]						

¹ Gap: the distance between the needle and the collector; ² depends on the polymer solution.

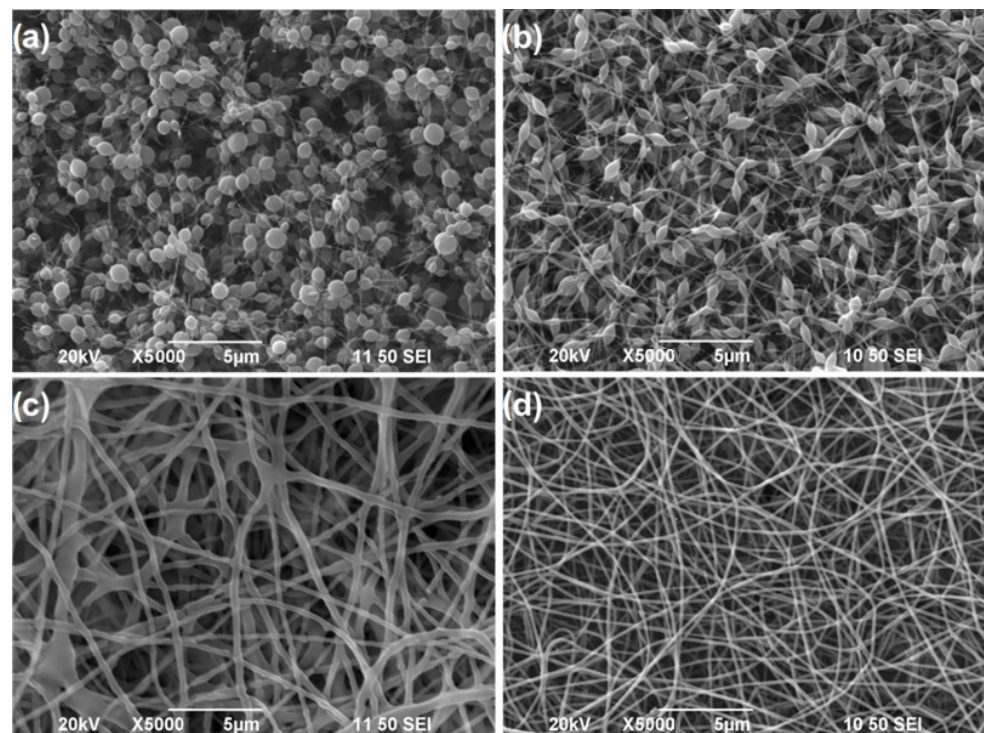


Figure 4. An example of how electrospun fiber shape can vary: (a) circular beads; (b) elongated beads; (c) flat ribbons; (d) continuous and smooth fibers [109].

7. Polymers Used in Electrospinning

The electrospinning technique is becoming a valuable means of producing functional polymeric nanofibers with well-defined morphological properties, especially for drug delivery applications due to their biocompatibility, adhesiveness, sterility, and efficiency in delivering diverse cargoes [94]. Given their biocompatibility with human tissues and cells, polymers are the most widely utilized biomaterials in the medical profession for applications in prosthetics, medical devices, implantation, medical coatings, and tissue engineering [16]. In general, they fall into two categories: natural and synthetic polymers. Natural polymers that are taken from the environment have good biocompatibility and are biodegradable; they are renewable resources and may also intrinsically exhibit antimicrobial activity [110,111]. Naturally occurring biomaterials known for their naturalness, safety, and kindness to the environment are polysaccharides. Some polymers that have been used in the electrospinning technique by some researchers are collagen [112], chitosan [113–116], gelatin [117,118], silk fibroin [119], cellulose acetate [120], alginate sodium [121], agarose acetate [122], hyaluronic acid [123,124], soy protein [125], and zein [126,127]. On the other hand, there are four primary types of synthetic polymers: elastomers, thermoplastics, thermosets, and synthetic fibers. All synthetic polymers are produced with petroleum oils as their primary component [16]. Therefore, they are biologically inert, uniform, and can be made with unique properties for specific applications [111]. The intended breakdown rate and the necessary mechanical qualities (viscoelasticity and strength) are two advantages that synthetic polymers often have over natural polymers [81,128]. They have also been used for the manufacture of nanofiber for different applications, for example, polylactic acid (PLA) [129], polylactic-co-glycolic acid (PLGA) [130], polycaprolactones (PCL) [131], polyglycolic acid (PGA) [132], polypropylene carbonate (PPC) [133], poly(vinyl alcohol) (PVA) [134], polyvinylpyrrolidone (PVP) [135], polyaniline (PANI) [136], polyethylene terephthalate (PET) [137], polyurethane (PU) [138], polyethylene oxide (PEO) [139], polyimide (PI) [140], polyacrylonitrile (PAN) [141], poly(ethylene-co-vinyl alcohol) (EVOH) [80]. Thus, natural, synthetic, or a combination of the two types of polymers can be used to create electrospun nanofiber mats [127], for example, gelatin/poly(vinyl alcohol) (PVA) [142], sodium alginate/polyethylene oxide (PEO) [84,143], soy protein/polyethylene oxide (PEO) [144], poly(D,L-lactide-co-glycolide) (PLGA)/gelatin [145], keratin/polyethylene oxide (PEO) [146]. There is a wide range of polymer solutions or melts that can be spun; namely, the polymer can be dissolved in a suitable solvent and electrospun, or the polymer can be directly electrospun from a melt [79]. Due to their versatility and ability to create submicron range fibers, more than 100 natural and synthetic polymers have been employed in the creation of electrospun nanofibers [93]. Natural and/or biodegradable polymers are still a requirement to overcome some environmental concerns of polymer applications in agriculture, especially for smart agrochemicals' development [147].

Polymers-Coated Used in Agriculture

Coated polymers used in agriculture can be made of hydrophobic or hydrophilic polymers. The most commonly used methods for coating fertilizers are dipping and spraying a liquid onto the substrate, but various ways can be used, including liquid spraying, liquid dipping, precipitation of supercritical fluids, and electrostatic deposition of energy [50].

Fertilizers coated with hydrophobic polymers provide considerable control over the rate at which nutrients flow, as the coating partially degrades over time, becoming porous and compressing, slowly releasing nutrients. Therefore, hydrophobic polymers offer reasonable control over the release rate since they are less sensitive to soil and environmental factors. The most hydrophobic polymers utilized in the creation of SRFs are polyethylene (PE), polypropylene (PP), ethylene-vinyl acetate (EVA), polyurethane (PU), polystyrene (PS), and polystyrene-co-butadiene (SBR) [71] among others. Several investigations have been carried out with the aim of encapsulating urea granules in a suitable covering material

to avoid the possible negative effects of their excessive use and to synchronize the release of nitrogen. PS is often used as a urea fertilizer cover; however, PS has a low biodegradability of less than 1%, and its decomposition ceases after 90 days, which may cause environmental difficulties. Furthermore, PS cannot be used as a urea fertilizer coating material in isolation; it must be mixed with other polymers to optimize nitrogen efficiency [148]. The PU has been in studies on the structure and properties of bio-based PU coatings [149], in the synthesis of urea-formaldehyde/PU microcapsules [150], for improving water absorption and controlled nitrogen release [151], and nanocomposite-coated urea [152]. Recently, Sasson et al., 2024 used PP to synthesize and characterize a novel thin coating loaded with thymol for anti-mold and pest control purposes [153].

In the case of hydrophilic coatings, the most significant hydrophilic polymers are super absorbent polymers (SAPs), a type of polymeric material with a high capacity for absorbing and holding onto water and aqueous solutions. Their composition consists of three-dimensional polymeric networks that exhibit significant swelling in aqueous media but do not dissolve in water [154]. Due to their superior qualities, they have been widely employed in agricultural processes and have garnered much interest when utilized as materials for water management on farm land that is dry, such as in desert and arid conditions. Additionally, they are polymers that can reduce the rate at which plants die and lessen the amount of water used for irrigation [71]. These polymers can be natural or synthetic and are used for preparing SAP are polysaccharides-based (cellulose, starch, alginate, and agarose) and polypeptide-based (gelatin, collagen) and synthetics (polyacrylic acid, methacrylic acid, vinyl acetate, polyethylene glycol) [154]. SAPs are designed for polymer-coated fertilizers and include soluble nutrients as a core surrounded by a polymer [71]. Sufficient hydrophobicity of the materials used to create CRFs is crucial for regulated release without abrupt coating wall breakdown [155].

