

Electrospun fibrous constructs towards clean and sustainable agricultural prospects: SWOT analysis and TOWS based strategy assessment

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ABSTRACT

Clean and sustainable agricultural production that is organic and minimally assisted by chemicals is one of the major challenges of the 21st century. In view of the unpredictable climatic changes, destruction of natural resources, loss of biodiversity, contamination of soil-water interfacial ecosystems due to overuse of fertilizers and pesticides, and towering food demands with a fast-multiplying population. Therefore, polymer-based electrospun micro/nanofibers and their structured assemblies offering design-versatility, manufacturing-viability, and economically efficient scalability can significantly contribute to the agrotechnological revolution and thus exhibit the imminent potential to reform the agricultural system by promoting both yield and environmental sustainability via a significant reduction in the application of chemicals. Agrochemical-based fibrous assemblies with diversified micro/nano-morphological attributes can potentially boost agricultural production, leading to a paradigm shift from the conventional “sow (seeds)-throw (fertilizers)-spray (pesticides)” to smart and clean “fix-it and forget-it” approach for sustainably ensuring agro-yield, agro-practices, agro-crop quality, and agro-economy. However, the viability of the application of such functionally efficient fibrous structures in agriculture and their qualitative parametric analysis and assessments remain unexplored till date. The current analytical overview summarizes the applications of electrospun assemblies in a variety of controlled agrochemicals (such as fertilizers, pesticides, and biocontrol agents) delivery systems, seed coating, sensors for soil and crop quality, and protective clothing for farmers. Integrated decision-making methodologies (SWOT and TOWS) were applied to evaluate and develop effective and adaptable strategies to improve the production chain and promote environmental sustainability. The review extends further to the potential concerns associated with electrospun mats in agricultural applications along with some novel insights to address the apposite challenges so as to foster prospective designing and commercialization of innovative biodegradable and sustainable nanostructured materials for precision agriculture.

1. Introduction

The current growth rate of the world population (with its projected number at ~ 8 billion) points to an enormous increase in the demand for food (which is likely to increase by ~ 70% by 2050) and has now become a major challenge for agricultural sectors, with the various biotic and abiotic stresses impacting crop yield and crop quality (Mittal et al., 2020). Therefore, the pertinent question is, how to enhance the agro-output to feed the population in the most sustainable and economical way? According to a survey by the Food and Agriculture Organization of the United Nations (FAO), various plant diseases and invasive insects cost the world economy ~ \$220 billion, and ~US\$70 billion respectively, while the damage caused by plant pests may lead to

~ 20–40% loss in the total crop production (Kumar et al., 2021; Charaya et al., 2021; Sawicka and Egbuna, 2019). Furthermore, climate change, evolving species of pests and pathogens afflicting plants, shrinking arable land, and deficits of clean water are alarmingly affecting the agricultural sectors in terms of output, employment, efficiency, and its related secondary (industrial) and tertiary (service) sectors (Doering and Sorensen, 2018; Raven and Wagner, 2021; Das et al., 2021). Numerous approaches have been adopted to improve the crop yields such as the deployment of agrochemicals (fertilizers, pesticides, biocontrol agents, etc.), genetic modification of the crops, plant breeding, designing diagnostic tools for early detection of plant disease, introduction of vulnerable and smart agricultural practices to empower small-scale farmers, implementing and integrating the circular economy and

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agriculture 4.0/5.0 practices such as internet of things (IoT), drones, 3D food printing, robotics, machine learning, cellular agriculture nano-technology, microalgae bioreactor, and sensors connected to precision farming technology, and artificial intelligence (Benyam et al., 2021; Azadi et al., 2021; Klerkx and Rose, 2020). For instance, nano-sensors and other field-sensing devices can also be used for quantitative estimation of soil nutrients, soil moisture, plant pests (weeds, insects, rodents, etc.), pathogens affecting agro-crops, and so forth (Lakhia et al., 2018).

The excessive use of agrochemicals (like fertilizers and pesticides) in the agricultural sectors has endangered food safety and quality, leading to excessive loss of energy and water. According to FAO reports, the average pesticide application per hectare of cropland has increased by ~1.09 kg during the period 1990 to 2017 and is projected to increase ~300% by 2050 (Pirzada et al., 2020; Tilman et al., 2001). Similarly, as per the USDA estimation, the application of pesticides to the major crops in the USA was observed to be enhanced from ~196 million in 1960 to ~516 million pounds in 2008 (Fernandez-Cornejo et al., 2014). Such a global rise in pesticides production and its subsequent applications has targeted the organisms at lower trophic levels due to escalated levels of soil, air, and water pollution, which in turn has killed many non-target organisms like small mammals, bees, fish, and birds (Sharma et al., 2019). Over-exposure to pesticides causes unintentional pesticide-induced poisoning, i.e., up to ~860 million (~44%) agricultural workers annually (Boedeker et al., 2020). Reportedly, > 90% of pesticides are lost via wind, photodegradation, evaporation, hydrolysis, surface water drainage, soil leaching, and microbial activity, leaving a small percentage to be biologically available for targeted organisms (Tudi et al., 2021).

Nowadays, synthetic fertilizers such as urea and Nitrogen-Phosphorus-Potassium (NPK) are frequently being used to improve crop yield and crop quality. However, the high water solubility of NPK fertilizer may result in the surface run-off to waterbodies and/or leaching to groundwater via soil and infiltrating water (Noeaid et al., 2021). Similarly, urea, an important source of nitrogen for plants, may result in ammonia formation via dissociation and hydrolysis caused by soil enzymes. This may undesirably increase the soil alkalinity due to ammonia release in the soil ecosystem and environment. As per the database estimated by Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) and World Input-Output Database (WIOD), the total transfer of embodied agricultural N_2O and CH_4 emissions via international trade were at ~54.6% and ~45.4% respectively, with a total emission of ~622.4 Mt CO_2 -eq (metric tons of carbon dioxide equivalent) in 2014 (Han et al., 2019). The inhalation and/or dermal exposure to urea may result in adverse health issues (like eye irritation, nausea, and asthma) among farmers (Zafar et al., 2021). The inefficient assimilation of all the fertilizer nutrients at the seed germination and sprouting stage usually results in continuous erosion of excess nutrients to water bodies thereby giving rise to eutrophication. To ensure the sustainability of the agroecosystem, biofertilizers and/or manures were profoundly accepted as an alternative to chemical fertilizers due to their positive effects on the physical and biochemical properties of soil (such as lowering the bulk density of soil, increasing water holding capacity, cation exchange capacity (CEC), build-up of beneficial soil-microbes, improve soil structure and enhance stable soil aggregates). However, the use of biofertilizers and manures is associated with various constraints such as shorter life span, seasonal demand, higher cost, unavailability of set-up space and lab utilities, production, and storage, thereby affecting the soil characteristics like acidity, salinity, drought, water logging, etc. In this background, there is a dire need to develop novel strategies (like “farm to fork”) and technologies (remote-controlled based spraying, moisture sensing, weeding, animal and bird scaring, smart vigilance, etc.) in order to effectively deal with the issues such as the global need of food safety, sustainable agricultural practices, utilization of green agrochemicals and avoidance of water contamination/eutrophication, etc., to promote efficient development

of sustainable agricultural production systems and thereby meeting the provisions of the 2030 Agenda. Some of the emerging sustainable approaches to facilitate a sufficient supply of safe and high-quality food with minimal environmental impact are the encapsulation of agrochemicals (Sampathkumar et al., 2020), formulating, and devising biosensors (Kundu et al., 2019), seed coating (Farias et al., 2019), and deployment of genetically modified crops (Kamle et al., 2017). Recently, the design and development of engineered electrospun micro/nanofibrous mat with tailorable physicochemical attributes that are compatible to (a) facilitate controlled release of fertilizer, pesticides, and other plant growth hormones, (b) promote land use efficacy by resorting to artificial agricultural platforms and (c) enhance soil ability to retain water moisture without interfering and deteriorating soil alkalinity and pH have garnered immense interest (Noruzi, 2016; Meraz-Dávila et al., 2021; Hussain et al., 2019).

Electrospinning of polymeric micro/nanofibers from melts and/or solutions with very high surface-volume ratio, complex interconnected porous structures with excellent pore interconnectivity, and diverse fibrous morphologies (Wang et al., 2019) have been known to exhibit remarkable potential in numerous applications such as tissue engineering, pharmaceutical storage, wound healing, sensors, sound absorption, amplification, water filtration and agricultural membranes (Ibrahim and Klingner, 2020). The electrospun fibrous assemblies have been known to exhibit significant potential in drug release applications (Sharma and Satapathy, 2021a,b; Sharma et al., 2022). Such engineered nanostructured materials can also be extensively used for the encapsulation and controlled release of agrochemicals like pesticides, fertilizers, and biocontrol agents not only to regulate their overuse but also to minimize the damage due to atmospheric oxidation of such agrochemicals. These electrospun nanofiber-based biosensors and sorbents can also be used for the precise estimation of residual pesticides in crops and soils. Electrospun sub-micron fibrous mats/membranes/assemblies exhibit excellent potential for designing protective clothing for farmers to prevent dermal exposure and permeation of agrochemicals into the body.

Such fibrous assemblies can be manufactured on large scale with a wide range of fiber diameters and can potentially boost the coverage of agricultural requirements. If explored efficiently, this class of porous materials may pave the way for a paradigm shift from the conventional “sow-throw-spray” to smart and organically engineered “fix-it and forget-it” approaches while conforming to the clean and sustainable manufacturing routes of such functionally diverse materials in sustainably ensuring agro-yield, agro-practices, agro crop quality, and agro-economy. In this background, the present review not only critically summarizes the current advances and applicability of the engineered electrospun nanofibers in agricultural applications such as encapsulation of agrochemicals, seed coating, biosensors generation, and providing protective clothing to the farmers but also traverses beyond to discuss some future perspectives associated with the present challenges in the development of engineered nanofibers and their derived composites for boosting agro-production and sustainability, so as to pave a way for the researcher to strategically design novel materials for agricultural applications. Qualitative decision-making models using SWOT (strength-weakness-opportunity-threat) analysis and beneficial strategic designs using the TOWS matrix have also been explored.

2. Methodology

This paper provides an overview of the current advances and applicability of the engineered electrospun micro/nanofibrous assemblies for strategic designing of novel future materials for agricultural applications such as carrier systems for controlled release of agrochemicals (fertilizers, pesticides, and biocontrol agents), seed coatings, biosensors, and protective clothing for the farmers for boosting agro-production and affirming sustainability.

A systematic literature review was performed by adopting a three-

step process from September 2021 to January 2022. The steps involved are, (i) identification and collection of materials, (ii) screening of the articles and collection of data, and (iii) reporting and dissemination. The scientific databases that have been used for the literature search were mostly obtained from peer-reviewed papers in addition to conference proceedings and book chapters. The databases and cited literature were collected from Science Direct (<http://sciencedirect.com>), Google Scholar (<http://scholar.google.ca>), Web of Science (<http://webofknowledge.com>), and Springer Link (<http://springerlink.com>). All the relevant articles (~227) were thoroughly investigated through titles, abstracts, and conclusions, out of which ~113 directly related articles were included in this review to understand the significance and intensity of the study. The collected data was analyzed in detail and the outcomes of the analysis have been reported in the article with relevant references. Research on electrospun mats for various emerging applications started in 2014, however, the research progress and development of the type of new generation agro-augmenting materials in the context remained kinetically lagged and as a consequence, the exploration of this topic remained largely scatted and unstructured in the literature. Therefore, the contextual review showcases the progress in the performance effectiveness of the micro- and nano-structured agricultural devices over the conventional agricultural approaches which in turn influence the various facets of agriculture including plant growth, soil fertility, biodiversity, sustainability, and ecosystem at large, and thereby fulfilling the 2030 sustainable development agenda. The development of engineered fibrous assemblies for boosting agro-production and ensuring sustainability thereby paves a way for the community of researchers and scientists to strategically design novel materials for modern agricultural practices. The manuscript also includes the future scope such as minimizing polymeric material usage, agrochemical wastage, and exposure so that issues related to micro-plastic contamination and chemicals and pesticide-induced eco-toxicity can be avoided. Further, a systematic SWOT-assisted qualitative analysis for parametric assessment of various scenarios and favorable strategic conceptualization as a guideline to implement such material advancements has been proposed, using the data available in the literature.

3. Electrospun nanofibers

Over the past decade, numerous methods have been developed for the fabrication of nanofibers, encompassing both bottom-up (phase separation, drawing process, self-assembly, interfacial polymerization) and top-down (melt blowing, electrospinning, carbon dioxide (CO₂) laser supersonic drawing (CLSD), three-dimensional printing, melt electrospinning, islands-in-the-sea) approaches (Alghoraibi and Alomari, 2018). Nowadays, the electrospinning technique is being rigorously explored for the fabrication of porous 1-D and 3-D graded assemblies. A wide range of materials, from organic to inorganic or from small molecules to supramolecules, can be electrospun using various set-ups such as side-by-side, emulsion, coaxial, multi-jet, etc., as shown in Fig. 1C. Additionally, it offers precise control over aspect ratio, morphology, porosity, and pore size distribution, thereby making these fibrous assemblies an ideal candidate as a porous membrane with an open-pore structure (pore size: 10^1 nm– 10^3 nm), high surface area, and high gas permeability. The high encapsulation efficiency of bioactive materials (such as drugs and antioxidants), ease of functionalization, target-specific tailorable microstructures, and mechano-structural integrity encouraged their applicability in numerous aspects of agriculture (Locicento et al., 2019; Sharma and Satapathy, 2021c). Polymers are mostly used for the fabrication of electrospun fibers due to their cost-effectiveness and easy processability of the polymeric solutions and melts, resulting in the hassle-free fabrication of nano/micro-scale fibers in the presence of continuous electrostatic potential (Ibrahim and Klingner, 2020).