A wide range of investigations were reported using hydrophilic polymers. Szymanek et al., in 2024, examined the degradation of blends of poly(lactic acid) (PLA) with poly(propylene carbonate) (PPC) films in soil. The results showed that the deterioration rate of PLA/PPC blends was proportional to the ratio of both components, regardless of the degradation medium; nevertheless, their temporal degradation was not met. The phytotoxicity test of PPC revealed no detrimental effects of this polymer on monocotyledonous and dicotyledonous plants, but the maximum dosage marginally impeded the development of oat roots. In this regard, this polymer is suitable for environmental protection and agricultural applications, such as mulching films and agrochemical CRFs [156]. Liu et al., 2024 used a degradable lignin/PVA polymer as a urea slow-release coating material. The coating formulation was created by adding varying amounts (2, 5, 8, 14 wt%) of aminated lignin (AL) to a 5% polyvinyl alcohol (PVA) solution. The results showed that the PVA-AL (8%) formulation had good physical and chemical qualities in terms of water absorption and mechanical properties, and it degraded well in soil, losing 51% of its weight after 45 days. Potting trials confirmed that *Brassica napus* received a steady supply of nitrogen from PVA-AL-coated urea. Thus, the lignin-based composite can be employed as a coating material to create a new slow-release nitrogen fertilizer for long-term crop production [157]. Coating formulations containing Polyvinyl pyrrolidone (PVP), polyvinylalcohol (PVOH), or poly(methyl vinyl ether) (PMVE) have been used in the use of biological seed coatings based on bacteriophages and polymers against *Clavibacter michiganensis* subsp. *nebraskensis* in maize seeds [158].

The lack of water for irrigation is one of the most pressing issues in agriculture, according to a review by Krasnopeeva et al., 2022. The use of SAPs as containers for water and plant nutrients is widespread in arid and semiarid regions, as they significantly enhance water utilization efficacy. The most appropriate rate for increasing seed and dry matter yields and satisfying economic aspects is 100 kg SAP per hectare, allowing a 15% increase in cereal seed yield [159]. Similar outcomes were reported by Cheng et al., 2018 highlighting how to develop a superabsorbent (SA) to improve the N release created by polymerizing acrylic acid (AA) and urea. A 1.0 mol urea/mol AA ratio yielded the

highest water absorption (909 g/g). The maize seed germination in various types of soil with different amounts of SAP was proposed. Treatment with 0.2% of this SAP promotes seedling and root length for different studied types of soils, and the N could release 3.71% after being incubated in distilled water for 40 days [160]. In 2014, Yang et al. studied the effect of SAP on soil water retention, seed germination, and plant survival in rocky slopes eco-engineering. They find that the addition of SAP to soil could significantly boost the water retention of the soil and its use of water for plant growth. The evaporation rate decreased by 88.85% compared to the controls, which is to say, soils without SAP. The germination rate increased more than twice as much in grass and around 3.5 times in woody plants compared with the controls [161]. The rate at which nutrients are released through these polymer-based coatings is dependent on numerous factors. The most crucial factors are the type of polymer (hydrophilic or hydrophobic), its concentration in the coating solution, the solution's viscosity, any additional modifying agents, the number of layers, and the coating methods are the most crucial factors [50].

8. Nanofibers as Carriers of Agrochemical

A good deal of research recently studied the main applications of nanofibers in agriculture due to their tailoring properties, which include biocompatibility and biodegradability, high surface area and porosity, ease of active ingredient additions, and flexibility of electrospun nanofibers. One of the main applications of nanofibers in agriculture can be to promote growth through the encapsulation of fertilizers to protect plants by administering agrochemicals such as fungicides, insecticides, herbicides, pesticides, and coating seeds to improve germination [47]. Given the importance of nanofibers in agricultural applications, as explained above, various morphologies can be generated by optimizing the electrospinning conditions. The researchers created nanofibers with thinner, aligned, continuous, core-shell, porous morphologies of various diameters to be used as controlled release systems and seed coatings. Table 2 shows the data of the electrospinning process parameters used in the research to produce fertilizer-carrying nanofibers, which will be explained later.

8.1. Nanofibers as Carriers of Fertilizers

The electrospun nanofibers are less likely to wash away than nanoparticles as they are better at regulating fertilizer encapsulation. Thus, farmers may be able to reduce fertilizer loss by using nanofiber networks to stop potential pollution and fertilizer runoff. Existing research has focused on developing delivery strategies aimed at enhancing fertilizer release [162].

Castro-Enriquez et al. (2012) studied the preparation, characterization, and release of urea of membranes created from wheat gluten (WG) via electrospinning. The variables of the technique of electrospinning are shown in Table 2. The optimal conditions for obtaining membranes were an 8% *w/v* concentration of WG, an ethano/2-mercaptoethanol solvent system, a distance of 10 cm between the needle and the collector plate, a solution flow rate of 0.01 mL/h and an applied voltage of 15 kV. They reported that the morphological characteristics of the membranes obtained were a homogeneous thin membrane with a thickness of 40 μm being desirable for the potential applications in a prolonged-release system of the membrane. The fiber diameter varied from 0.683 to 5.45 μm , and the pore diameter was around 613 nm. The entrapment efficiency of urea in electrospun membranes was 86% of efficiency [163]. This value is higher than reported by Chen et al. (2008), who created a new kind of slow-release membrane-encapsulated urea fertilizer with starch-g-poly L-lactic acid (PLLA) as the biodegradable carrier materials by casting method. In their research, they discovered that starch-g-PLLA had an encapsulation effectiveness of 81% and unmodified starch of 53% [164]. These results suggest that, because of its low membrane thickness (40 μm), the electrospinning approach is better than the casting procedure for producing membranes for encasing compounds [164]. In addition, the average porosity was estimated to be 6.05%, which suggests that is a characteristic desirable for increasing the encapsulation efficiency. According to the release, studies revealed that after 10 min,

the release rate decreased until equilibrium was reached in approximately 5 h, with a total of around 98% urea released. Compared to the traditional practice of adding uncoated urea, the urea dissolves immediately, resulting in losses of up to 90% [163].

The coaxial electrospinning method was used for prepared core-shell fibers with polyhydroxybutyrate (PHB) as the shell and polylactic acid (PLA) mixed with fertilizer (NPK 21-21-21) as the core was investigated by Kampeerapappun and Phanomkate, (2013), who examined the morphology, release rate of fertilizer, and biodegradability of neat and fertilizer-loaded core-sheath electrospun fiber mats. Core-shell electrospun fiber morphology was determined by altering the core solution feed rate and fertilizer concentration in the core solution. It was found that different feed rates (0.2 to 2.2 mL/h), applied voltage 16 kV (Table 2), and fertilizer concentrations (20 to 160 *w/w*) did not significantly change the fiber morphologies and outer diameter of the fiber. The range of diameters of core-sheath electrospun fibers was 4.0 to 4.5 μm . A higher feed rate produced a faster release of the fertilizer. For instance, at 300 h, the total fertilizer release was 57.77% and 87.60%, while the core solution feed rate was 0.6 and 2.2 mL/h, respectively. Based on the amount of PLA utilized (6% *w/w*), the analysis of the impacts of concentration on release rate was carried out by increasing the fertilizer concentration in the core solution from 20 to 160% *w/w*. The core solution supply rate was set at 1.4 milliliters per hour. Fertilizer concentration was found to have no effect on the release rate of the electrospun fiber mats, meaning that the fertilizer can be released for up to 30 days. Nonetheless, the core solution's increased fertilizer concentration led to a larger release of fertilizer content. After releasing fertilizer for a month, the electrospun mats began to distort. Two months later, the fiber mats became brittle and began to break apart. Three months later, the electrospun mat vanished completely. The authors mentioned that these findings made sense because diffusion through the shell regulates fertilizer release. By computing the difference between the total and inner fiber diameters, the shell thicknesses of the fibers were found. Fiber shell thickness was considerably reduced by raising the input rate of the cores' solution. The fertilizers that were trapped in the fiber's cores dissolved and came out through the shell. Fertilizers diffused through thinner shells more quickly than through thicker ones; hence, shell thickness is the primary factor regulating the rate of active agent release [165].

Because of their larger surface area, porosity, ease of processing, and negligible solvent residue, electrospun fibers have advantages over polymer films, according to Krishnamoorthy et al. (2016). They utilized polyvinylpyrrolidone (PVP) combined with fertilizer urea, and cobalt nanoparticles (CoNPs) were employed to cover seeds for Cowpea (*Vigna unguiculata*). First, four different solutions were electrospun: (1) PVP solution 5% (*w/v*): chloroform/ethanol mixed solution; (2) PVP-CoNPs; (3) urea PVP; and (4) urea-PVP-CoNPs. The solution prepared was electrospun with the conditions described in Table 2. The results showed that ultra-fine continuous smooth fibers were formed, and the surfaces were found to be smooth without any imperfections. Diameters of the nanofibers in solution 1, 2, and 3 were 0.43 to 1.5 μm , 0.8 to 1.6 μm , and 0.6 to 0.8 μm , respectively. The conductivity of the solution increased when CoNPs were present; as a result, the average diameters of CoNPs incorporated fibers were reduced. The coexistence of CoNPs in the fibers and knot-like features were observed with the combination of PVP-CoNPs. Electrospinning and dip coating methods were used to coat the seeds with PVP fibers. When comparing the release of urea and CoNPs, the fibers released only 12%, while the film showed a rapid release of almost 50%. It is shown that the fibers were more effective for plant growth and nutrition because the fibers allowed gas circulation and did not clog the pores of the seeds, unlike the films. Additionally, the fibers will provide better handling and protection during storage, as the fiber-coated seeds were kept intact for 6 months in airtight containers [166].

De Cesare et al. (2018) claim that by combining organic farming techniques with biodegradable nanostructured materials, environmentally friendly, low-toxic bioactive goods are created that can provide iron to plants that are iron deficient. For this objective, free-standing electrospun nanofibrous polycaprolactone (PCL)/polyhydroxybutyrate (PHB)

(1:0.26, *w/w*) thin membranes loaded with catechol (CL-NMs) (5 mM, 10 mM) as an iron-chelating natural agent were created in an effort to mobilize Fe from insoluble forms and transfer it to duckweed (*Lemna minor* L.) plants. In duckweeds that were given CL-NMs with higher catechol concentrations for four days under controlled hydroponic conditions, most of the physiological and growth performances that had been compromised by the Fe limitation were restored. According to the authors, more research is needed to ascertain whether the efficacy of the nanofibrous PCL/PHB membranes in releasing catechol is dependent either on the concentration gradient of this model molecule between the outer solution and the interior of the fibers or on the physical characteristics of the fibers that are caused by the presence of the specific Fe chelator that is used [167].

Bulus et al. (2020) obtained fibers with liquid fertilizer-reinforced polycaprolactone (PCL) by electrospinning technique, and it was determined by providing morphological and mechanical characterization of the composite structure. They prepared a solution of 10% PCL, and the percentage of liquid fertilizer was varied: 1%, 5%, and 8%. Nanofiber formations were observed in all samples, and it was observed that PCL fibers became thinner, and the surface area increased with the increase in the amount of liquid fertilizer. According to the nanofiber mechanical analysis, as the amount of liquid fertilizer increases, the strength increases in composites is a result of the high load-bearing capacity polymeric matrix, the additive of different substances, and the homogeneous distribution in the composite. The composite material obtained will be able to show the characteristics of an environmentally friendly band organic fertilizer cover that is healing for agriculture [168].

On the other hand, Nooeaid et al., 2021 evaluated the manufacturing feasibility fibers of polyvinyl alcohol (PVA) as the core phase and polylactic acid (PLA) as the shell phase to encapsulate a conventional fertilizer (NPK 21-21-21). Also, NPK-loaded PVA monolithic fibers without PLA-shell coverage were produced under the conditions of 15 kV voltage, 10 cm collector-tip distance, and flow rate of 0.2–0.5 mL/h. The results demonstrated PVA/PLA core/shell fibers with micro-sized diameters. The submicron PVA fibers ranged in size from 0.1 to 0.3 μm , with a little increase (0.2–0.5 μm) after the loading of fertilizer. In terms of encapsulation efficiency, PVA/PLA core/shell fibers held more fertilizer ($42\% \pm 2\%$) than PVA monolithic fibers ($31.7\% \pm 0.6\%$). The loading capacity of the core/shell was $32 \pm 1\%$, whereas the monolithic PVA fibers had a loading capacity of $23.8 \pm 5\%$. The core/shell fibers released fertilizer in a controlled way over a longer period of time, whereas NPK-PVA fibers showed fertilizer release at higher amounts in a shorter time. Because NPK-PVA/PLA core/shell fibers can delay the release of fertilizer, the authors classify them as CRFs. However, NPK-loaded PVA fibers did not retain their structural stability in aqueous solutions, making them unsuitable for use as a controlled-release fertilizer. Furthermore, the use of NPK-loaded PVA and NPK-loaded PVA/PLA core/shell fibers successfully promoted improved plant quality, and the plants exhibited the same quality as those produced with conventional fertilizers. In potted green cos lettuce and red cos lettuce, both types of fibers increased vegetative growth, which was noticeably greater than the control, that is, without applying fertilizer [169].

Javazmi et al. (2021) reported that the engineered multilayer nanofibers could be considered as a way to delay the release of urea from the PLLA nanofiber matrix. The team analyzed the encapsulated and released urea molecules using multilayer electrospinning nanofibers as the support. Single-layered PLLA nanofiber loaded with urea and triple-layer polyhydroxybutyrate (PHB) nanofibrous structures as external layers with PLLA nanofibers impregnated with urea fertilizer as the middle layer (PHB/PLLA/PHB) were fabricated. This was used to determine the cumulative percentage of nitrogen released from single and triple-layered nanofibers containing 10%, 20%, and 40% urea, respectively. Results revealed that the diameter of the electrospun PLLA nanofibers increased from 496 to 782 nm as the urea concentration increased from 0 to 40%. The average diameter of the outer layer PHB nanofibers was 418 ± 64 nm, and the thickness of the three-layer nanofiber structure was about 21 μm . For the urea release results, they showed that the triple-layer nanofiber structure containing 10% urea released nitrogen more slowly than the

single-layer nanofiber structure encapsulating urea. Due to the physical barrier of the PHB nanofiber layer covering the PLLA nanofiber layer, the three-layer nanofibers containing 10% urea resulted in slower urea release compared to the single-layer PLLA nanofibers. Furthermore, increasing the urea content of single- and triple-layered PLLA nanofibers increased the number of globules in the samples. For PLLA impregnated with 10 wt% urea, the three-layer nanofiber mat released less than 50% after 39 h, while the single-layer mat released more than 80% [162].