A typical electrospinning set-up comprises of a syringe pump with a metal needle, a high voltage electric field system, and a metal collector as shown in Fig. 1A. A molten polymer or polymeric solution with appropriate molecular entanglement is initially allowed to flow through the metallic capillary at a constant flow rate, which is maintained by a syringe pump. Application of an appropriate electrostatic potential to overcome the surface tension of polymeric solutions results in the formation of charged jet, i.e., stretched and elongated along with simultaneous solvent evaporation prior to deposition on the oppositely charged grounded collector (Xue et al., 2019). Several electrospinning process parameters govern the size, shape, thickness, diameter

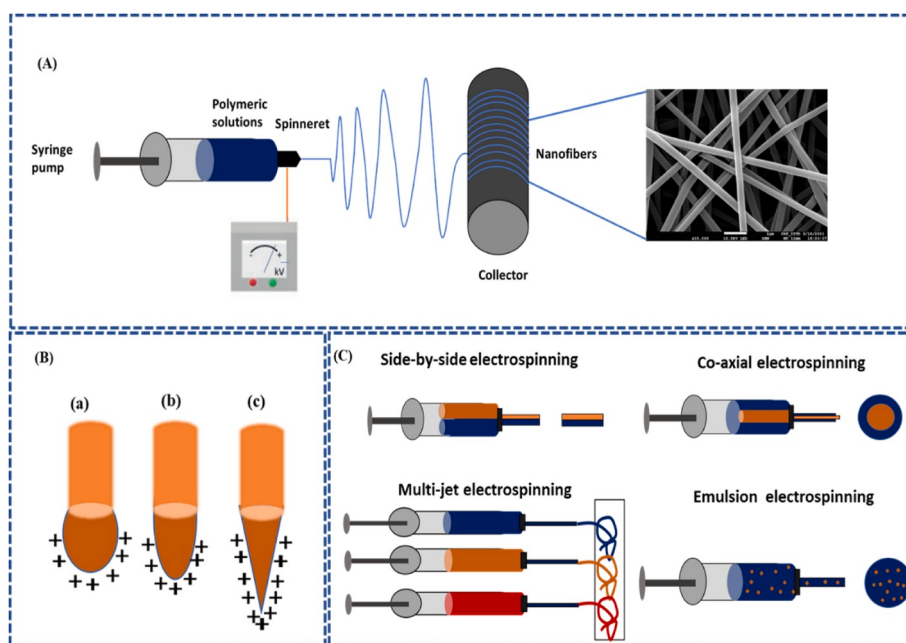


Fig. 1. Schematic representation of (A) typical electrospinning set-up used to prepare polymeric nanofibers. (B) different stages of Taylor cone formation [(a) surface charges are induced due to the applied electric field (b) pendant drop elongation (c) deformation of the pendant drop to form a fine Taylor cone] (C) different types of electrospinning process (multi-jet, emulsion, side-by-side and co-axial).

distribution, porosity, spinnability, and desired morphological attributes of electrospun nanofibers such as solution properties (polymer relative molecular mass, viscosity, concentration, surface tension, conductivity), operational parameters (voltage, orifice diameter, receiving distance), and environmental parameters (temperature, humidity, and airflow) (Can-Herrera et al., 2021). Nozzle configurations (single-jet, multi-jet, and coaxial), and polymeric feed types (aqueous, melt, or emulsion), tend to significantly influence the morphological and physicochemical attributes of the desired electrospun fibers.

Conventionally, electrospinning was being used to fabricate single polymer-based nanofibers, but, nowadays, novel three-dimensional structures are also being designed, and broadening the scope of these fibers in their application from multicomponent/morphology for kinetically controlled and compositionally graded release, protection, and sensing applications (Ibrahim and Klingner, 2020). The reduction in the average fiber diameters to micro/nanoscale not only attributed to the enhancement in surface-to-volume ratio and mechanical properties (e.g., stiffness and resistance to traction) but also facilitates the tunability of physicochemical attributes (conductivity, percolation limit, and degree of hydrophobicity) of the resultant electrospun mats, thereby enhancing their applicability in designing smart and sustainable devices for numerous emerging applications (Ibrahim and Klingner, 2020). However, the potential application of electrospun nanofibers in the agricultural sectors is relatively novel and has not yet been well-established. Some of the challenges associated with polymeric nanofibers are biodegradability, low choice of solvent mixtures for fabrication, and cost-effectiveness. For example, some biodegradable and biocompatible polymers such as neat chitosan are not electro-spinnable because of the high viscosity, strong inter-, and intra-molecular bonds (Garcia et al., 2021). In order to favorably address the present limitations, including the use of biodegradable biopolymers, their blends, and copolymers, large-scale production of desired electrospun fibers, and their post-processing modifications, are being currently explored. The uses of more advanced electrospinning assemblies (like coaxial, multi-jet, hollow, side-by-side, etc.) have lately been designed and explored, instead of conventional electrospinning setup, for widening the scope of applicability and to meet the crop and plant-specific demands pertaining to the controlled release of soil nutrients, pesticides, encapsulation of seeds and their protection on a gradient-based precision.

4. Electrospun bio-based materials

As a versatile polymer processing technique, electrospinning has gained prominence for the fabrication of several polymers ranging from natural biopolymers (such as chitosan, starch, cellulose, collagen, and gelatine) to synthetic biopolymers [such as polyglycolic acid (PGA), polycaprolactone (PCL), polyvinyl alcohol (PVA), polyethylene glycol (PEG) and polylactic acid (PLA)] (Keshvaridoostchokami et al., 2021). However, the applicability of electrospun fibers and their efficacy in agricultural sectors remains largely unexplored. The designing of agricultural devices not only to refine and escalate production but also to promote a sustainable agro-economy has become a thematic challenge. Nowadays, nature-derived polymers and their blends are widely used in specialty crop production systems due to their biodegradability via numerous enzymatic catalytic mechanisms propelled by microorganisms and non-enzymatic pathways like chemical hydrolysis (Sampathkumar et al., 2020). Polymer-based nano-fertilizer (such as chitosan and hydroxyapatite), and nano-pesticides (such as cyclodextrins, chitosan, and alginate) are reportedly being used to improve soil fertility via an efficient supply of nutrients and to provide protection against herbs, weeds, and pests. Similarly, biopolymer-based controlled release systems have been extensively explored to address conventional agricultural challenges (environmental contamination and human health concerns), by improving the functional efficiency of fertilizers, pesticides, pheromones, and growth regulators (Milani et al., 2017;

Sampathkumar et al., 2020). Bio-based superabsorbent polymers (such as PVA, PAM, and acrylate-based polymers) and their mulches in combination with the fertilizers exhibited sustained release of nutrients, improvement of soil quality, and enhancement of fertilizer efficacy. For instance, Zafar et al. prepared a controlled release fertilizer (CRF) system using PVA/starch biodegradable nanocomposite, modified with different combinations of maleic acid (MA), citric acid (CA), and acrylic acid (AA) for coating urea pills (Zafar et al., 2021). Such coated fertilizer system exhibited excellent urea release efficiency (~70.10%) with good water uptake potential. Some aspects of various advanced polymers used in agriculture-related applications are shown in Fig. 2.

5. Electrospun mats and assemblies for agricultural application

Conventional farming practices like sowing seeds, spraying pesticides, and inadequate usage of manures and biofertilizers may no longer be able to address the food security concerns due to rapid population growth. The global transition toward sustainable, farm-labor efficient, and IoT-based agricultural practices (Agriculture 4.0) present a plausible alternative to address the growing concerns. Some major concerns are associated with the increase in toxic pesticide-resistant pests, and irreversible soil contamination due to indiscriminate use of subsidized fertilizers, thereby compromising the integrity of the environment and the aim of the 2030 agenda for sustainable development (Vågsholm et al., 2020). Nowadays, precision in agriculture is focused on designing engineered and renewable nanomaterial-based green nanotechnology for the controlled delivery of agrochemicals, by adopting an encapsulation pathway, thereby leading to enhancement in resource efficiency and resilience of the agro-ecosystem. Additionally, the use of green nanomaterials reduces the emission of greenhouse gases (like methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2)) from the agricultural domain, thereby minimizing the sustainability concerns in modern agricultural practices. For instance, nano-zinc oxide (ZnO) and nano-rock-phosphate are used for enhancing the efficiency of nitrogen uptake by simultaneously reducing the N_2O emission from soil (~30–40%) (Kundu et al., 2016). Further, bio-inoculants (beneficial endophytic or rhizosphere microorganisms) are also being used to promote plant growth and resilient agricultural practices while reducing greenhouse gas emissions and mitigating the use of chemical pesticides and fertilizers (Kumar et al., 2022).

Among the one-dimensional nanostructures that can be used for the agricultural sectors, polymeric nanofibers are particularly favored due to their excellent physicochemical attributes. Such modified and deliverable nanoproducts aid to improve the nutrient uptake and augment the plant growth and crop yield, when the fertilizers, pheromones, pesticides, and growth regulators are suitably combined and applied (Shang et al., 2019). For instance, electrospun nanocarriers are being used for the transport and delivery of pesticides at a slower and more controlled release rate to facilitate “precision farming”, i.e., selectively targeting agricultural production, without inflicting significant water and soil pollution. Such materials can be used to design nano-sensors and other quantitative estimation devices for the detection and measurement of nutrient levels in plants, pest populations, pathogens, weeds, moisture, and soil fertility, so as to monitor plant growth by providing critical data for precision farming practices for minimizing costs and maximizing yields (Supraja et al., 2020). Therefore, the current advances in electrospun fibers as agricultural devices to envision a fix-it and forget-it approach as a next-generation sustainable agriculture philosophy are discussed in the subsequent sections.

5.1. Encapsulation of agrochemicals

Numerous agrochemicals (such as fertilizers, pesticides, growth promoters, and biocontrol agents) can be encapsulated by using a range of hierarchically designed and compositionally appropriate electrospun fibers obtained by adopting different approaches of mixing such as (a)

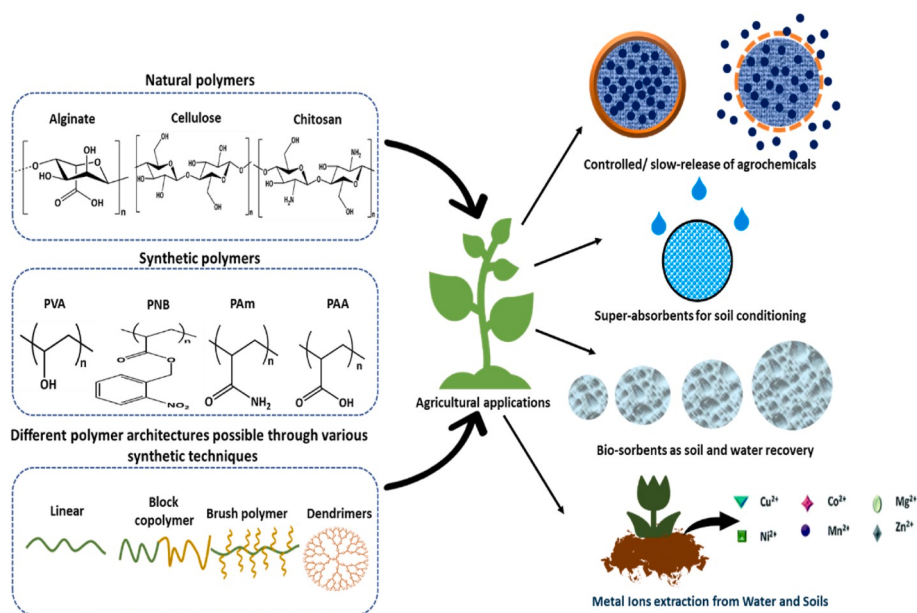


Fig. 2. Representative schematic for different aspects of advanced polymers used in agriculture-related applications.

uniform dispersion of agrochemicals in polymeric precursor solution, (b) fabrication of agrochemical loaded electrospun nanocarriers, (c) surface agrochemical treatment of polymeric electrospun nanofibers, and (d) coaxial electrospinning, as shown in Fig. 3A. Coaxial electrospinning is one of the most promising approaches for encapsulating agrochemicals so as to modulate their release efficacy (Torkamani et al., 2018). Coaxial systems mostly comprise of a single special nozzle with two concentric capillaries with inner and outer needles ejecting the polymeric precursor solution forming the core and shell respectively, as illustrated in Fig. 4A. The encapsulated agrochemicals forming the core of the polymeric precursor shell solution are mostly employed for facilitating target-specific controlled release. Reportedly, the degree of dissimilarity between two polymeric systems, in terms of compositional, physical, and rheological characteristics tend to govern the release efficacy of resultant core-shell nanofibrous assemblies (Naeimrad et al., 2018). The fiber undergoes various types of diffusion and

degradation-assisted release mechanisms on interaction with aqueous media, as shown in Fig. 3B (Milani et al., 2017). In the diffusion mechanism, the polymeric membrane withstands the development of osmotic pressure, and the core fertilizer is released slowly via diffusion, where concentration and/or pressure gradient, is the driving force. A schematic representation of the diffusion-based release mechanism of the fertilizer from the surface of the conventional solid thick membrane and multi-layered porous fiber membrane is illustrated in Fig. 3C. The figure shows that the fertilizer release from the thick film initially follows a rapid diffusion-controlled release mechanism, which decreases with time. The understanding of the release mechanisms and kinetics are essential for modulating the release behaviour by suitably altering the structural and compositional aspects, such as, porosity, polymeric composition, agrochemical loading, and average fiber diameters.

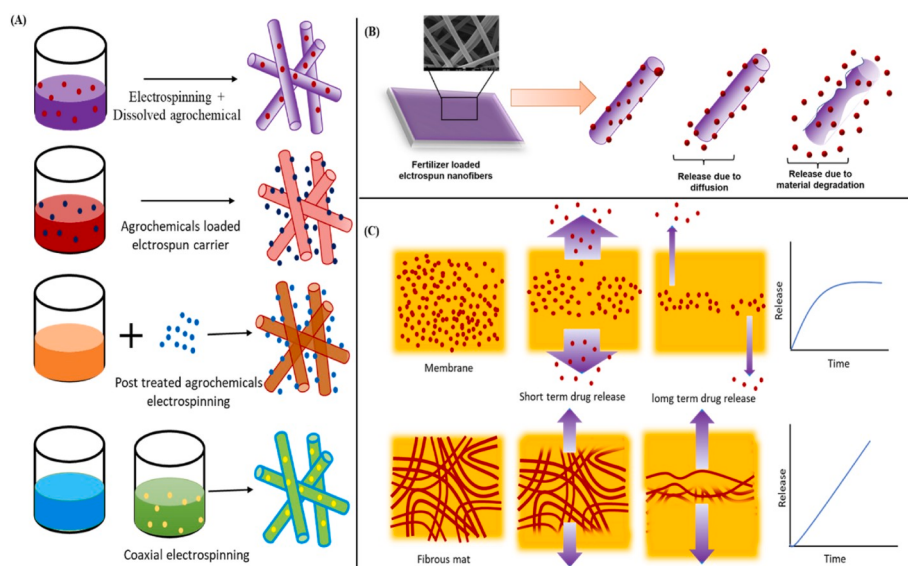


Fig. 3. Schematic representation of A) different strategies for loading of agrochemicals into the electrospun polymeric nanofibers, B) fertilizer release from fibrous mats by diffusion followed by degradation, and C) controlled fertilizer release from solid films/membranes and multi-layered fibrous mats along with its release kinetics over time.