In another study by Salehi and Kazemikia (2022), they prepared urea encapsulated by Cellulose Acetate (CA) nanofibers by electrospinning. This study analyzed the effect of changes in two important parameters, such as concentration of polymer solution and dissolved feed rate on nanofiber. Thus, high-quality nanofibers with an average fiber diameter of around 87 nm were obtained with electrospinning process conditions of 25 kV, feed rate of 0.5 mL/h, solution concentration of 14%, and needle-collector distance of 10 cm (Table 2). A very high proportion of fiber diameters in the range of 60–100 nm indicated the high quality of the produced fibers. In addition, they evaluated the release of urea fertilizer from the CA nanofibers; the results showed that the fiber diameter and the amount of fertilizer loaded on the fiber substrate (17%, 21%, and 23%) affected the release rate of fertilizer, with a direct correlation to the diameter and amount of the fertilizer loaded, that is, for nanofibers containing 17% urea fertilizer the amount of fertilizer released from the polymer substrate is lower than other percentages (21% and 23%). Likewise, it was also observed in nanofibers containing 23% urea fertilizer that the release rate is initially higher than 17% and 21%, inferring that it is due to the increase in the diameter and percentage of fertilizer loaded on the nanofiber substrate [170].

Recently, Ahmad et al. (2023) described that the inadequate zinc (Zn) availability in alkaline calcareous soil is one of the primary causes of low wheat yield and quality; that is why conventional application of Zn sulfate (ZnSO_4) fertilizer results in low Zn efficiency since it is easily fixed in such soils. Therefore, they conducted a study to assess the efficacy of new oxozinc nanofiber (ZnO_{NF}) generated by electrospinning and tested for wheat (*Triticum aestivum* L.) Zn biofortification utilizing several application methods such as foliar spray, seed coating, and seed priming, and ZnSO_4 was applied as a control. The results demonstrated that regardless of the application method, a significantly lower number of nanofibers ZnO_{NF} was required for Zn nutrition compared to the application of conventional fertilizer (ZnSO_4), and the use of ZnO_{NF} increased plant height (14.5%), spikelets per spike (13.7%), and Zn usage efficacy (611%) in comparison to control. The most noteworthy Zn take-up effectiveness (34%) for nanofibers was obtained for the seed primed, taken after by seed coating (23%), and finally, foliar application (7%). In addition, the combination of ZnO_{NF} and $\frac{1}{2}$ ZnSO_4 can improve Zn nourishment since the accumulation of Zn was maximized in grain, leaf, root, and stem. The authors concluded that oxozinc nanofibers application modes may be recommended for wheat biofortification, either alone or in combination with ZnSO_4 in zinc-deficient calcareous soils [171]. An important element with numerous uses in plant metabolism is manganese. In plants, manganese functions as a co-factor and activator for hundreds of metalloenzymes. Mn plays an essential part in a wide range of enzyme-catalyzed events, including redox reactions, phosphorylation, decarboxylation, and hydrolysis. This is due to its capacity to shift oxidation state in biological systems with ease. The only form of Mn that plants can absorb is the divalent form (Mn^{2+}); therefore, deficiencies are common in dry, calcareous, and sandy soils [172]. In that sense, a polymeric matrix in the form of PLA/starch nanofibers was created by Malafatti et al. (2023). To obtain the fibers, the starch concentration in the polymeric matrix was varied from 10% to 50% (*w/w*) using the electrospinning method. It was possible to create the nanocomposite with manganese carbonate (MnCO_3) as a source of Mn^{2+} ions. The findings demonstrated that PLA/starch blends with 20% (*w/w*) had superior fiber affinity with water, which is essential for fiber degradation time. With a starch content of 20% (*m/m*) in PLA fiber helped to better control the release of Mn^{2+} . After five days in contact with the 2% citric acid extractive medium, the entire release happened. In this

way, PLA/starch fiber serves as a substitute for other materials in the packaging of particle fertilizers, increasing the contact area during root application, delivering mineral nutrients gradually, and reducing leaching loss [173]. Table 3 summarizes the polymers, solvents, encapsulated fertilizer, morphology, diameter, and applications of nanofibers used in the research previously discussed.

Table 2. Electrospinning parameters utilized for electrospun nanofibers as carriers of fertilizers.

Author	Applied Voltage (kV)	Collector-Tip Distance (cm)	Flow Rate (mL/h)	Collector
Castro-Enriquez et al. (2012) [163]	10–20	10, 15	0.01 to 0.1	AF
Kampeerappun and Phanomkate (2013) [165]	15	15	0.2–2.2	AF
Krishnamoorthy et al. (2016) [166]	20	15	5.0	AF
Bulus et al. (2020) [168]	30, 35	15	3.0, 3.5, 5	----
Nooeaid, et al. 2021 [169]	15	15	0.2, 0.5	----
Javazmi et al. (2021) [162]	12, 20	15	1.0	AF
Salehi and Kazemikia (2022) [170]	25	10	0.5, 1.0, 1.5	AF
Ahmad et al. (2023) [171]	----	20	0.5	AF
Malafatti et al. (2023) [173]	16–20	5	0.6	----

AF: aluminum foil.

Table 3. Summary of fiber morphology and application, polymers/solvent, and encapsulated fertilizer.

Reference	Polymers/Solvent	Encapsulated Fertilizer	Fibers Morphology/Diameter	Fibers Application
Castro-Enriquez et al. (2012) [163]	WG Acetic acid/ethanol/1-propanol/ 2-propanol/acetone /2-mercaptoethanol	Urea	Smooth and porous/ 0.683 to 5.45 μm	Design for a controlled-release system
Kampeerappun and Phanomkate, (2013) [165]	PLA/dimethylformamide (DMF) PHB/Choloform	NPK 21-21-21	Core-shell/3.9 to 4.5 μm	Design for a controlled-release system
Krishnamoorthy et al. (2016) [166]	urea-PVP-CoNPs/ ethanol and chloroform	Urea-CoNPs	Smooth surface, aligned and continuous/ 0.43–1.5 μm ; 0.8–1.6 μm , and 0.06–0.8 μm	Coatings cowpea seeds (<i>Vigna unguiculata</i>)
De Cesare et al. (2018) [167]	PCL/PHB	Catechol(CL-NMs)	Mean diameter 0.502 $\pm$ 0.173 μm	Coating duckweeds (<i>Lemna minor</i> L.)
Bulus et al. (2020) [168]	PCL/DMF	Liquid fertilizer	Smooth, thinner/ 150–300 nm	Design for a controlled-release system
Nooeaid, et al., 2021 [169]	PVA/deionized PLA/DMF/Dichloromethane (DCM)	NPK	Core-shell/ 0.1–0.3 μm ; 0.2–0.5 μm	Growth of green cos lettuce and red cos lettuce
Javazmi et al. (2021) [162]	PLLA/chloroform: acetone PHB/DMF: chloroform	Urea (N-P-K; 46-0-0)	Smooth fibers/PLLA 496–782 nm PHB/428 $\pm$ 64 nm.	Design for a controlled-release system
Salehi and Kazemikia (2022) [170]	CA/acetic acid, distilled water	Urea	Continuous, uniform fibers/87 nm	Design for a controlled-release system
Ahmad et al. (2023) [171]	PVA	Zn nanoparticles	Round, irregular, and hexagonal shape/not explicitly valor	Foliar application, seed priming, seed coating to wheat (<i>Triticum aestivum</i> L.)
Malafatti et al. (2023) [173]	PLA/starch/chloroform, DMF	MnCO ₃	Homogeneity and smooth structure/not explicitly valor diameter	Design for a controlled-release system

8.2. Nanofibers as Carriers of Pesticides

Applications of NM-based nanopesticides can help manage a wide range of crop pests. In comparison to conventional pesticides, nano-based pesticides have a stronger potency due to their high efficacy, durability, good dispersion, and wettability, as well as their low dose release, which boosts effectiveness and lowers toxicity, environmental losses, and soil degradation [44]. Given the significance of nanofiber in agricultural applications, some investigations are described, and Table 4 shows the data of the electrospinning process parameters used in the research to produce pesticides-carrying nanofibers, which will be explained later.