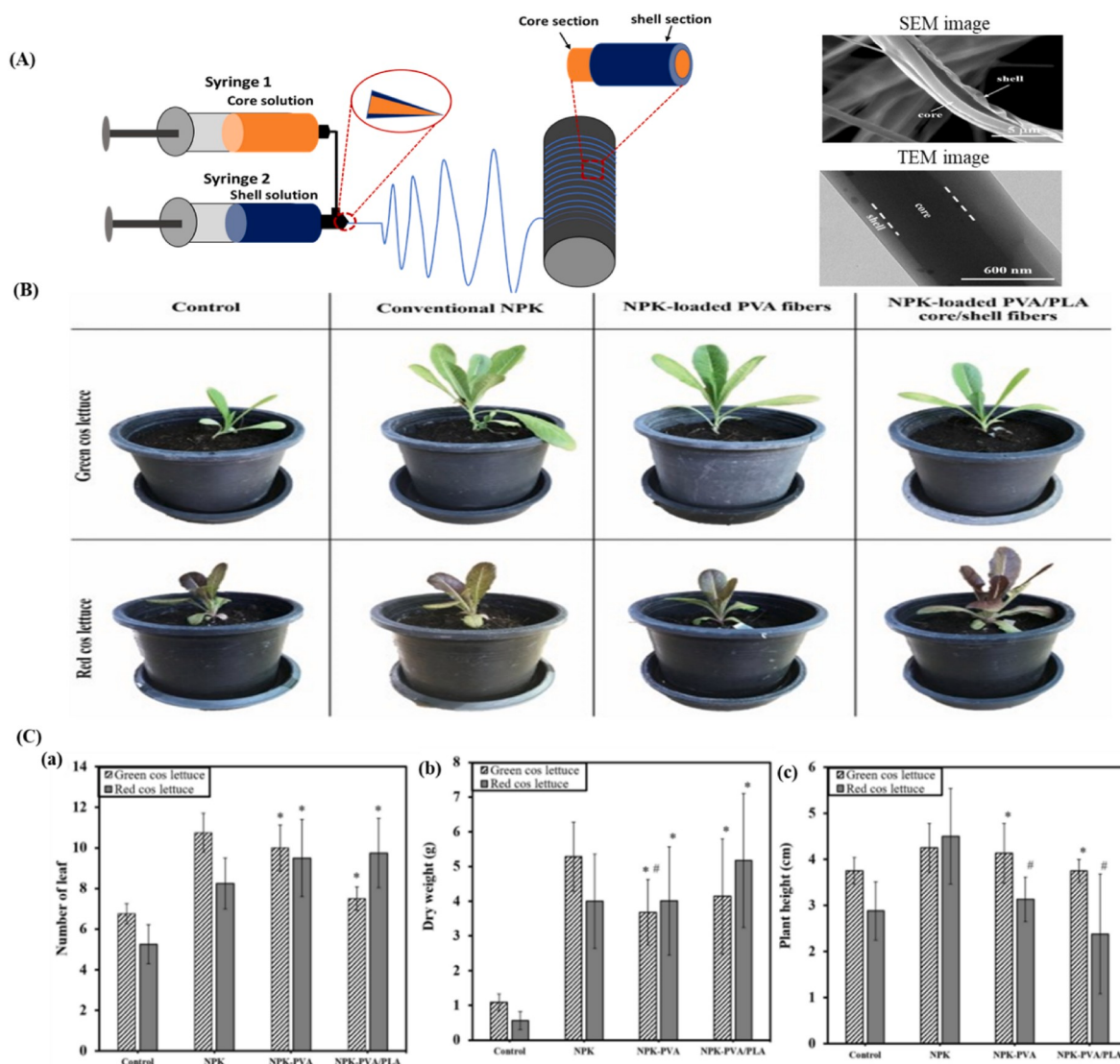


Fig. 4. Schematic illustration of (A) core-shell electrospinning set-up with surface morphology of core-shell nanofibers (SEM and TEM images), (B) visible assessment growth of green cos lettuce (top row) and red cos lettuce (bottom row) after 45 days of planting for NPK-loaded PVA/PLA based core/shell fibers, (C) plant growth assessment of treatments, presenting the results of (a) leaf number (b) dry weight, and (c) plant height of green cos lettuce and red cos lettuce (Noeaid et al., 2021).

5.1.1. Encapsulation of fertilizers

Contemporary agricultural practices mostly depend on the use of manures, and fertilizers, which are used not only to maintain soil fertility and increase yields but also to improve the quality of crops. However, large proportions of conventional fertilizers are mostly lost in the field applications resulting in significant economic losses due to increased input costs for cultivation and severe environmental pollution due to randomly scattered fertilizer on unwanted buds washing off to waterbodies causing eutrophication (Martínez-Dalmau et al., 2021). The most promising strategy to address this limitation is the introduction of slow- or controlled-release of fertilizers, in which the active nutrients are released in a kinetically modulated manner, so as to enhance the nutrient efficacy, crop yield, and agroecological resilience. Moreover, fertilizer loaded electrospun fibers restrict the direct interaction of fertilizer with water, microorganism, soil, and such loaded fibers tend to offer stimulated release to be directly absorbed by the plants. Some of the polymers that are extensively used in the controlled release of fertilizers are given in Table 1.

Castro et al. prepared wheat gluten-based electrospun fibers (~40 μm), with an entrapment efficiency of ~86%, to facilitate the slow and sustained release of urea (Castro et al., 2012). However, the release of

these fertilizers is accelerated (~56% of the fertilizer was released in the first 10 min, and the release reached ~98% after ~5 h) and such rapid release of urea did not follow the desirable slow-release criteria. A similar study has been carried out by Chen et al. where starch-g-PLLA cast membranes were used as biodegradable carrier material for the encapsulation of urea, exhibiting a maximum entrapment efficiency of ~81% (Chen et al., 2008). To desirably modulate the extent of entrapment efficiency, electrospinning remains more suitable for obtaining membranes for encapsulation of substances than the film casting process. In a similar study, Sonora et al. also demonstrated the influence of the temperature and pH on the release efficacy of urea from wheat-gluten electrospun membranes along with their potential applications at pH ~7 and a soil temperatures range of ~25 °C and ~40 °C (Sonora, 2018).

In an advanced approach, the co-axial electrospinning technique was used to prepare core-sheath nanofibrous mats with PLA-fertilizer as core and polyhydroxy butyrate (PHB) as the shell, so as to facilitate the slow and prolonged release of fertilizer from the membranes (Kampeerappun and Phanomkate, 2013). The release kinetics of such co-axially electrospun core-shell structures showed encapsulated fertilizers to have undergone a significant reduction in release rate (~1 month), and

Table 1

Overview of polymeric electrospun nanofibers used in controlled release fertilizers system (CRFs).

Polymers	Solvent system	Fertilizer	Electrospinning	Properties	Nutrient release performance in aqueous media	References
Wheat gluten	Ethanol/2-mercaptoethanol	Urea (~40 wt %)	Simple electrospinning	Easy availability, 100% natural, biodegradable, inexpensive material Porous structure and strong hydrogen bonding interactions between urea and wheat gluten proteins promote the prolonged-release	Urea release rate ~ 98% after 300 min	Castro et al. (2012)
PVA/PEO	Deionized water (DI)	Urea (~25 wt %)	Simple electrospinning	High loading efficiency of active urea in PEO than PVA-based electrospun mats	–	Hassounah et al. (2014)
PHB- (shell)/ PLA-(core)	CF/DMF (90:10)-shell, DMF-core	NPK (20–160 wt%)	Coaxial electrospinning	Biodegradable, biocompatible modulated surface wettability, high fertilizer loading capacity, controlled drug release	Controlled fertilizer release of urea for ~1 month without degradation and ~3 months post degradation Dependence of fertilizer release rate on the feed rate of core electrospinning solution (For example, at 300 h, the cumulative fertilizer release was ~57.77% and ~87.60% when core solution feed rate was at 0.6 and 2.2 ml/h, respectively)	Kampeerapappun and Phanomkate (2013)
PVA-(shell)/ PLA-(core)	DI-shell, DCM: DMF-core	NPK (7.5 wt%)	Coaxial electrospinning	Controlled degradation behavior and fertilizer release, without any chemical cross-linking agents Higher encapsulation efficiency (~42%) than PVA monoclinic fibers (~32%)	Initial burst release of NPK (~60%) was found within 3 days, followed by a gradual increase to ~ 80% post 28 days, and the release maintained at ~ 90% post 90 days in an aqueous medium	Nooeaid et al. (2021)
PHB -outer layer/ (PLLA) inner layer	DMF: CF (30:70 v/v)/CF: acetone (3:1 v/v)	Urea (10–40 wt %)	Customized electrospinning apparatus	Double-layered hollow nanofiber yarn (lightweight, high volume, and large surface area); promote encapsulation and sustained release of fertilizers.	Urea release rate of double-layer hollow nanofiber yarn was ~24% compared to ~82% for control and ~79% for single-layer hollow nanofiber yarn	Javazmi et al. (2020)
PHB external layers and PLLA middle layer	DMF:CF (30:70 v/v)/CF: acetone (3:1 v/v)	Urea (10–40 wt %)	Customized electrospinning apparatus	Triple-layered urea-impregnated nanofibrous assemblies: promote the sustained and prolonged release of urea fertilizer (>3 months).	Low release rate, i.e., <50% for triple-layer nanofiber mats than single layer mats, i.e., >80%	Javazmi et al. (2021)

continued till complete decomposition (~3 months). Such co-axially electrospun core-shell structures elucidated that the release was controlled by a diffusion mechanism instead of degradation, as the release has reached its completion prior to polymeric decomposition. NPK-type fertilizer release was observed to vary with PHB shell thickness, i.e., the fertilizer diffusion was faster for electrospun fibers with thinner shells. Therefore, structurally smart core-sheath nanofibers are being used for the controlled release of fertilizers which not only protect the nutrients but also promote effective plant growth. In another study dealing with the PVA and PEO as two different polymers, Hassounah et al. developed three-dimensional urea-loaded nanofibrous polyethylene oxide (PEO) and PVA assemblies (Hassounah et al., 2014). It was observed that PEO exhibited better urea encapsulation ability than PVA for active urea release enhancing the precision in availability of urea as a fertilizer. In a recent study, Nooeaid et al. fabricated NPK-loaded engineered core/shell electrospun nanofibers using eco-friendly polymers such as PVA at the core with PLA forming the shell (Nooeaid et al., 2021). These core/shell fibers reportedly enhance the stability, by reducing the burst release behavior, thereby facilitating controlled and prolonged release of plant nutrients. The core/shell fibers with micro-sized average fiber diameters exhibited higher encapsulation efficiency compared to the individual PVA-based fibers. The plant growth assessment for green cos lettuce and red cos lettuce for ~45 days performed using NPK-loaded PVA and NPK-loaded PVA/PLA type core/shell fibers elucidated the absence of toxicity and stimulating effects on various plant growth parameters (leaf number, size of leaf and plant height) as shown in Fig. 4B and Fig. 4C. Similarly, polymers like polyvinylpyrrolidone (PVP) and polyphosphazene (PPZ) not only exhibit good fertilizer encapsulation and release efficacy but also

provide apt nutrients to plants, as structurally these polymers are rich in phosphorus and nitrogen.

Architecturally, three-dimensional nanofibrous constructs with hollow nanostructures bring together lightweight, high volume, and large surface area attributes for chemical adsorption and/or storage applications (Chiang et al., 2021). For instance, porous electrospun webs aid the dynamic release of targeted molecules. Similarly, the agrochemical encapsulation amongst nanofibrous assemblies promotes the encapsulation of several agricultural additives in electrospun fibers with different morphological attributes, thereby facilitating prolonged release for several months. Reportedly, single-layered and double-layered hollow electrospun nanofibrous mats were fabricated (via customized electrospinning setup), and evaluated as potentially novel delivery systems for encapsulation and sustained release of fertilizers (Javazmi et al., 2020). The procedure for fabricating urea loaded double-layered hollow nanofibers from quad-layered core-shell nanofibers is shown in Fig. 5B. The urea-impregnated double-layered nanofibrous hollow strands exhibited significantly less nitrogen release (~24%) than single-layer nanofibrous hollow strands (~79%) within initial 12 h of incubation in aqueous media (Fig. 5C). Similarly, novel electrospun tri-layer nanofibrous assemblies with poly-L-lactic acid (PLLA) loaded urea nanofibrous layer flanked with PHB nanofibrous membrane on both sides have been developed (Javazmi et al., 2021). After ~39 h, triple-layer nanofibrous structures containing ~10% urea exhibited a significant reduction in the initial release rate of nitrogen (<50%) than the single-layer nanofibers (>80%), resulting in a prolonged-release profile extending up to 3 months (Fig. 5D). Such engineered tri-layer nanofibrous assemblies exhibited excellent potential for controlling the release of urea-type fertilizers and exposure of

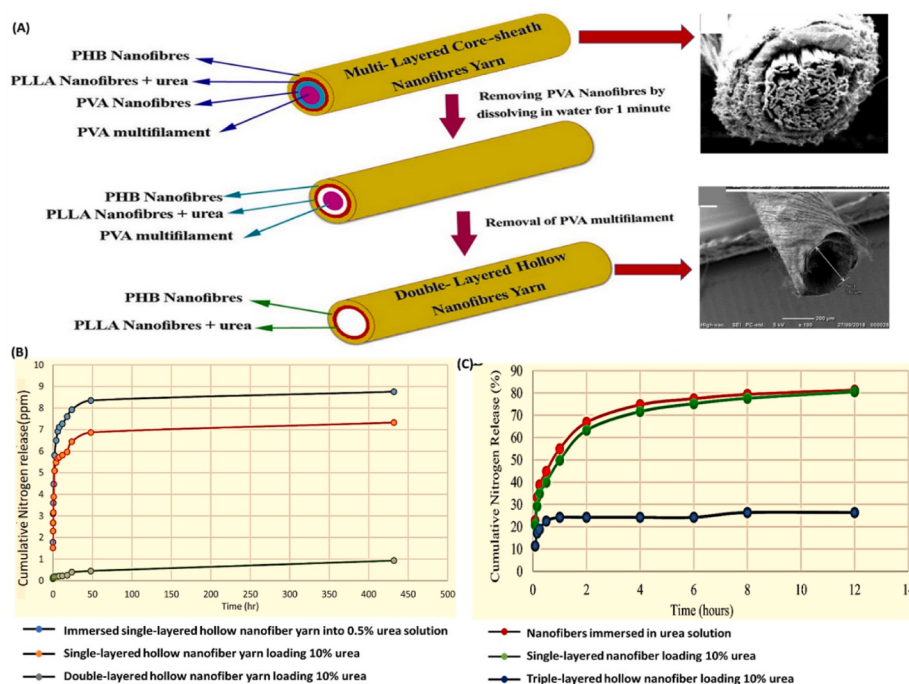


Fig. 5. Schematic diagram of (A) fabrication methodology for the preparation of urea-loaded double-layered hollow nanofibers using quad-layered core-sheath nanofibers yarns along with their respective SEM images; (B) cumulative release of nitrogen from single- and double-layered hollow nanofibrous yarns (Javazmi et al., 2020), (C) cumulative release of nitrogen from immersed nanofibres in urea solution and from single- and triple-layer nanofibrous structure containing 10% urea (Javazmi et al., 2021).

agrochemicals.

5.1.2. Encapsulation of pesticides

Global grain output suffers from significant losses in production (~2.102 million tons) and storage (~35% of total production) because of attacks by insects/pests and various plant diseases. Pesticides of different classes are often used to control plant pests (de Oliveira et al., 2018). Conventional pesticide formulations exhibit not only poor efficacy due to excessive use of harmful organic solvents and non-specific applications with respect to the plant/crop type but also adversely affect, both human health and the environment (Mfarrej and Rara, 2019). Consequently, there is an urgent need to develop safe and effective formulations of organic pesticides via synthetically advanced technologies in order to facilitate target-specific sustained release. Presently, electrospun fibers are considered as potential nanostructured material substrates for encapsulation and efficient release of pesticides for a longer duration. Thiram (tetramethyl thiuram disulfide, $C_6H_{12}N_2S_4$) pesticides loaded PLLA electrospun nanofibers have successfully been fabricated for various thiram concentrations (~5–25% (w/w), depending on the weight of polymer) (Roshani et al., 2017). UV absorption spectrophotometry exhibited thiram loading independent, sustained thiram release profile from the PLLA nanofibers (~40 days) in DI. Reportedly, diffusion and degradation both are attributed to controlled release characteristics of highly durable PLLA nanofibers.

5.1.3. Encapsulation of pheromones and biocontrol agents

An alternative approach to the use of pesticides so as to protect plants from insects/pests is to use pheromones, known for inducing behavioral responses amongst individuals of the same species (Khan et al., 2015). Sex pheromones are the most extensively used pheromones as they are effective when used in small amounts and are non-toxic to animals. Pheromones-loaded electrospun fibers exhibit tremendous potential as suitable designer delivery systems to ensure the sustained release of pheromones for prolonged durations. Nowadays, studies are being carried out on nanofibers with high concentrations of encapsulated and immobilized plant protection pheromones integrated onto the electrospun nanofibers to avoid the growth of large populations of insects. For example, Hellmann et al. encapsulated the pheromones in electrospun cellulose acetate (CA) (~100–1000 nm) and polyamide (PA) based

nanofibers (~150–600 nm) (Hellmann et al., 2011). This study revealed not only the uniform distribution of pheromones amongst nanofibers but also the possibility of a higher extent of loading in CA than in PA, which may be attributed to the higher solubility of pheromones in CA than in PA. The *in-vitro* studies revealed the linear release kinetics of pheromones from the loaded nanofibrous networks for ~100 days for enabling prolonged plant protection. Recently, Kikionis et al. incorporated the sex pheromones of *Bactrocera oleae* (*B. oleae*) and *Prays oleae* (*P. oleae*) in PCL, CA, and PHB-based electrospun nanofibers (~404–1346 nm), and observed promising release profile indicating their effectiveness in attracting the target insects (Kikionis et al., 2017). Gas chromatography-assisted mass spectrometry (GC/MS) revealed that a sustained release of pheromone was maintained for ~16 weeks irrespective of pheromones concentration and matrix composition. The morphological attributes of ~5% w/w 1,7-dioxaspiro-[5.5]-undecane loaded PHB and ~5% w/w (Z)-7-tetradecenal loaded PCL based EMs were observed to be almost twice as effective in attracting *B. oleae* and *P. oleae* males, compared to the positive controls.

Electrospun nanofibers can also be used to produce nanoscale dispenser functioning on attract-and-kill strategies. The strategy allows an attractive component (e.g., sex pheromone) to be mixed with a kill component (e.g., granulosis virus or insecticide), and may act as an aggressive and smart pesticide, as shown in Fig. 6A. For instance, Jaoge et al. fabricated insecticide (Cypermethrin), (*E*)-8, (*Z*)-8-dodecenyl acetate, and (*Z*)-8-dodecanol (~0.87 mgL⁻¹), a female *Grapholita molesta* (Lepidoptera: Tortricidae) (Busck) pheromone loaded nanofibers (Czarnobai De Jorge et al., 2017). The male electroantennographic (EAG) responses and the evaluation of mortality (tarsal-contact and attract-and-kill behavioral cages) bioassays for nanofibers (with and without insecticide) indicated >87% mortality of insects in tarsal-contact bioassays upon exposure for ~84 days. In the attract-and-kill bioassays, mortality ranged from ~28.4% to ~56.6%, and the incorporation of cypermethrin amongst nanofibers did not alter the attractiveness of the *G. molesta*. Such smart plant protection strategies integrally assisted by innovative nanofibrous mats can be used to design both attractant and killing effects along with the controlled release of insecticide and pheromone.

Another class of functionally smart electrospun nanofibers has exhibited great potential for the development of an innovative push-

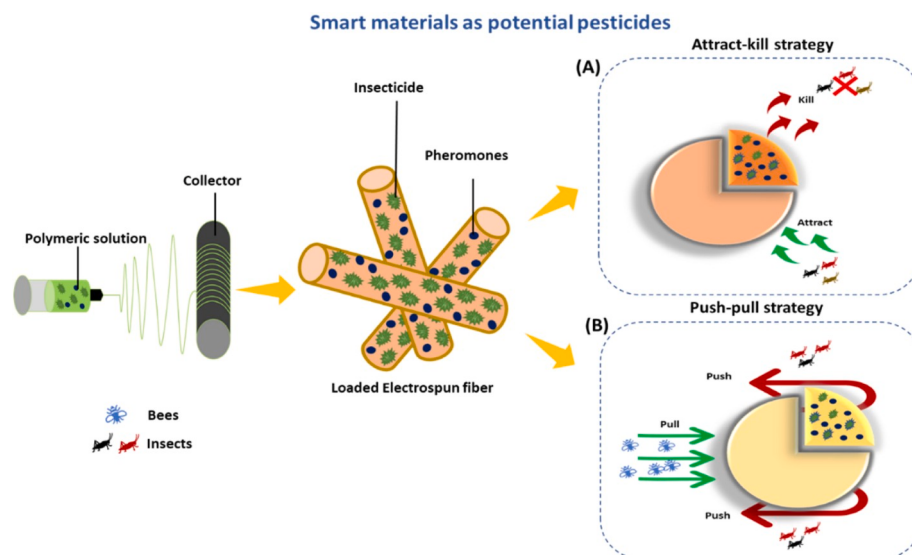


Fig. 6. Designing functional smart materials based on (A) attract-kill, and (B) push-pull strategy of pesticides.

and-pull strategy-assisted material so as to deliver the desired effect in the form of both an attractive compound (pull), as well as the repulsive effect in the form of insect repellents (push) in order to control phytoplastic plant diseases, especially in fruit-bearing trees (Fig. 6B) (Czarnobai et al., 2019). For instance, in a study by Czarnobai et al. nano-fibers with both insect repellent (push) and attractive components (pull) were employed to prevent psyllids migration and reproduction by keeping them (a) away from gardens and (b) in special traps and thereby leading to a significant reduction in the number of new phytoplasma infections (Czarnobai et al., 2019).

In order to avoid the exploitation of pesticides, biocontrol agents such as bio-fungicides (*Trichoderma*), bio-insecticides (*Bacillus thuringiensis*), and bio-herbicides (*Phytophthora*) are used, which may not only help in protecting the plants against pathogens but also extend their viability in storage and processing and thereby extending protection against different environmental factors (Ram et al., 2018). Another possible strategy to improve the effectiveness of biological control agents is the use of suitable polymeric carriers so as to facilitate the storage of microorganisms and offer protection against environmental factors and consequently increase their viability (Noruzi, 2016). Polymers like polyacrylamide, chitosan, and PEO have proved to offer sufficient protection against phytopathogenic agents (such as *Fusarium* and *Alternaria*), by supporting favorable conditions for the growth and storage of microorganisms. These polymers also promote environmental protection, moisture retention, and an adequate supply of nutrients. It is well known that fungal spores-loaded electrospun fibers tend to grow and reproduce even when subjected to high voltage exposure during the electrospinning process. Such electrospun materials protect the plant without causing any phytotoxicity and any inconvenience to plant nutrition. For example, a simple approach for fungicides encapsulation was proposed by Farias et al. where soybean seeds were coated with electrospun nanofibers (~242 nm) of cellulose diacetate (CDA) encapsulating or *fluopyram* as standard fungicides (Farias et al., 2019). A sustained and controlled release of fungicides [both *abamectin* (*Abm*) and *fluopyram* (*Flp*)] was observed from *in-vitro* assessment exhibiting consistent inhibition of fungal growth against the plant pathogen *Alternaria lineariae* for *fluopyram*-loaded nanofibers. It was demonstrated that electrospinning did not affect the viability of fungal spores and the antifungal potential of nanofiber mats making nanofiber mats a promising material concept as a substrate candidate and electrospinning a versatile fabrication platform of such mats for pesticide delivery. Although encapsulation is effective in preventing plant diseases or infections, some polymers such as poly(hexamethylene guanidine)

(PHMG) have antimicrobial properties which on combination with poly (butylene adipate-co-terephthalate) (PBAT) and Lactide/glycolide copolymer (PLGA) may lead to an easy fabrication of electrospun nanofibers and that allows the plant to transpire in freshly cut areas, by avoiding the penetration of spores in grapevine crops (Meraz-Dávila et al., 2021).

5.2. Seed coating

Polymeric film coating is a modern approach for inoculation of seeds, i.e., generally carried out on an industrial scale using fluidized beds, rotary coaters, or rotating pan approaches. However, such thick non-porous coatings restrict gas and moisture exchange, thereby adversely affecting seed germination and resultant plant growth. Recently, a looming area of research is the development of agrochemicals (such as nutrients, pesticides, and fertilizers) based on novel nano-activated seed coating materials for sustainable and targeted delivery of these agrochemicals. As compared to the conventional seed coating process, the electrospun fibrous coating has engrossed significant attention and is attributed to continuous water permeability and the absence of residual solvents. In an independent study, urea and cobalt nanoparticles (CoNPs) loaded PVP-based electrospun nanofibers were fabricated to potentially aid the seed germination phenomena and thereby improving the crop yield (Krishnamoorthy et al., 2016). However, the hydrophilic nature of the PVP remains a great concern, as the moisture in the soil may facilitate the fibers to rapidly dissolve, causing an accelerated release of active nutrients (release occurred for only ~200 h). Krishnamoorthy and Rajiv reported the efficacy of PVP-based electrospun mats coated with 2,2,4,4,6,6-hexaaminocyclotriphosphatriene (HACTP) and CoNPs (as micronutrients) to inoculate cowpea (*Vigna unguiculata*) seeds (Krishnamoorthy and Rajiv, 2017). Electrospun nanofibers exhibited better performance than the same composition-based cast films due to their higher surface area, absence of residual solvents, and porous surfaces. Electrospun nanofibers (~450 nm) coated seeds exhibited an improvement in the rate of swelling, and fertilizer deposition near the packaged plant leading to an increase in the germination rate and faster rooting. Similarly, the incorporation of PPZ into PVP nanofibers reportedly tends to improve the hydrophobic nature resulting in the retention of the active nutrient among coated membranes (Krishnamoorthy and Rajiv, 2018). Further, PPZ undergoes hydrolytic degradation in ~84 days (12 weeks) releasing phosphates and ammonia as degradation products, as per the schematic shown in Fig. 7B. Mechanistically, the initial release of nutrients from PVP, is followed by

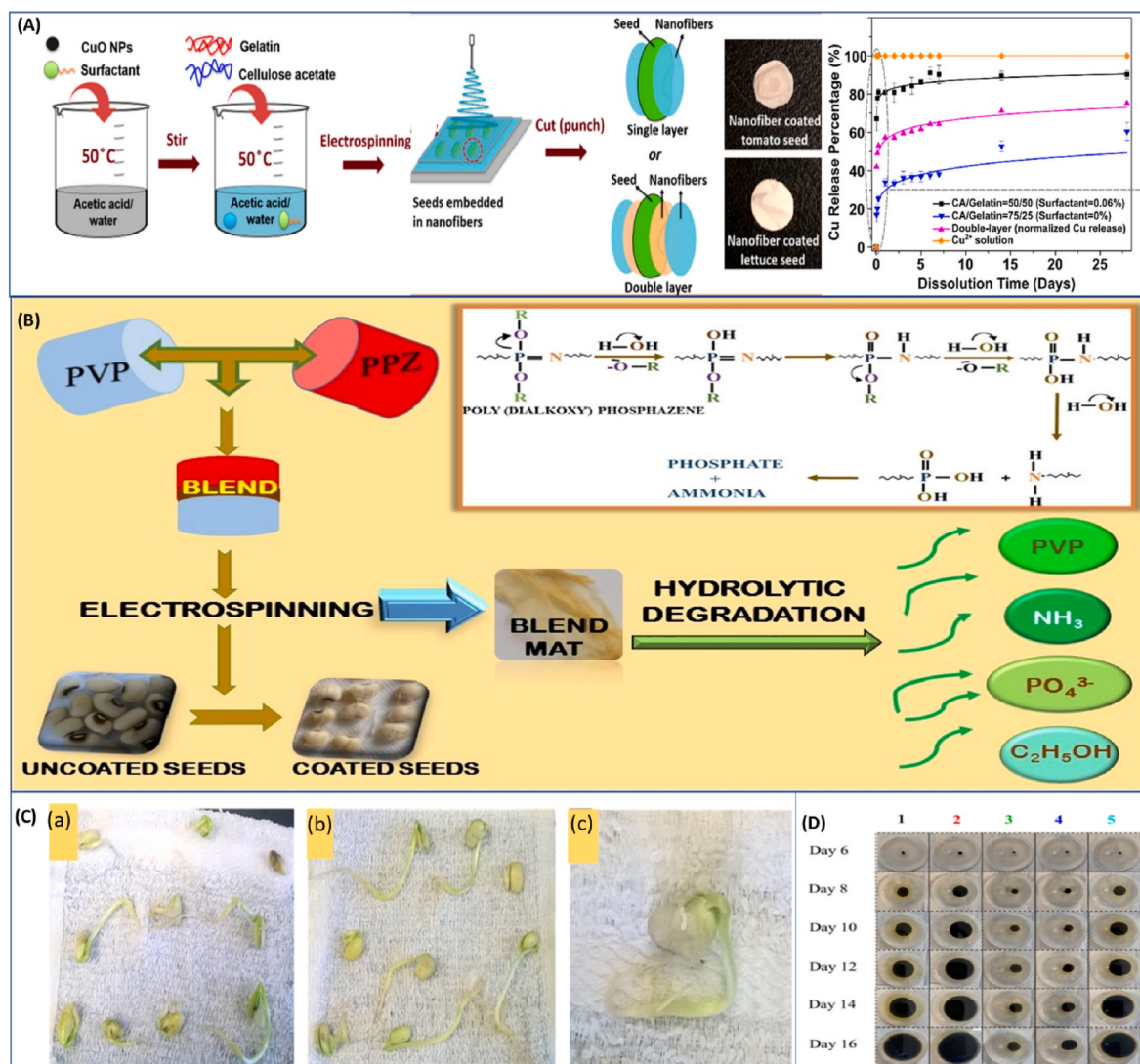


Fig. 7. (A) Schematic for preparation of Cu^{2+} loaded CA/gelatin-based electrospun nanofibers as seed coating along with Cu^{2+} release profile for 28 days (Xu et al., 2020); (B) mechanism involved in seed coating and release (Krishnamoorthy and Rajiv, 2018) (C) post-germination stages of (a) uncoated seeds (as positive control); (b) coated for 2 h showing successful germination; and (c) coated seeds for 4 h (presence of seed shell), and (D) fungal growth post-treatment (Farias et al., 2019).