Cellulose acetate (CA) nanofiber mats containing 2,6-dichloro-4-nitroaniline (DCNA), an agrochemical with antifungal properties, were created by electrospinning. The parameters of electrospinning are shown in Table 4. In addition, they also prepared CA films by solvent-casting technique for comparison of studies. The morphology, water retention, and weight loss of the neat and DCNA-loaded electrospun CA fiber mats were studied. The results showed that the fibers' surfaces were smooth, and there was no sign of DCNA aggregates. Both the unloaded and DCNA-loaded CA fibers had a diameter between 241–320 nm. The surface morphology of the as-cast films revealed a smooth surface, suggesting that DCNA was well incorporated within the films. The amount of water retention for the neat and the DCNA-loaded CA fiber mats ranged from 679 to 687%, whereas the values for the as-cast CA films ranged from 122 to 137%. The weight loss for the neat and DCNA-loaded CA fiber mats ranged from 51 to 59%, but the as-cast CA films lost between 29 and 35%. Both water retention and weight loss values for the fiber mat specimens were higher than those for similar films. The total immersion method was employed to determine the release properties of DCNA from the DCNA-loaded CA fiber mats and as-cast CA films. The amounts of DCNA released from the CA fiber mat and film specimens loaded with DCNA increased gradually. The maximum DCNA released for the CA fiber mats loaded with 5, 10, and 15% DCNA was approximately 91.8, 95.1, and 92.0%, respectively. In contrast, lower DCNA release values were noted in the equivalent film situations, where the maximum DCNA release levels were only roughly 68.1, 69.4, and 73.1%, respectively. It could be observed that all of the DCNA-loaded CA fiber mats released more DCNA than the corresponding films. In this way, the authors argue that the fact that the amounts of DCNA released from the DCNA-loaded CA fiber mats were greater than those from the DCNA-loaded CA films could be attributed to the observed higher levels of water retention and weight loss in all of the DCNA-loaded CA fiber mats compared to the DCNA-loaded CA films, as well as, the highly porous nature of the fiber mats, which contributed to a larger surface area than that of the films [174].

A research group first fabricated and characterized poly (lactic acid) PLA/cellulose nanocrystal nanofibers, and Columbia Blue (CB) was incorporated into the fibers as a model pesticide. Next, they studied the ability of nanofibers to encapsulate and release a pesticide in a greenhouse. They reported that no statistically significant difference in the fiber diameter was found among the PLA nonwoven fabrics with three percent of cellulose nanocrystals (0%, 1%, and 10%) and that 50% of CB was successfully incorporated into the nanocomposite fibers electrospun. The diffusion-controlled release of CB was significantly affected by the hydrophobicity of the electrospun PLA nanocomposite fibers, with increasing cellulose nanocrystal content in the fibers increased the fiber degradation rate and the CB release rate. The plasticizing impact of CB on the thermal properties of the electrospun nanocomposite fibers showed the miscibility of CB inside the electrospun nanocomposite fibers. To evaluate the efficiency of the PLA/cellulose nanofibers in terms of pesticide encapsulation and release, three different dosages of the systemic insecticide thiamethoxam were encapsulated into them. The effectiveness of killing whiteflies in a greenhouse was then examined. Lethality was 100% in the case of the greatest thiamethoxam concentration [175].

The article from Castañeda et al. (2014) provides results of a study that evaluated rice seed coating (*Oryza sativa*) with ethyl cellulose nanofibers incorporating commercial, active agrochemical ingredients (Vitavax® and Carbex®) using electrospinning (See Table 4).

Their result showed a germination percentage for three treatments: 95% for seed coating-Vitavax[®], 93.38% for seed coating + Carbex[®], and 87% for the control (without fungicide). The tests confirmed that the polymer coating that was applied had no effect on the seeds' physiological quality. The images of Scanning Electron Microscopy (SEM) showed fused fibers deposited on the surface, although beads were observed. Phytosanitary tests were carried out where the seeds were infected with *Penicillium*, *Fusarium*, and *Aspergillus*, and the three treatments were applied (seed coating + Vitavax[®], seed coating + Carbex[®], and control). *Penicillium* and *Aspergillus* fungi did not show significant differences between the applied fungicides since they inhibited the incidence of disease, but this was not the case for *Fusarium* since the incidence of disease was observed (between 3.72 and 2.72%). The Carbex[®] treatment was more efficient than Vitavax[®] [176].

Electrospinning and solution blow spinning (SBS) methods were compared by Souza et al. (2015). They investigated the encapsulation of linalool, a natural insecticide and larvicide, in poly (lactic acid) (PLA) nanofibers using electrospinning and SBS. The results of the characterization carried out showed that the average diameters of the electrospun and SBS were similar, in a range from 176 to 240 nm. The glass transition temperature (T_g), melting point (T_m), and crystallization temperature (T_c) decreased due to that linalool acted as a plasticizer for PLA. The time required to release half the amount of encapsulated linalool ($t_{1/2}$) decreased as the linalool concentration increased. The range in $t_{1/2}$ values for SBS nanofibers was greater (291–1645 s) than for electrospun fibers (76–575 s) [177].

The pesticide thiram (tetramethylthiuram disulfide, $C_6H_{12}N_2S_4$) is used to combat fungi on agricultural land. It is also employed to safeguard agricultural goods while they are being packaged, transported, and stored [150]. Due to the importance of this compound, the research of Roshani et al. (2016) aimed at a controlled release of thiram pesticide from poly(L-lactic acid) (PLLA) nanofibrous matrix. Scanning Electron Microscope (FESEM) micrographs of electrospun PLLA nanofibers and electrospun PLLA-thiram nanofibers before annealing were bead-free and uniform. The diameter decreases with increasing thiram content up to 10% and increases with further thiram increase. It is well known that lower viscosity and higher electrical conductivity typically lead to smaller nanofiber diameters. The viscosity decreased with increasing thiram content up to 10% and increased with further thiram addition, following the trend in nanofiber diameter. Up to 10% thiram acts as a plasticizer, reducing viscosity despite higher concentration. Beyond 10%, increased viscosity dominates over the plasticizing effect. Conductivity increases with thiram content due to thiram's dipole characteristic, leading to higher electrical conductivity in the solution. Fourier Transform Infrared Spectroscopy (FTIR) analysis showed H-bonding between the thiram insecticide and the PLLA nanofibrous matrix, however, did not reveal any chemical interaction between PLLA and thiram. The findings demonstrated that, in the absence of annealing, the Fick mechanism governed the regulated release of thiram from PLLA nanofibers but that, following annealing, the non-Fick mechanism predominated. Additionally, it was shown that annealing resulted in a decreased initial rate and level of controlled release. The usage of electrospun PLLA-thiram nanofibers for long-term, regulated thiram release in agriculture is concluded [178].

Similarly, the fabrication and characterization of systemic fungicide tebuconazole loaded in polyvinyl alcohol (PVA) nanofibers were studied by Latha et al. (2019). In this work, the fungicide was put into polyvinyl alcohol (PVA) nanofibers at a concentration of 250 ppm. SEM, Transmission Electron Microscopy (TEM), Energy-dispersive X-ray Spectroscopy (EDAX), UV-Vis spectrophotometer (UV-Vis), and FTIR were used to further analyze the fibers. SEM images showed that at low concentrations (5–6%), nanofibers began to form but with many beads. Fibers with the desired characteristics were developed at 10% PVA concentration, with diameters ranging from 293 to 373 nm, and without beads. The diameter of PVA electrospun loaded with fungicide has increased due to the entrapment of tebuconazole, from 405.9 nm to 556.7 nm. This result was confirmed by TEM, where there was an increase in the diameter of nanofibers observed after fungicide encapsulation (389.0 to 587.0 nm). The evaluation of EDAX spectra confirmed the elemental composition

of tebuconazole encapsulated in PVA nanofibre. A UV-Vis spectroscopy analysis also confirmed the presence of tebuconazole in the PVA electrospun fiber, as peaks appeared at 270 nm [179].

Farias et al. (2019) go on to discuss an effective approach for localized delivery of AI by coating seeds (soybeans) via electrospinning. Using cellulose diacetate polymer (CDA) and two model active ingredients, abamectin (Abm) and fluopyram (Flp), individually integrated into nanofibers were fabricated. The authors described that the fiber diameter for untreated CDA, CDA + Abm, and CDA + Flp were 335 ± 81 , 242 ± 162 , and 129 ± 28 , respectively. All the samples showed a smooth and defect-free appearance. To determine the impact of active ingredient incorporation on CDA electrospinnability, they examined the viscosity, conductivity, and surface tension of the corresponding solutions. The results revealed that the addition of active ingredients to the polymeric solution results in an increase in its conductivity, with a more pronounced effect observed in the case of Flp conductivity ($40.06 \pm 0.69 \mu\text{S}/\text{cm}$), while viscosity (with an average of 2.83 Pa.s for three solutions) and surface tension (average 34.12 mN/m for three solutions) remain unchanged. They also observed a nearly two-fold increase in the conductivity of the CDA solution after the addition of Flp, resulting in significantly thinner fibers. It can be concluded that with the reduction of the diameter of the Flp-loaded fibers, the morphology of the electrospun Flp-loaded nanofibers is driven by the conductivity. Then, soybean seeds were coated with nanofibers by placing them on a collector plate. Optical images revealed clear differences between uncoated seeds and those coated for two hours. Surface profilometry using a confocal laser microscope showed that the thickness of the coating increased with time: 926 μm for 2 h, 1463 μm for 3 h, and 1265 μm for 4 h. The nanofibers were randomly coated, and the depth profiles indicated that longer coating times resulted in thicker and rougher coatings, which could potentially impact germination. The coated seeds showed that all seeds germinated at 90% or higher, regardless of coating time or thickness. This suggested that coating thickness and coverage do not significantly affect seed germination, indicating that uniformity of the coating is not a critical factor for germination. The release profile of active ingredients from nanofiber mats was investigated using High-Performance Liquid chromatography (HPLC) over a two-week period. This period reflects early seedling growth and protection against pathogens. Abm released only 5.5% of its content after 2 weeks, while Flp released 25% of its content. The higher release rate of Flp is attributed to its smaller fiber diameter ($\sim 129 \text{ nm}$ vs. $\sim 242 \text{ nm}$ for Abm) and higher water solubility. Water contact angle measurements indicated that Abm is more hydrophobic than Flp, affecting its release rate. Despite immersion in water for two weeks, SEM images showed that the nanofibers retained their structure, indicating durability and suggesting that the coating will remain effective for the critical 5–6 weeks needed for seedling protection. Lastly, they used Flp-loaded nanofibers to consistently limit fungal growth against the plant disease *Alternaria lineariae* in order to assess the bioavailability of the active ingredient. When combined with moisture stability, the sustained release profile indicates that nanofibrous seed coverings have great promise as a substitute platform for managing plant diseases, including fungus and nematodes [180].

In other approaches, the use of electrospinning in agriculture is still being assessed for its ability to repel insects. The majority of the time, repellents are sprayed directly onto the skin or infused into fabric surfaces. Unfortunately, the repellents' effectiveness is only temporary due to their volatile nature, necessitating regular reapplication. When coated on the fabric surface, its longevity and abrasion resistance are also in doubt. Furthermore, when applied directly, certain repellents irritate the skin and eyes [181]. Ciera et al. (2019) focused their study on the direct microencapsulation of repellents from an emulsion and the electrospinning integration of repellents that have already been encapsulated into nanofibres. Repellents such as permethrin, catnip oil, chili oil, and ρ -methane-3, 8-diol microcapsules (PMD) were electrospun into polyvinyl alcohol (PVA) nanofibrous structures. The integration of PMD microcapsules into electrospun PVA nanofibers was achieved without compromising their structural integrity. Permethrin and catnip oil-loaded fibers

showed bead-like structures, while chili oil-loaded fibers had pores. Adding 16% PMD microcapsules reduced the average fiber diameter (386 ± 55 nm) against the electrospun PVA fibers (408 ± 67 nm). The fiber diameter decreased as permethrin concentration increased, whereas chili and catnip oil increased it, with chili oil causing more variability. According to mechanical properties, the tensile strength, Young's modulus, and elongation at break of the resultant nanofibrous structure were not considerably altered by the introduction of PMD microcapsules, permethrin, chili, and catnip oil into PVA nanofibrous structures. Samples containing catnip did exhibit a modest drop in mechanical characteristics, but not significantly. Statistical analysis revealed that any concentration (2–16%) of PMD microcapsules significantly reduced mosquito landings compared to the control, indicating increased repellency with higher PMD concentrations. When testing nanofibers with permethrin, chili, and catnip oil, all showed a significant reduction in mosquito landings compared to the control. Permethrin was the most effective, reducing landings by 89%, while chili and catnip oil reduced them by 51% [181].

Gao et al. (2020) reported that the solid fungicidal nanodispersion of thiabendazole/hydroxypropyl- β -cyclodextrin (TBZ/HP β CD) complex is a new type of formulation that can enhance the water solubility of thiabendazole in order to improve the solubility and its antifungal activity because is a fungicide poorly water-soluble. Electrospinning was performed to prepare TBZ/TBZ/HP β CD nanofibers (TBZ/HP β CD-NF) (Table 4). The formation of TBZ/HP β CD-NF significantly improved the antifungal activity of TBZ, as shown by the inhibited mycelial growth of *Gibberella* sp. The EC₅₀ values for TBZ and TBZ/HP β CD-NF were 0.406 and 0.222 μ g/mL, respectively, with TBZ/HP β CD-NF being 1.83 times more effective. This enhancement was attributed to improved water solubility. SEM images confirmed the successful electrospinning of beadless, uniform nanofibers without a carrier polymer matrix, with an average fiber diameter of 370 ± 198 nm. The TBZ/HP β CD-NF nanofibers dissolved completely in water, unlike the poorly soluble TBZ powder, indicating improved water solubility. X-ray Diffraction data suggested minimal crystalline TBZ in the nanofibers, and no undissolved TBZ was observed, likely due to its homogeneous distribution in the nanofibrous webs. Enhanced water solubility facilitates drug efficacy and reduces residuals [182]. In 2021, the same authors [183] used the same complex but now integrated the fungicide thiram (thiram/hydroxypropyl- β -cyclodextrin). They described that nanofibers (thiram-HP β CD-IC-NF) might be electrospun to create a water-based drug delivery system in which they dissolve rapidly. SEM images demonstrated that the thiram nanofibers had a homogeneous and bead-free morphology, and the average diameter was 270 ± 133 nm. The solubility of thiram showed an excellent linear relationship with the change in HP β CD concentration, as demonstrated by the findings of the phase solubility experiment. Research on fungicidal activity revealed that the E₅₀ of untreated thiram against *Gibberella* sp. was 0.532 ± 0.013 μ g/mL, and E₅₀ of thiram-HP β CD-IC-NF was 0.403 ± 0.007 μ g/mL. Similarly, thiram/HP β CD-NF was 1.32 times more effective and had strong antifungal efficacy against *Gibberella* sp. [183].