controlled release via PPZ degradation, which promotes both seed germination and shortening of the harvesting time. However, the high cost associated with the use of PPZ polymer remains a major drawback to the exploitation of these systems for widespread applications. Reportedly, soybeans were coated with electrospun CDA-based nanofibers containing two types of active nutrients, i.e. *Abm* and *Flp* (Farias et al., 2019). The advantage of such coating systems lies in the fact that they provide a sustained and localized release because of the hydrophobic nature of the CDA. Although nanofibrous mats were directly electrospun on seeds, they did not affect the seed germination process regardless of the thickness and uniformity of electrospun coating (Fig. 7C). Further, *in-vitro* fungal tests revealed the remarkable efficacy of the *fluopyram*-containing nanofibers in consistently inhibiting fungal growth even after 16 days, with a mycelial diameter of ~ 3.5 cm for the electrospun nanofibers comprising of fungicide versus a mycelial diameter of ~ 7.5 cm for the controls, as shown in Fig. 7D. The hydrophilicity of electrospun coating material significantly influences their nutrient release potential. Similarly, the nature and type of the interactions between the polymer and nutrients significantly influence the delivery of active nutrients.

In a recent study, tunable, biodegradable, and biopolymer-based nanomaterials were developed by Xu et al. where nanofibers are

synthesized using polymeric blends of CA and gelatine without any toxicity of the used chemicals or any post-treatment (Xu et al., 2020). The tuneability of the agrochemical release is enabled solely by modulating the polymeric composition and hydrophilicity of nanofibers. Further, the germination and subsequent growth of seeds were evaluated in a greenhouse model on various nanofibrous (CA/gelatin (75/25); $\sim 203 \pm 31$ nm and CA/gelatin (50/50); $\sim 227 \pm 51$ nm) coatings, such as on tomatoes and lettuce as a function of the agrochemical release kinetics, both in the presence and absence of a fungal active ingredient like *Fusarium* species (Fig. 7A). It was observed that nanofibrous coating not only improves germination but also increases the biomass of the model seedlings compared to the conventional film coating processes used in industry. Typically, the film coating of seeds inhibits water and gas exchange and hinders root or shoot emergence/growth during germination. Table 2 summarizes polymeric nanomaterials encapsulated with agro-additives and/or growth promoters for the seed coating application.

Plant growth-promoting rhizobacteria (PGPR) are a group of microorganisms that promote the development and growth of plants by protecting them from environmental stress and also enhancing the resultant water and nutrient uptake. It is because of this reason that seeds are usually sowed with PGPR to prevent seed infestation by

Table 2

Overview of the recent development of polymeric nanomaterials and agro-additives used for seed coating.

Polymers	Agro-additives	Solvent systems	Seeds used	Fiber diameter	Characteristics and applications	References
PVP/PPZ	–	CF/ethanol	Cowpea (<i>Vigna unguiculata</i>)	PVP ~790 nm, PVP/PPZ ~1.5 μ m	PVP: biocompatible, biodegradable; PPZ: hydrophobic, phosphorus and nitrogen-rich polymer: promote seed coating and controlled fertilizer release applications	(Krishnamoorthy and Rajiv, 2018s)
Ethylcellulose	Fungicide carboxin-thiram and carbendazim	Dichloromethane (DCM), ethanol, DMF	Irrigated rice seeds	130–210 nm	Improved protection against fungal disease, enhanced germination rate (~93–95%), and phytosanitary characteristics	Castañeda et al. (2014)
PVP	Urea/Co-NPs	Distilled water (DW)	Cowpea	PVP- 0.43–1.5 mm, PVP/CoNPs-0.8–1.6 mm, and PVP/Co-NPs/urea- 0.6–0.8 mm	Micronutrient and nitrogen source for promoting germination	Krishnamoorthy et al. (2016)
PVP	Co-NPs/HACTP	DW	Cowpea	PVP-800nm, PVP/Co-NPs/HACTP- 430 nm	Adequate source of nutrition for seedlings growth in soil: increase in germination rate (~98%)	Krishnamoorthy and Rajiv (2017)
PVA/PVP/Glycerol	Microbial consortium (bacillus subtilis plus seratia marcescens)	DI	Canola (brassica napus L.)	PVA/PVP ~100 nm, PVA/PVP/Glycerol ~350 nm	Seed coat for promoting seed germination, seedling growth, plant dry biomass, leaf numbers, and root system; Bioinoculant for root–soil interface and improved nutrient acquisition	Hussain et al. (2019)
PVA	Rhizobium	DI	Soybean	–	Promotes bacteria survival up to 48 h of seed storage: Increased nodule formation rate on soybean seedlings than neat rhizobia	Damasceno et al. (2013)
CA/Gelatine	–	DW	Tomato and lettuce	CA/gelatine (75/25) ~ 203 nm and CA/gelatin (50/50) ~ 227 nm	Protection against fungi disease in crop seeds; Improvement in germination rate (Tomato- ~ 90% and lettuce- ~ 100%) and phytosanitary characteristics	Xu et al. (2020)
PVA	–	DW	Soybean	PVA/ <i>B. caribensis</i> ~620, PVA/ <i>P. agglomerans</i> ~540 nm	Improved soybean production via successful colonialization of a microbial inoculant such as <i>B. caribensis</i> ISIB40 and <i>P. agglomerans</i> ISIB55 (survival time ~30 days) and the germination rate was ~99%	De Gregorio et al. (2017)
CDA	<i>bm</i> and <i>lp</i>	DW	–	Untreated CDA- 335 $\pm$ 81 nm, CDA with <i>Abm</i> 242 $\pm$ 162, CDA with <i>flp</i> - 129 $\pm$ 98	Slow and sustained release of both <i>Abm</i> and <i>Flp</i> from the nanofibers; High moisture stability protects against plant pathogens such as fungi and nematodes	Farias et al. (2019)
					Seed germination rate was ~100%	

pathogens/microorganisms during storage and germination on one hand, and on the other hand, biologically enriched seeds are employed to improve germination, seed development, and overall plant fertility. However, maintaining their viability during seed treatment and storing remains a major concern. In this regard, De Georgia et al. developed rhizobacteria [*Pantoea agglomerans* ISIB55 (*P. agglomerans* ISIB55) and *Burkholderia caribensis* ISIB40 (*B. caribensis* ISIB40)] loaded PVA based EMs and investigated their viability by bacterial immobilization on nanofibers (De Gregorio et al., 2017). The encapsulation facilitates the survival of rhizobacteria on the surface of soybean seeds for ~30 days, contributing to the successful colonization of both bacteria on the plant root with ~2 and ~4 log unit decrease in viability of incorporated and un-incorporated *P. agglomerans* ISIB55, and ~1.5 and ~4 log unit decrease in viability for incorporated and un-incorporated *B. caribensis* ISIB40, respectively. Particularly, *P. agglomerans* ISIB55 was observed to increase the germination rate, root length, and dry weight, while *B. caribensis* ISIB40 augmented the number of leaves and the dry weight of the shoots, as illustrated in Fig. 8. In a similar study, Hussain et al. coated canola seeds with glycerol plasticized PVA/PVP blend-based electrospun nanofibers, containing a microbial consortium (Hussain et al., 2019). The viability of such bio-composite seed coating was reported to be ~15 days at room temperature and the intrinsically enhanced bio inoculant tendency improved at the root-soil interface, thereby increasing the level of nutrient pool. Further, a much larger number of rhizobia remained viable for ~48 h on encapsulation in PVA-based electrospun nanofibers than the unprotected rhizobium, thereby potentially protecting them from environmental stresses such as temperature and dehydration. However, no significant variation in the number of nodules between rhizobia encapsulated in PVA nanofiber and

the positive control (unprotected rhizobia) was observed over a period of ~30 days. These studies elucidate PVA encapsulation as a viable method for safe storage and delivery of rhizobacteria.

5.3. Fabrication of biosensors for plant growth regulation and quality

In agricultural technology, sensors are being used to analyze and detect the quality of agricultural products and pesticide residues. Reliable, fast, and sensitive materials need to be designed for effective and accurate detection of pesticides, agricultural chemicals, and toxic elements adhered or integrated into the plants. So, biosensors are rapidly used for identifying and responding to pathogen and pest outbreaks, exhibit excellent potential in reducing analytical cost by promoting flexibility in fabrication, miniaturization, and portability and thereby addressing the mission of USDA in numerous ways (Kundu et al., 2019; Fritz et al., 2019). An ideal sensor should be easy to use, without the need for complicated and time-consuming preparation and/or handling of field samples.

Over the past decades, electrospinning has brought in a promising pathway of nanotechnology for designing and developing smart and ultra-sensitive detection systems (Cleeton et al., 2019). The interconnected porosity, desirable geometries, specific surface area, 1-D confinement characteristics, tunable fiber diameter (μ m to nm) and the edge in functionalization of fibers using a variety of different nanomaterials (such as graphene, carbon nanotubes, and conjugated polymers) make electrospun fibers potential candidates for the development of biosensors (Cavalcante et al., 2021). Further, the ability of porous electrospun fibers in trapping gases, and reactive chemicals tend to justify them as materials for numerous biosensing applications like

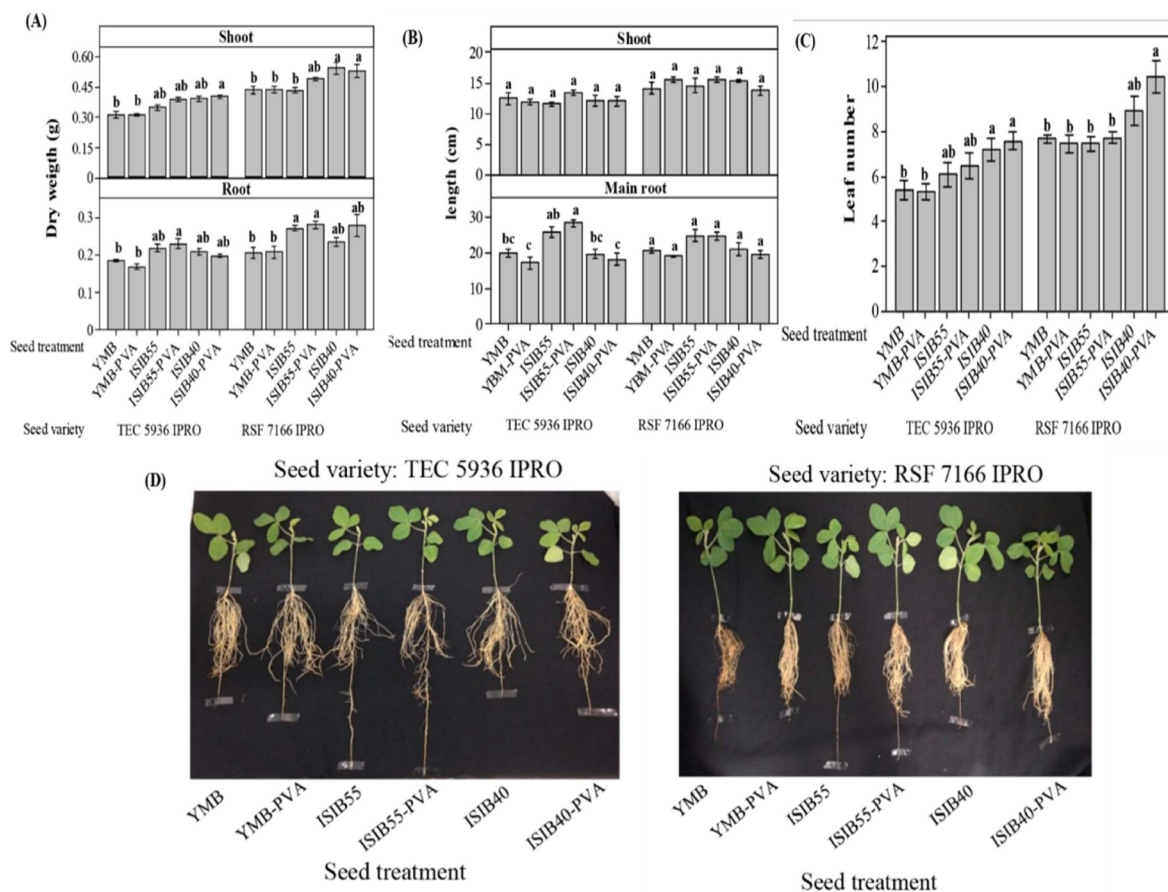


Fig. 8. Effect of nanofiber-immobilized rhizobacteria-based seed coating on the growth of soybean plants, representing (a) dry weight of shoot and root (b) length of shoot and main root (c) leaf number determined in plants grown from the seeds (RSF 7166 IPRO and TEC 5936 IPRO varieties) inoculated with Yeast Mannitol Broth medium (YMB), YMB (YMB-PVA), *P. agglomerans* ISIB55 (ISIB55-PVA), *B. caribensis* ISIB40 (ISIB40-PVA), *P. agglomerans* ISIB55 (ISIB55) and *B. caribensis* ISIB40 (ISIB40) cultures, and (d) photographic images representing the growth of soybean plants (TEC 5936 IPRO and RSF 7166 IPRO varieties) post 25 days of seed coating (De Gregorio et al., 2017).

toxic gas detection systems.