Ryan et al. (2020) report the incorporation of repellent picaridin via coaxial electrospinning (Table 4) onto nylon-6 nanofibers (nylon/picaridin). Investigations were conducted into the effects of fiber composition on monofilament fiber morphology and release kinetics. The research arrived at the conclusion that picaridin was physically trapped in the nylon matrix, displaying negligible interactions between picaridin and nylon molecules. The effect of repellent content on fiber morphology using SEM confirmed that all nylon/picaridin composite fibers were free of defects and could be electrospun with all repellent compositions. Unloaded nylon fibers exhibited an average fiber diameter of 279 ± 76 nm and incorporating picaridin did not significantly affect their morphology and size, even at high loadings (up to 50 wt%). The composition of the electrospun fibers was evaluated using Thermogravimetric Analysis (TGA), revealing that most of the picaridin was retained during the electrospinning process, though a small amount was lost due to evaporation. The long-term release capability of nylon/picaridin fibers was evaluated using isothermal TGA at elevated temperatures. Results showed that the release rate of picaridin increased

with temperature and repellent loading, but none of the samples released all the picaridin after 300 min at 100 °C, indicating significant stability and potential for long-term release at lower temperatures. These studies clearly show that their findings may find application in the field of agriculture [184]. It is worth mentioning that, in addition to encapsulating pesticides into nanofibers, the effect of entrapping bacterial cells as *Methylobacterium aminovorans* in an electrospun PVA polymer matrix has been studied by Mukiri et al. (2021). This study explored the viability, survivability, and effect of seed coating in groundnuts for enhanced germination, seedling, and growth of plants. The optimal fiber diameters were found to be 93.3–166.1 nm, 164.8–218.2 nm, and 194.4–303.2 nm at PVA concentrations of 7%, 8%, and 9%, respectively, without bead formation. Higher viscosity prevented bead formation, unlike at lower concentrations (5% and 6%), where poor-quality fibers with beads were formed due to low viscosity and surface tension effects. During electrospinning (Table 4), low-viscosity solutions had insufficient viscoelastic force to counter electrostatic and columbic repulsion, leading to bead formation due to surface tension. Under the effect of surface tension, the high numbers of free solvent molecules in the solution come together into a spherical shape, causing the formation of beads. In the microbial cell optimization study, significant bacterial growth was observed when blending 5 mL of microbial broth with 5 mL of 14% PVA. Encapsulation increased the fiber diameter, ranging from 379.9 nm to 845.5 nm. TEM images confirmed the encapsulation of rod-shaped bacterial cells sized 267.7 nm to 466.0 nm. Viability tests of *Methylobacterium aminovorans* showed that microbial cell viability decreased over time when stored at room temperature, with CFU counts of 1.85×10^5 , 2.2×10^4 , and 1.2×10^4 observed on days 10, 20, and 30, respectively. In addition, the study demonstrated that *Methylobacterium aminovorans* cells, encapsulated in polymeric electrospun nanofibers, remained viable for over 30 days under ambient conditions. This viability is likely due to the polymeric matrix acting as a protective shell against environmental stress and dehydration. Seeds inoculated with these nanofibers showed improved growth metrics: germination rates increased to 84%, root length to 11.4 cm, shoot length to 16.3 cm, seedling vigor to 2322, and dry matter production to 3.67 g per 10 seedlings, compared to untreated controls. These improvements were attributed to the secretion of phytohormones by *Methylobacterium aminovorans* and the hydrophilic nature of PVA, which enhances water uptake and maintains moisture around the seeds. In the pot culture study, seeds with encapsulated microbial cells also showed higher seedling emergence (83%), root growth (9.60 cm), shoot growth (18.08 cm), and vigor (2294) compared to controls. The increases in seedling emergence, root growth, shoot growth, and vigor were 9.0%, 15.1%, 26.6%, and 36.3%, respectively. These enhancements are attributed to the combined effects of the encapsulated microorganisms and the polymer matrix, which improve nutrient availability and promote plant growth. After sowing, measurements were taken at 25 and 45 days, and the nanofiber-coated seeds had greater plant height, biomass, root volume, number of nodules, and fresh weight compared to the controls. Overall, the results highlight the effectiveness of electrospun nanofibers in encapsulating beneficial microorganisms improving plant growth and yield. In general, the findings showed that when *Methylobacterium aminovorans* cells are immobilized in polymeric electrospun nanofibre, their viability can be preserved for over 30 days in an ambient environment because the polymeric matrix serves as a protective shell that shields the microbial cells from environmental stressors and dehydration [185].

Das et al. (2023), in order to create a structurally stable agro-augmenting assembly for a controlled herbicide release system, report the development of atrazine/hydroxypropyl- β -Cyclodextrin (H- β CD) inclusion complex (IC) loaded PVA-based sustainable electrospun mats (EM). The atrazine (ATZ) (2-chloro-4-ethylamino-6-isopropylamino-s-triazine) is the most widely used triazine-based herbicide, and it is applied in the dosage range of approximately 0.75–2.5 kg/ha. It has been shown to be effective in preventing the growth of broadleaf, grassy, and grass-like weeds in a variety of crops, including corn, wheat, fruit trees, sorghum, orchard, and other agricultural commodities. The encapsulation of ATZ into the cavity of H- β CD was successfully indicated by the thermal, morphological,

and microstructural characterization. Moreover, the synthesized IC was added to the PVA precursor solution to create homogenous and bead-free IC-loaded EM. The existence of hydrogen bonding connections between IC and PVA EM was validated by microstructural investigation of IC-loaded PVA EM. The fabricated EM demonstrated enhanced surface-hydrophobicity and ATZ release effectiveness in soil at about 6.2%, as well as water at ~13.6%. The results of the thermal and mechanical analysis showed that adding IC at a lower concentration increased the mechanical characteristics of PVA-based EM from ~24.3.7 to ~27.4 MPa while also increasing the thermal stability from ~284 to ~395 °C. Furthermore, the results of the herbicidal activities showed that free ATZ was less effective than IC and IC-loaded PVA EM against *L. sativa* [186].

Table 4. Electrospinning parameters utilized for electrospun nanofibers as carriers of pesticides.

Author	Applied Voltage (kV)	Collector-Tip Distance (cm)	Flow Rate (mL/h)	Collector
Thitiwongsawet et al. (2010) [174]	15	15	1.0	---
Xiang et al. (2012) [175]	15	10	0.6	AF
Castañeda et al. (2014) [176]	30	16	3.0	-----
Souza et al. 2015 [177]	25	12	0.4	----
Roshani et al. (2016) [178]	14	21	0.14	----
Latha et al. (2019) [179]	20	----	0.3	----
Farias et al. (2019) [180]	12.5	15	0.5	AF
Ciera et al. (2019) [181]	12–23	14	1.0	AF
Gao et al. (2020) [182]	15–20	12–16	0.5	----
Gao et al. (2021) [183]	15–20	12–16	0.5	AF
Ryan et al. (2020) [184]	15	10	0.9	----
Mukiri et al. (2021) [185]	15	----	0.6	----
Saileela et al. (2023) [11]	15	15	0.6	----
Merlini et al. (2023) [187]	24	12	0.5	----

The effects of covering black gram seeds with PVA nanofibers injected with pendimethalin on germination and growth were examined by Saileela et al. (2023). Nanofibers were created using polyvinyl alcohol (PVA) solutions at concentrations of 7, 8, 9, and 10%, resulting in diameters ranging from 231.6 to 313.5 nm, 182.7 to 261.2 nm, 143.2 to 210.3 nm, and 115.3 to 158.5 nm, respectively, without bead formation. The optimal concentration for herbicide loading was found to be 10%, as higher PVA concentrations increased viscosity and improved chain entanglement. According to the results of encapsulation of pendimethalin in PVA nanofibers led to increased fiber diameters. Post-encapsulation, the fiber diameters ranged from 245.6–305.4 nm at 25 ppm, 291.8–445.3 nm at 50 ppm, and 230.0–445.3 nm at 75 ppm. For PVA-coated seeds and pendimethalin-encapsulated PVA-coated seeds, fiber diameters ranged from 331.2–472.1 nm and 515.6–970.3 nm, respectively. Seed germination rates with pendimethalin-encapsulated nanofibers were comparable to untreated seeds. Control seeds showed 81% germination, 19.20 cm root length, 10.52 cm shoot length, 124.26 g dry matter per 10 seedlings, and a vigor index of 2115.75. In contrast, seeds coated with 75 ppm pendimethalin exhibited similar germination (80%), root length (19.24 cm), shoot length (10.1 cm), dry matter production (123.12 g per 10 seedlings), and vigor index (2111.75). The herbicide-infused PVA nanofibers provided a larger surface area, enhancing water absorption and accelerating germination compared to untreated seeds. The FTIR results confirmed the presence of pendimethalin within PVA nanofibers [11]. Similar results were found by Mukiri et al. (2021) [185].

Furthermore, Merlini et al. (2023) described the results of developing poly(lactic acid) (PLA) electrospun mats using di-, tri-, and tetra-epoxidized imidazolium, ionic liquids (ILs) as insect-repellent active agents, as well as the effect of ILs' microstructure, thermal properties, mechanical performance, and hydrophobicity. The electrospun PLA mats presented a three-dimensional (3D) structure with randomly oriented continuous fibers, high porosity, and rough surfaces, which increases their surface area and flexibility, as

demonstrated by SEM images. According to the study, the fiber diameter increased from $0.55 \pm 0.13 \mu\text{m}$ (pure PLA) to $1.00 \pm 0.20 \mu\text{m}$ when 3 wt% of di-, tri-, and tetra-epoxidized ILs were incorporated. This rise is due to the chain-extending effects of epoxidized ILs, which increase PLA's molecular weight. However, larger IL concentrations decreased fiber diameters. This reduction is related to the solution's higher ionic conductivity, which promotes polymer stretching during electrospinning. Smaller fibers offer a greater surface area for IL-insect interaction and enhance the mat's elongation and elasticity. The contact angle of PLA electrospun mats (132°) increases compared to non-porous PLA films (76°), which is attributed to the higher roughness and porosity of the electrospun mats. Tensile characteristics depend on the kind and concentration of ILs: Tetra-epoxidized ILs improve Young's modulus from 50 to 100 MPa while retaining a consistent strain at a break of approximately 60%. This is attributed to enhanced crystallinity in the PLA at higher IL concentrations. Di-epoxidized ILs also showed a small improvement in Young's modulus from 60 to 80 MPa and improved strain at break from 50% to 80% with 5 wt IL. At 10 wt%, both modulus and strain decreased due to reduced fiber diameters, and Tri-epoxidized ILs provided an acceptable balance between rigidity and deformation, providing favorable results in both characteristics. The repellent activity demonstrated that ILs had a substantial effect on aphids at concentrations of 5 and 10 wt%, but di-epoxidized IL had an effect at 5 and 10 wt%, with negative repellent indices (RI). Tri-epoxidized ILs are repellant at 5 wt% (RI 14.6%) and more effective at 10 wt% (RI 48.44%). Tetra-epoxidized IL repels at 5 wt% with an RI of 41.0% but has decreased repellency at 10 wt% with an RI of 18.8%. High amounts may be hazardous to aphids. They came to the conclusion that the mechanical characteristics, hydrophobicity, and repellent activity of PLA electrospun mats with epoxidized ILs are improved. In particular, tri- and tetra-epoxidized insecticides (ILs) have a strong repelling effect on aphids, but at greater doses, they may be hazardous [187]. Table 5 summarizes the polymers, solvents, encapsulated pesticides, morphology, diameter, and applications of nanofibers used in the research previously discussed.

Table 5. Summary of fiber morphology and application, polymers/solvent, and encapsulated pesticides.

Reference	Polymers/Solvent	Encapsulated Pesticide	Fibers Morphology/Diameter	Fibers Application
Thitiwongsawet et al. (2010) [174]	CA/dimethylacetamide (DMA)	2,6-Dichloro-4-nitroaniline	Smooth/241–320 nm	Design for a controlled-release system
Xiang et al. (2012) [175]	PLA: cellulose nanocrystal/dimethylformamide (DMF)	CB (model pesticide) Thiomethoxan	Smooth/326 $\pm$ 139 nm 335 $\pm$ 144 nm 306 $\pm$ 90 nm	Design for a controlled-release system control whiteflies
Castañeda et al. (2014) [176]	PVP/ethanol, DMF	Vitamax® Thiram®	Fused fibers, beads	Rice seed coating
Souza et al. (2016) [177]	PLA/Hexafluoroisopropanol (HFIP)	Linalool	Smooth/176–240 nm	Design for a controlled-release system
Roshani et al. (2016) [178]	PLLA/DMF	Thiram	Bead-free/no specific value of diameter	Design for a controlled-release system
Latha et al. (2019) [179]	PVA/acetronile organic	Tebuconazole	Beads-free/293–373 nm 405.9–556.7 nm	Design for a controlled-release system
Farias et al. (2019) [180]	CDA/acetic acid, DMA	Abamectin (Abm) Fluopyram (Flp)	Smooth, defect-free/ 335 $\pm$ 81 nm, 242 $\pm$ 12 nm, 129 $\pm$ 28 nm	Soybeans seeds coatings antifungal
Ciera et al. (2019) [181]	PVA/water	Permethrin Catnip oil, chili oil, PMD	Bead-like, porous/ 386 $\pm$ 55 nm, 408 $\pm$ 67 nm	Repellent

Table 5. Cont.

Reference	Polymers/Solvent	Encapsulated Pesticide	Fibers Morphology/Diameter	Fibers Application
Gao et al. (2020) [182]	HP β CD/water	TBZ	Beadless, uniform/ 370 $\pm$ 198 nm	Design for a controlled-release system antifungal activity (<i>Gibberella</i> sp.)
Gao et al. (2021) [183]	HP β CD/water	Thiram	Homogeneous, beads-free/ 270 $\pm$ 133 nm	Design for controlled release antifungal activity (<i>Gibberella</i> sp.)
Ryan et al. (2020) [184]	Nylon-6,6/formic acid	Picaridin	Defect-free/279 $\pm$ 76 nm	Design for a controlled-release system
Mukiri et al. (2021) [185]	PVA	<i>Methylobacterium aminovorans</i>	Defect-free/ 93.30 nm–166.1 nm 164.8–218.2 nm 194.4–303.2 nm	Design for controlled release viability microbial
Das et al. (2023) [186]	H-P β CD/PVA	ATZ	Homogeneous, bead-free	Design for a controlled-release system activity herbicide (<i>L. sativa</i>)
Saileela et al. (2023) [11]	PVA/acetone	Pendimethalin	Bead-free/ 231.6–313.5 nm 182.7–261.2 nm 143.2–210.3 nm	Seed coating (black gram seeds) germination and growth
Merlini et al. (2023) [187]	PLA/DMF, dichloroethane (DCE)	ILS	3D, randomly, continuous, porosity rough surfaces/ 0.55 $\pm$ 0.13 μ m–1.00 $\pm$ 0.20 μ m	Aphid-repellent activity (<i>Acyrtosiphon pisum</i>)

9. Conclusions

The encapsulation of agrochemicals using the electrospinning method is a way to immobilize different types of molecules for greater effectiveness. However, the magnitude of the impact results depends on the multiple factors involved. Most of the reports presented described the effect on the morphology and diameters of the nanofibers when the different parameters of the electrospinning process were adjusted. In general, they reported that the fibers obtained presented a bead-free or defect-free morphology; the diameter of the fibers increased due to the incorporation of the active ingredient. In some investigations, the influence of viscosity, conductivity and surface tension was reported, which varied depending on the composition of the encapsulant system. The nanofibers were designed as controlled release systems and applied as carriers or coatings for fertilizers, antifungal compounds, herbicides, repellents, and microorganisms. When the nanofiber mats with agrochemicals were compared with polymer films, the fibers turned out to be more effective since they allowed a more controlled release of fertilizers and greater gas circulation, unlike the films. When exploring the use of electrospun fiber mats as a seed coating, they confirmed that the polymer used as a coating did not affect the physiological quality of the seeds, which facilitated enhanced water absorption, accelerating the imbibition process and consequently increasing the germination percentage in addition to providing better protection during storage. Undoubtedly, there are still challenges that mainly correspond to a detailed understanding of the real response of these nanoagrochemicals, given that most experiments are carried out under controlled laboratory conditions and very few experiments are carried out in real environmental contexts. In summary, while it may still be some time before nanotechnologies are widely used to address the main issues facing agriculture today, they do offer benefits in terms of environmental protection and productivity that will help ensure the sustainability of agriculture and food production in the future.

Author Contributions: J.C.-O. wrote the manuscript, and E.C.-O. and R.V.-B. verified and edited it. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflicts of interest.

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