It is well reported that the nitrogen content in the soil, is conventionally used as a standard for the estimation of the quality of crops and/or soil contamination. However, the traditional techniques used for nitrogen detection are very time-consuming. To overcome such a limitation, Ali et al. have developed a microfluidic impedimetric biosensor for a fast and highly sensitive nitrogen detector using poly (3,4-ethylene dioxythiophene) (PEDOT) conjugated with graphene oxide (GO) nano-sheets and nitrate reductase (NIR) enzyme molecules as an electrochemical bioelectrode (Ali et al., 2017). The mechanism of electrochemical nitrate detection by catalytic conversion of nitrate to nitrite is shown in Fig. 9A. The sensor offers a sensitivity of $\sim 61.15/(\text{mg/L})/\text{cm}^2$ over a wide concentration range of $\sim 0.44\sim 442$ mg/L for nitrate ions in agricultural lands and the electrochemical impedance spectra (EIS) of synthetic as well as real sample is shown in Fig. 9B. The modified nanofibers-based sensor demonstrated the ability to accurately detect and quantify nitrate ions in real soil samples. Aflatoxins produced by the *Aspergillus* species are known to be extremely toxic and carcinogenic, which cause severe food contamination. Xu et al. fabricated Fe_3O_4 nanoparticles loaded in polymethylmethacrylate (PMMA) nanofibers and carbon horns in a magnetic electrode to develop an electrochemically luminescent (ECL) immune sensor, which has a high sensitivity to aflatoxin B1 (AFB1) (Xu et al., 2016). Similarly, Supraja et al. developed a multiwall carbon nanotube (MWCNT)-embedded ZnO nanofiber-based electrochemical sensing platform for the detection of atrazine (1-chloro-3-(ethylamino)-5-(isopropylamino)-s-triazine; ATZ) (Supraja et al., 2020) and synthesis is shown in Fig. 9C.

Such an immune sensing platform (with a wide detection range of 10 zM–1 μM) exhibits good selectivity, stability, reproducibility, and repeatability, and is less prone to interference. The EIS analysis of anti-atrazine antibody-immobilized bioelectrode is shown in Fig. 9D. The detection of organophosphate pesticides, such as malathion, is very crucial owing to their high toxicity and harmful effects on several non-target organisms. In this regard, Migliorini et al. developed a novel nanoscale architecture-based platform using Polyamide 6 (PA6) on the surface of polypyrrole (PPy) with reduced graphene oxide (RGO) deposited on a fluorine tin oxide (FTO) substrate for designing an electrochemical sensor for the detection of pesticides (malathion) and/or other contaminants at a very low detection limit of ~ 0.8 ng ml^{-1} (Migliorini et al., 2020).

Acetylcholinesterase (AChE) inhibitor-based enzymatic biosensors are being widely used for analyzing pesticide concentrations in plants and agro-sectors. The biosensors detect the content of organophosphorus (OP) compounds that otherwise interfere with the appropriate functioning of the AChE enzyme. The detection mechanism records the inhibited activity of AChE in the presence of OP and carbamate-based insecticides thereby increasing the acetylcholine concentration, which eventually leads to the killing of insects (Kaushal et al., 2021). The number of inhibited enzymes is recorded to be proportional to the concentration of pesticides and is used as a standard for the calibration of the biosensors. As enzymes offer significant potential in fabricating enzyme-based biosensors due to the higher number of recognition sites, therefore, electrospon fibers with enhanced sensitivity are being widely explored. For the first time, Moradzadegan et al. demonstrated the AChE

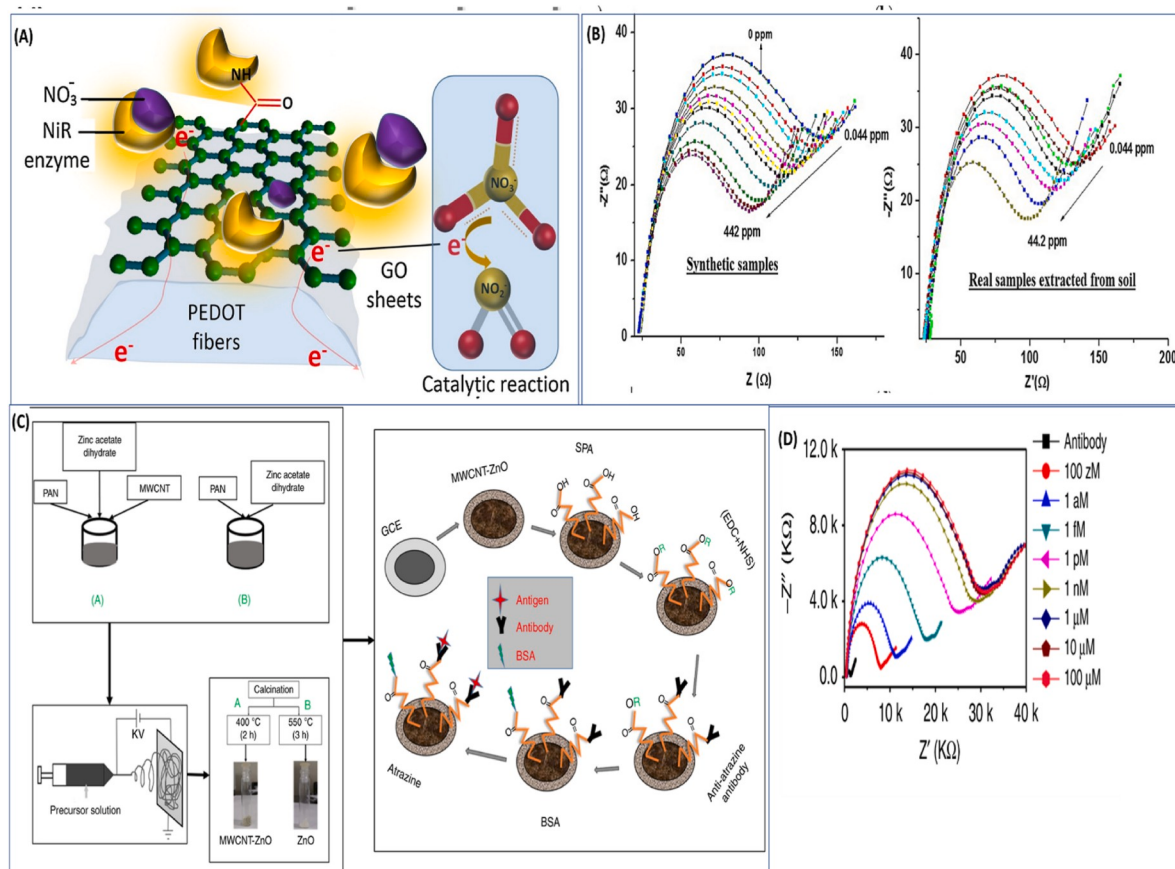


Fig. 9. Schematic representation of (A) surface immobilization of PEDOT-GO based electrospun fibers with NiR enzyme for electrochemical nitrate detection by catalytic conversion of nitrate to nitrite, (B) EIS of fabricated NiR/PEDOT nanofiber bioelectrode as a function of nitrate concentration in synthetic and real samples extracted from soil (Ali et al., 2017), (C) synthesis of MWCNT embedded ZnO nanofiber-based biosensing platform for detection of atrazine, and (D) EIS analysis of anti-atrazine antibody-immobilized bioelectrode (Supraja et al., 2020).

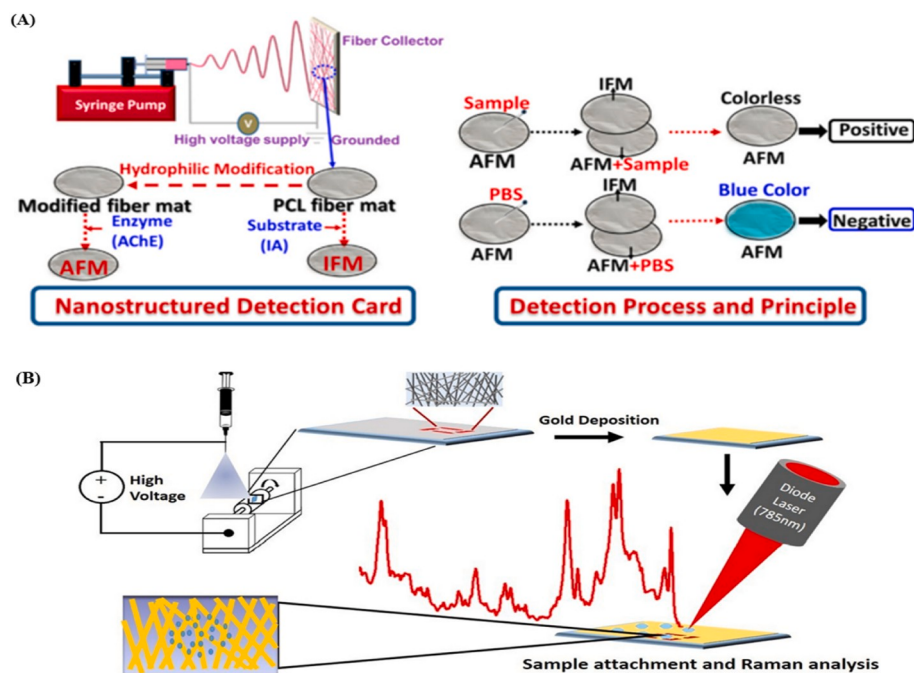


Fig. 10. Schematic representation for the fabrication process and detection principle of (A) PCL- electrospun nanofibers-based smart detection card (Feng et al., 2021), and (B) Au-coated electrospun PVA nanofibers as SERS substrates for the detection of pesticides (Chamuah et al., 2018).

immobilization using PVA/bovine serum albumin-based glutaraldehyde crosslinked electrospun nanofibers (Moradzadegan et al., 2010). The immobilized enzyme retained ~40% enzymatic activity with strong stability of ~100 days. These immobilized electrospun mats demonstrated reusability up to ~10 ECL cycles, with a net decrease in enzymatic activity by ~30% at the end of the last cycle. Similarly, Stoilova et al. developed glutaraldehyde crosslinked AChE immobilized functional styrene-maleic anhydride copolymers based electrospun membranes (Stoilova et al., 2010). The membranes exhibited an increase in thermal and storage stability with a decrease in the enzymatic activity by ~65% post 5 cycles. In a recent study, Zhai et al. developed AChE and IA-loaded PVA-based nanostructured OP residue and carbamate (CM) pesticides (Zhai et al., 2020). Such a detection card exhibited stable storage life at room temperature for ~4 months. Similarly, a novel micro/nano-structured pesticide detection card for the absorption of IA and AChE was fabricated by using neat and hydrophilic-modified PCL electrospun mats, as shown in Fig. 10A (Feng et al., 2021). The card exhibited better storage stability at ~4 °C and room temperature, with high detection efficacy, i.e., ~1.5 to 5-fold reduction in the minimum detectable concentration of carbofuran, malathion, and trichlorfon. Some novel alternatives for pesticide detection using surface-enhanced Raman scattering (SERS), for efficient chemical identification and quantification, are currently being explored (Chamuah et al., 2018). For instance, Chamuah et al. prepared gold (Au) coated electrospun PVA nanofibers as a SERS substrate for the detection of three commonly used pesticides namely deltamethrin, quinalphos, and thiacloprid (Chamuah et al., 2018). The fabrication of electrospun nanofiber-based SERS substrate and Raman signal measurement system is shown in Fig. 10B.

5.4. Preconcentration and quantification of pesticides

Pesticide preconcentration is now being considered a crucial parameter for the quantitative estimation of low concentration of pesticides present in crops as well as environmental samples (like water and soil). Nowadays, electrospun nanofibers are being explored for designing alternative materials to traditional sorbents for the estimation of preconcentrated pesticides and other environmental pollutants, which exhibit better performance in terms of analytical parameters (e.g., precision, detection limit, linear dynamic range, enrichment factor, and limit of quantification (LOQ)) (Maddah et al., 2017). Reportedly, smooth and bead-free PA/PPy nanofibers were fabricated for preconcentration and quantification of an OP insecticide such as malathion, in aqueous solutions with the reusability of >200 cycles and LOQ of ~100 mg/L (Bagheri et al., 2011). Similarly, Bagheri et al. used PPy/PA nanofibers packed into a syringe, to preconcentrate five OP pesticides, with concentrated ethion, diazinon, profenophos, fenitrothion, and fenthion (Bagheri et al., 2012). Analyte's desorption and their subsequent determination using GC/MS exhibited stability of nanofibrous sorbent against most of the organic solvents and reusability > 200 times. Further, the same group used PA nanofiber-based sorbents for clodinafop propargyl determination in paddy fields, wheat grains, contaminated river water, and soil (Bagheri et al., 2014). Meanwhile, Maddah et al. reported an extraction recovery of >90% by preconcentration of diazinon and fenitrothion, in contaminated groundwaters using PS nanofibers (Maddah et al., 2015). As per the above studies, electrospun fibers not only reduce the amount of sorbent and organic solvents for desorption of pesticides but also enhance reusability and extractable recovery.

5.5. Protective clothing for farmers

The farmers are mostly exposed to various neurotoxins such as pesticides and fertilizers which can potentially lead to serious and irreversible damage to their health. This gives rise to an imperative need for protective clothing that should have good barrier properties and sufficient air/water vapor permeability so as to provide adequate thermal

gradient and dermal breathability as per the farmer's comfort needs. However, most conventional protective clothing possesses good protective properties with low air and moisture permeability, which may cause an increase in the risk of hyperthermia (Garrigou et al., 2020). Recent studies illustrated the good breathability of electrospun nanofibers due to their large surface area and porosity (Baji et al., 2020). Moreover, electrospun nanofiber-based protective clothing is lightweight, less toxic, and highly resistant to entrapment of any atmospheric particles (such as ammonia, and CO₂) (Baji et al., 2020). The high specific surface area favors the functionalization efficacy of nanofibers for both detoxification and adsorption of toxins on the surface of protective clothing. For instance, PAN nanofiber-based protective clothing can be successfully functionalized to be useful in the detoxification of neurotoxins (Bhuiyan et al., 2019). Electrospun fibers possess high porosity with micro/nano-sized pores, thereby resisting the penetration of chemicals on aerosols (such as metaldehyde, and acephate). Similarly, chemicals to be used to deactivate dangerous compounds can be easily incorporated into polymeric precursor solutions (such as antimicrobials, heavy metals, or biocides) and it does not alter the water vapor and gas permeability for engineered clothing. However, the low production efficacy and comparatively poor mechanical properties limit their large-scale production and utilization. Thus, more advanced industrial electrospinning systems and support structures for fabrics should be designed, so as to maximize their production and utilization. For the first time, Lee and Kay Obendorf developed a nanofiber-coated protective cloth where electrospun polypropylene (PP) nanofibers were deposited on a nonwoven substrate with high barrier properties and an acceptable level of breathability (Lee and Kay Obendorf, 2006). Further, the retention, repellence, and penetration characteristics exhibited a clear difference in penetration characteristics for various pesticide mixtures, by offering ~95% protection performance. Further, air and water vapor permeability was observed to decrease upon lamination and increase in thickness of the nanofiber-based fabrics. However, the permeability remained over ~100 cm³/s/cm², i.e., higher than commonly used protective clothing materials such as PPE, despite a layer of lamination. Nanofibers exhibit excellent potential in designing the next generation of lightweight, breathable, stable, and tough protective clothing materials, particularly to the chemicals, pesticides, fertilizers, etc. that are used in the agricultural processes.

5.6. Currently explored nanostructured electrospun fibers in augmenting agricultural efficacy

Many plant-extracted essential oils/phytochemicals have been known to exhibit antimicrobial activity. However, thermal stability, volatility, higher loading requirements for effective protection, low water solubility, and oxidative capacity-related limitations need to be addressed before unitizing such plant extracts as alternatives for pest control systems (Chouhan et al., 2017). Electrospinning has evolved as a reliable technique for successful encapsulation of essential oils (such as neem oil, clove oil, and odoriferous oil) so as to address the aforementioned challenges and provide sustained release, stabilization, and solidification of oils. Allahvaishi et al. encapsulated *Mentha piperita* L. and *Salvia officinalis* L.-based extracted essential oils in PLLA-based electrospun mats so as to facilitate prolonged and sustained release of such phytochemicals (~72 h) and to design a novel biobased pesticide for pest control (Allahvaishi et al., 2017). Current research has led to the elucidation of a fresh perspective for the development of new-age bio-pesticides derived from phytochemicals to promote sustainable agricultural practices.

Struvite, is a white crystalline fertilizer (often referred to as a bacteria-assisted growth on kidney stones in the urinary tract) whose high aqueous precipitation is governed by solution pH, dissolved magnesium, ammonium, and phosphate ion concentration, and the specific surface area of the solid support (Siciliano et al., 2020). Electrospun materials with high surface area, pliability, porosity, and good

mechanical properties offer significant potential in promoting struvite precipitation. For instance, Di Gesù et al. fabricated struvite-loaded PLLA-based electrospun mats that were reportedly fabricated for promoting the crystallization of struvite crystals and thereby facilitating the adsorption of both nitrogen and phosphorus from a nutrient-rich solution onto the surface of such functional electrospun mats (Di Gesù et al., 2020). Here, struvite-loaded PLLA fibers, as crystal seeds enhanced the firmness in attachment and precipitation on the surface of electrospun fibers, and also encourage their efficacy in designing engineered ready-to-use fertilizers.

Iron (Fe) is an essential element for plants as it enhances both crop productivity and quality by promoting electron transport in mitochondria and photosynthesis in chloroplasts. Fe is one of the most abundant materials but the rapid oxidation tendency limits its potential bioavailability for both plants and micro-organisms. Nowadays, farmers are using Fe-chelates as fertilizers, however, their rapid leaching potential in groundwater limits their efficacy as a sustainable Fe source for plant growth. De Cesare et al. encouraged the use of natural and biodegradable nanostructured materials for designing environment-friendly and less toxic bioactive products (De Cesare et al., 2019). For instance, Catechol (CL), a natural iron-chelating agent when loaded in thin PCL/PHB-based electrospun nanofibrous membranes tends to mobilize Fe from insoluble forms to duckweed (*Lemna minor* L.) plants, thus promoting their physiological growth without introducing any significant toxicity. The use of natural biodegradable alternatives for designing low-impact and sustainable nano bio-stimulants in agricultural applications may offer immense potential and should be explored further.

The grafting of plants is commonly practiced in modern agriculture in which different types of tissues of living plants such as rootstock and scion are joined so as to facilitate their growth and development. However, the low survival rate (~30%) of plants post-grafting limits their potential grafting efficiency in breeding improved varieties of crops (Álvarez-Hernández, 2019). These exogenous auxins are manually added by dip-coating sprouts in the auxin solution. However, such an approach is still challenging due to the unavailability of sufficient resources for the farmers. Electrospun nanofibers with a high surface/volume ratio and porosity may facilitate cell adhesion, improved migration, and proliferation efficiency. For instance, Guo et al. developed 6-Benzylaminopurine (6-BA) loaded CA/PU co-axial electrospun fibers for the sustained release of exogenous auxins (Guo et al., 2017). Here, the prolonged-release profile of 6-BA for ~10 days promoted stimulating callus proliferation for efficient healing of plant wounds and improvement in grafting and survival rate.

Fungi and other similar micro-organisms are responsible for a range of serious plant diseases that can cause major concerns in agricultural activities and losses in agro-output, i.e., food production. For instance, esca is caused by *Phaeomoniella chlamydospora* (*P. chlamydospora*) and *Phaeoacremoniumaleophilum* (*P. aleophilum*). Spasova et al. used CA/PEG-based electrospun fibers containing 5-chloro-8-hydroxyquinolinol (5-Cl8Q) to protect vines against *P. aleophilum* and *P. chlamydospora*. Electrospun fiber loaded with 5-Cl8Q showed an inhibitory effect on *P. chlamydospora* and *P. aleophilum* fungi (Spasova et al., 2019). The drug release test showed a sustained inhibitory effect for ~96 h with an initial burst release of ~83% that was observed for the first 30 min, allowing rapid attainment of the desired minimum inhibitory concentration.

Electrospun fibers have been widely known to facilitate efficient drug delivery in various medical applications. A similar approach is used in the recent study by Karuppannan et al., where progesterone-loaded electrospun zein fibers were fabricated for estrus synchronization of bovine. Such an approach is aimed to facilitate a sustained release of progesterone with a simultaneous increase in its sustained release over a week ensuring ~87% hormonal release (Karuppannan et al., 2017). With higher progesterone concentration, the half-life of the hormone release increases accordingly. Further, *in-vitro* pollen germination in an aqua liquid/gel tends to promote pollen viability. Electrospun fibrous

assemblies can also be used as a potential support material for germinating pollen in a liquid medium. For instance, Bodhipadma et al. used synthetic polymers for designing the germination substrate of *Artabotryshexapetalus* pollen (Bodhipadma et al., 2016). Here, ~8 µm thin membranes exhibited an increase in germination rate (i.e., >65%) than liquid (~60%) and agar gel (~50%) media. However, a decrease in germination rate to <3% with an increase in membrane thickness from ~8 µm to ~18 µm was observed. Some agricultural applications of electrospun fibers are given in Table 3.

6. Formulating decision-making strategies using SWOT analysis and TOWS matrix

6.1. SWOT analysis

A qualitative approach based on Strength (S), Weakness (W), Opportunities (O), and Threats (T) (SWOT analysis) as the subjective parameters have been adopted to compare the effectiveness of conventional and electrospun-assisted agricultural devices. The main objective of this study is to evaluate the positive and negative trends, develop strategies to strengthen the advantages, fix the internal weaknesses, and address the environmental threats. The analysis was carried out by taking four distinct parameters into consideration, which are, structural stability, productivity, ease in the implementation, and environmental friendliness of such fibrous constructs in real-time agricultural practices which paves a way to address the challenges of 2030 sustainable development agenda. SWOT analysis is an analytical method used to recognize and classify both the internal (i.e., strengths: S and weaknesses: W) and external (i.e., opportunities: O and threats: T) parameters of fabrication techniques, production, and application. Internal parameters include strength and weakness evaluated in terms of the

Table 3
Applications of electrospun nanofibers in agricultural applications.

Polymeric materials	Solvent systems	Applications	References
PEDOT/GO	Ethyl alcohol (EA)	Impedimetric sensor to detect and quantify nitrate ions in the soil.	Ali et al. (2017)
Fe ₃ O ₄ /PMMA nanofibers/ carbon horns	DMF	Sensitive detection of AFB1.	Xu et al. (2016)
PA6	Formic acid (FA)	Detection of pesticide (paraoxon) in the corn crop.	Oliveira et al. (2012)
PA6/PPy/RGO	FA	Detection of malathion pesticide.	Migliorini et al. (2020)
PVA/Au nanoparticles	DW	SERS substrate for pesticide detection.	Chamua et al. (2018)
PVA/ACH/IA	DW	Pesticide detection	Zhai et al. (2020)
PEG/PCL blend and polyvinyl acetate (PVAc)/PVP blend	PEG/PCL-Acetone/EA, (PVAc)/PVP-Chloroform/THF	Encapsulation of Polycore Trimedlureagrisense (TML) for <i>Ceratitis capitata</i> (Wied.) Control.	Bisotto-de-Oliveira et al. (2014)
CA, PCL, PHB (Individually electrospun)	PCL and PHB-(DCM)/Methanol, CA-acetone	Encapsulation of sex pheromones (<i>B. oleae</i> and <i>P. oleae</i>) for pest control.	Kikionis et al. (2017)
PLLA/struvite crystal	DCM/DMF	Recovery of nitrogen and phosphorous.	Di Gesù et al. (2020)
CA/PU	CA-DMF/acetone and PU- THF/DMF	Plant grafting	Guo et al. (2017)
Polyetherimide	THF/DMF	Used as a sorbent for detection of OP.	Vojtěch et al. (2016)
PCL/PHB/CL-NMs	CF/DMF	Used for supplying micronutrition (Fe) to plants.	De Cesare et al. (2019)

efficiency, product, price, placement, etc., whereas external factors include the proposed demographic, social, economic, technological opportunities, and threats of the technology. An extensive literature study was conducted to obtain the relevant data required to outline and analyze the potential attributes for the enhancement of production, commercialization, structural stability, and friendliness to farmers as the customer. The data obtained for all the four factors of the SWOT was then analyzed and ranked accordingly and is reported in Fig. 11.

On the basis of SWOT analysis, it can be concluded that electrospun-assisted agricultural approaches comprising continuous and functionally target-specific tailorable microstructures with mechano-structural integrity, mass production capacity, high agrochemical loading, and controlled release efficacy, can potentially boost agro-production compared to the conventional agro-farming practices. Meanwhile, the external factors associated with the electrospun fibrous assemblies fulfill the agriculture 4.0 criteria so as to eliminate the limitations of conventional agro-practices.

6.2. Assessment of strategic framework using TOWS matrix

A situational analysis framework i.e., TOWS analysis was used to design the best operational strategies and align the available resources and capabilities in the operational environment, for enhancing the resultant production, adaptability, and resilience toward the real-time agro practices. The designed TOWS matrix is comprised of internal and/or external factors to address specific weaknesses or threats associated with various technologies within their operational environments. Moreover, the matrix was incorporated into the decision-making process to evaluate the strategies so as to facilitate the development, strengthening, and growth of such technologies. Following the SWOT analysis, alternating strategies in SO, WO, ST, and WT were developed and are mentioned in Fig. 12. In this study, a total of 28 types of situational strategies were taken into consideration for evaluation.

The framework analysis using the TOWS matrix involves four possible types of strategies. They are.

- a) Aggressive strategies [principle of maximizing both strengths and opportunities (Max–Max)] are conceptualized for the structural strength of electrospun fibers/mats/assemblies to elevate sustainable agricultural opportunities.
- b) Turnover strategies [principle of minimizing drawbacks and maximizing opportunities (Min–Max)] are conceptualized to overcome or minimize the weaknesses by capitalizing its opportunities.
- c) Diversification strategies [principle of maximizing strengths and minimizing threats (Max–Min)] are conceptualized to strengthen the advantages so as to reduce or avoid the impact of threats in the external environment.
- d) WT strategies [principle of minimizing both threats and drawbacks (Min–Min)] are strategically conceptualized to address the weaknesses and threats being perceived by agro farms and relevant sectors.

The current research-based investigations and analysis highlighted some breakthrough strategies to enhance the structural stability, productivity, implementation ease, and environmental friendliness of present-day agricultural practices in a more sustainable and cleaner fashion. Further, the analysis aims to foster a more comprehensive dialogue on the options available for conceptualizing, designing, and implementing innovative agro-devices such as electrospun fibrous mats/constructs more aggressively and organically.

7. Electrospun nanofibers based agro-devices: realizing the promise of an agroecological approach

In the year 2018, FAO has identified some integral prospects for the agroecological approaches which can help in designing a transformative

and innovative agro-ecosystem such as enhancing the resilience to climate variability, crop diversification, and maintaining local genetic diversity, animal integration, soil organic management, water conservation, and harvesting (Wezel et al., 2020) (Bisht et al., 2021). The agricultural practices followed by the farmers in recent years (such as the use of synthetic fertilizers, and pesticides) may potentially lead to soil depletion and loss of biodiversity. Lately, fluctuating weather patterns and climatic variations also tend to adversely affect crop production and plant growth. In this regard, Lobell et al. estimated a significant reduction in crop yield, i.e., ~2.5% which was attributed to the fluctuating weather pattern (Lobell et al., 2011). To understand and attain the synergies between various agroecological approaches, the concept of 2030 agenda and agriculture 4.0 was introduced, and accordingly, synergistic approaches in agriculture are being adopted and implemented by farmers. For instance, electrospun micro- and nano-fibrous constructs are now being used for designing smart devices for numerous agro-applications, such as biosensors (e.g., microfluidic impedimetric biosensors and AChE inhibitor-based enzymatic biosensors) protective clothing, seed coating (e.g. biopolymer-based agrochemicals loaded seed coating), and encapsulation of agrochemicals (fertilizer, pesticides, biocontrol agents, plant growth promoters) (Noruzi, 2016) (Meraz-Dávila et al., 2021) (Mercante et al., 2017). Such systems can also be employed for maintaining both biodiversity and resilience to climate change by utilizing ecosystem functions and services and enhancing crop productivity and farm income under potentially adverse environmental conditions. For instance, biopolymer-based nanofibrous mats may potentially reduce (a) the wastage of fertilizers and increase crop productivity and thereby promoting “precision farming”, i.e., selectively targeting agricultural production, without significantly aggravating water/soil pollution and (b) harmful effects of chemicals (Castro et al., 2012) (Nooeaid et al., 2021) (Javazmi et al., 2021). The compositionally designed electrospun micro-nano fibrous mats do not affect soil health and can potentially act as compost for the next cycle of plant-growth post-decomposition. The residual bio-based materials, in the designed agro-systems, can also be extracted and reused in engineered agro-devices for promoting agro-output in a clean and sustainable manner (Maraveas, 2020) (Duque-Acevedo et al., 2020). Further, such a loop reiterates the recyclability, circular economy, and sustainability of new-age green agro-systems and thus enables strict compliance to the USDA and FAO agricultural approaches. A schematic representation of the agroecological framework in designing a transformative and innovative agroecosystem and promoting a circular economy may be shown in Fig. 14.

Although the agro-ecological approach is being widely recognized as a mainstream strategy to establish sustainable food production systems amid climate change, their adoption requires significant efforts, ranging from social awareness to affordable economic challenges (Bisht et al., 2021). Therefore, several measures, actions, advertisements, and policies guided by scientific understanding of agroecological elements is of need in the near future for plunging into the concept of establishing a modern agroecological system with significant potential to exponentially scale up the ecological and socio-economic resilience of such agro-augmenting systems in both local and global contexts.

8. Challenges and future directions

The electrospun nanofibers exhibit promising potential in designing new-age agricultural materials compared to conventional cast films. There are still two primary challenges that need to be addressed which are (1) large-scale production, and (2) accuracy and reproducibility at all fabrication stages. The major challenges associated with the mass production of solution-based electrospun fibers is the low output produced per spinneret, rigorous solvent evaporation, clogging of the spinneret tip leading to recurrence of charged jet interference, failure in the recovery of vaporized solvents, and non-uniform fiber orientation over a large area of thick mats. Thus, the employment of needleless

	Structures in conventional technical approach	Electrospun structures assisted organically engineered approach
Structural Stability	Strength (S) - High mechanical properties (tensile strength $\sim 28.2 \pm 2.44$ Mpa, modulus $\sim 5 - 256$ Mpa). - High thermal stability for synthetic polymers, e.g., mixture of polyolefin and ethylene-vinyl acetate-carbon monoxide (C_2H_4-VAC-CO) copolymer, polysulphones and LDH (layered double hydroxides) anionic clays Weakness (W) - Fabrication of target specific innovative constructs with high surface area is difficult. - Uniform fertilizer loaded polymer surface coating is difficult to achieve, e.g., Polyether sulfone-Fe_3O_4 nanoparticles loading increases coating thickness (3.3 ± 0.5 to 10.0 ± 0.5 μm) and reduces release rate (36 $\mu S/cm$ to 10 $\mu S/cm$) Opportunity (O) - Potentially viable material for production of environment-friendly controlled release fertilizers (CRFs) - Designing smart sustainable materials with high surface area and better nutrient loading and release efficacy integrated with soil moisture management around the rhizosphere Threats (T) - Use of non-degradable polymers cause soil/water pollution (such as PP, PET).	Strength (S) - Target-specific tailorable microstructures (core-shell, multi-layered, sandwiched), and mechano-structural integrity assisted application. (S1) - Ease of functionalization using a variety of different nanomaterials (such as graphene, carbon nanotubes, and conjugated polymers) (S2) - Produce continuous nanofibers and vary the fiber dimensions (μm to nm) as per the requirement of seed coating. (S3) Weakness (W) <i>In-vitro</i> Mechanical Properties retention: Major limitation (Degradation time of PLA Core shell is only 1 month) for biodegradable polymers (such as PLA, PCL). (W1) - Prolonged (35-37 folds in PLA) environmental exposure result in thermal degradation. (diameter of PVA and PEO nanofibers decreased from 667 nm to 161 nm and 252 nm to 75 nm with increase in humidity from 4% to 60%) (W2) Opportunity (O) - Performance improvement in electrospun fibers to promote sustained and prolonged release of agrochemicals and plant micro-nutrients. (O1) - Development of new strategies to control the structure and alignment of fibers (O2) - Increase the structural stability in harsh environment. (O3) Threats (T) - Different degradation modes for biodegradable polymers (such as enzymatic, hydrolytic, photodegradation). (T1) - Biodegradable polymeric membranes do not retain the structural stability for a long time (PVA/starch diminished in size when weight loss exceeded 50%). (T2)
Productivity	Strength (S) - Low operating cost, easily scaled - Optimization is not required - High production rate (ranges from 0.06-5 kg/h) Weakness (W) - High labor cost - Use of excessive pesticides leads to high production cost (50% fertilizer wastage) - Synthetic polymers are costly ($300-700$ $\\$ t^{-1}$) - Mostly expensive batch type manufacturing processes are used. Opportunity (O) - Up-scaling the productivity and rapid commercialization of the products. Threats (T) - Mass production of synthetic polymer-based agro-devices cause large scale pollution	Strength (S) - Mass production efficacy with a throughput of ~ 450 g/h (S1) - Reduce the application and labour cost (reducing fertilizer applications saves the farmer $\sim \\$5$ to $\\$7/acre$ broadcasting expense) (S2) - Can be a continuous process (S3) - Saving manual labor costs for crop surface dressing operations (S4) Weakness (W) - Time consuming and expensive than conventional techniques ($\\$ 17,000$ to $\\$ 60,000$ USD) (W1) - Energy consumption is comparatively high (0.564 W) (W2) - Viability for scaled-up production (W3) Opportunity (O) - Design modification in Electrospun setup to promote mass production (O1) - Robot added Electro spinning (O2) - Synthesizing a Core-shell fertilizer polymer system through increase the time duration of fertilizer application due to control release leading to less broadcasting expenses (O3) Threats (T) - Lack of awareness and resistance to adopt new and alternative agro based technology: limits both production and growth of the technology (T1)
Implementation ease	Strength (S) - Delivery of both water soluble solid and liquid fertilizer can be facilitated using irrigation water Weakness (W) - Unavoidable Human contact - Encapsulation efficiency is comparably low (up to 81%) - Excessive provision of wastage fertilizer is there. (50% wastage) - Unquantified sprinkling of fertilisers (losses in a winter wheat due to improper fertilizer spreading $\sim £16.60/ha$) Opportunity (O) - Employment of nitrogenous fertilizer in the paddy fields and dry lands. - Facilitates burst release (~ 3 hrs to 14 days) - Promotes fabrication of multi-layered assemblies, e.g., a compact construct with seven or more layers of different polymers of different thicknesses can be fabricated rapidly using cast film co-extrusion process Threats (T) - Non-directed release and spread of fertilizer throughout the field also promotes weed growth - Excessive fertilizer exposure may damage germinating seeds and seedlings.	Strength (S) - High encapsulation efficiency (up to 86%) (S1) - Primary human contact can be avoided (S2) - Promotes reduction in excessive fertilizer usage (S3) - Appropriate fertilizer application on the seed or root promote rapid growth (S4) Weakness (W) - Lack of technically skilled labors (W1) - Secondary processing is required (W2) Opportunity (O) - Multiple target applications: ranging from modulated agro-chemical delivery to unique biosensors devices (O1) - Invention of nutrient loaded electrospun fibers which can be placed in thereby leaves can easily absorb the nutrients through the stomatal opening and also through epidermis (O2) Threats (T) - Lack of awareness and resistance to adopt new or alternative agro based technology: limits both production and growth of the technology in the field (T1)
Environmental friendliness	Strength (S) - Controlled fertilizer application in late growth stage reduces damages to crops Weakness (W) - Climate induced variation in nutrient uptake, e.g., N uptake by the rice crop at harvest was high $\sim 75\%$ in dry season and $\sim 65\%$ in wet season. - Multiple applications of polymer coatings are required to increase its thickness ($\sim 100-600$ μm) around the fertilizer. Opportunity (O) - Novel designs to enhance the release efficacy of agro-chemicals can be formulated - Smart polymeric systems to diagnosis and detection of the pesticides and insecticides needs to be explored Threats (T) - Erosion of agrochemicals (such as fertilizers) to water bodies causes eutrophication - Pest and disease incidents (bacteria, wilt)	Strength (S) - Biodegradable polymer-based electrospun-assisted agro-devices: protect and promote the growth of seeds, plants without affecting soil biodiversity, plant life cycle and agro productivity (S1) - Prevent nutrient erosion (S2) - Less sensitive to soil pH and climate conditions: promote controlled and sustained nutrient release (S3) - Optimum fertilizer loading and controlled release: reduces associated costs, risks to crops and environment (S4) Weakness (W) - Compromised efficiency when different variables (cropping season, pH of soil and resources) are considered (W1) Opportunity (O) - Encapsulation of phosphorus or iron may benefit some crops like blueberry, potato, and sweet potato (O1) - Selection of non-toxic solvents (O2) Threats (T) - During large scale production, the rapid build-up of solvent vapor in the environment may result in air pollution and affect fiber morphology (T1) - Use of carcinogenic solvents may affect the pollen germination and viability of plant promoting bacteria.

Fig. 11. A comparative SWOT analysis of conventional agricultural approach without fibers and prospective modern electrospun fiber assisted organically engineered approach.

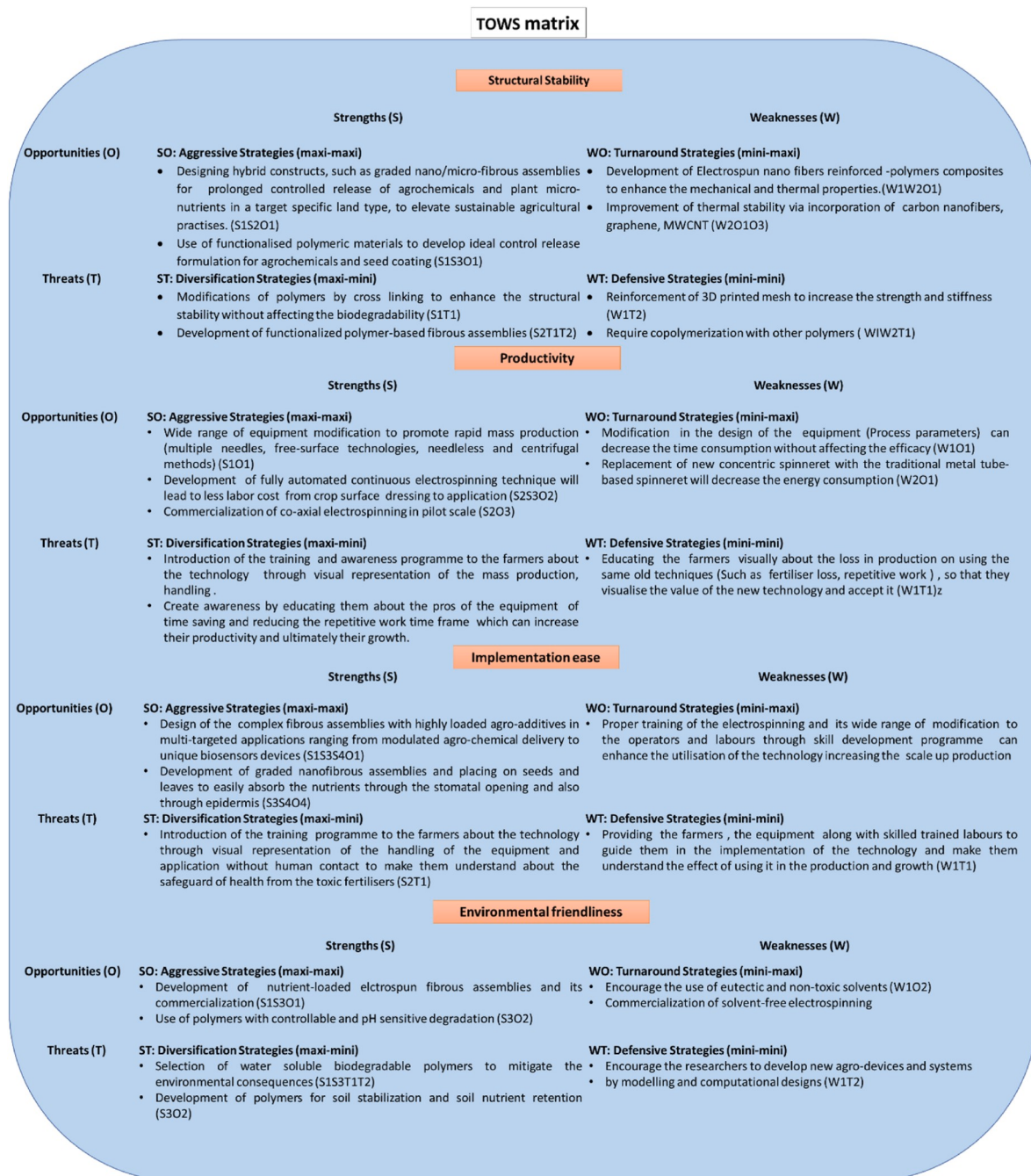


Fig. 12. Strategy formulation of electrospun-assisted agricultural practices by using the TOWs matrix based on the SWOT results.

electrospinning systems offers wider potential in promoting large-scale production of nanofibrous assemblies without any significant (a) spinneret clogging problem, (b) the perpetuation of Taylor cone stability issues, and (c) appropriate solvent selection requirement. Additionally, (a) replacement of spinneret ejection tips in a basic electrospinning system with explicit and precise applied electric field, and mechanical controls and (b) exploring an innovative alternative to conventional spinneret and collector set-ups by encouraging the use of ferroelectric material and reactive precursors for the atomic layer of nanostructured materials may offer fresh perspectives to address the aforementioned problems (Song et al., 2020).

However, the exclusive properties and performances of micro/nanofibrous electrospun materials provide numerous opportunities in designing innovative agro-promoting electrospun materials in the

future. Electrospun fibers tend to promote agrochemical encapsulation because fertilizers, pesticides, biocontrol agents, and pheromones can be easily incorporated in these sub-micron fibers for producing controlled release formulations (Noruzi, 2016). Thus, the morphological and microstructural attributes of graded nano/micro-fibrous assemblies (such as by using coaxial, side-by-side, emulsion electrospinning, etc.) can be easily tailored to encapsulate agrochemicals so as to bring forth new pathways for designing engineered sustained and prolonged release systems. A contrast of the conventional approach of agriculture vis-à-vis the smart adaptable approach in the broader realms of SWOT analysis is schematically reproduced in Fig. 13. However, some of the current challenges and perspectives associated with the design and development of electrospun fibers with micro/nano- structured morphologies for agricultural applications may be summarized below.

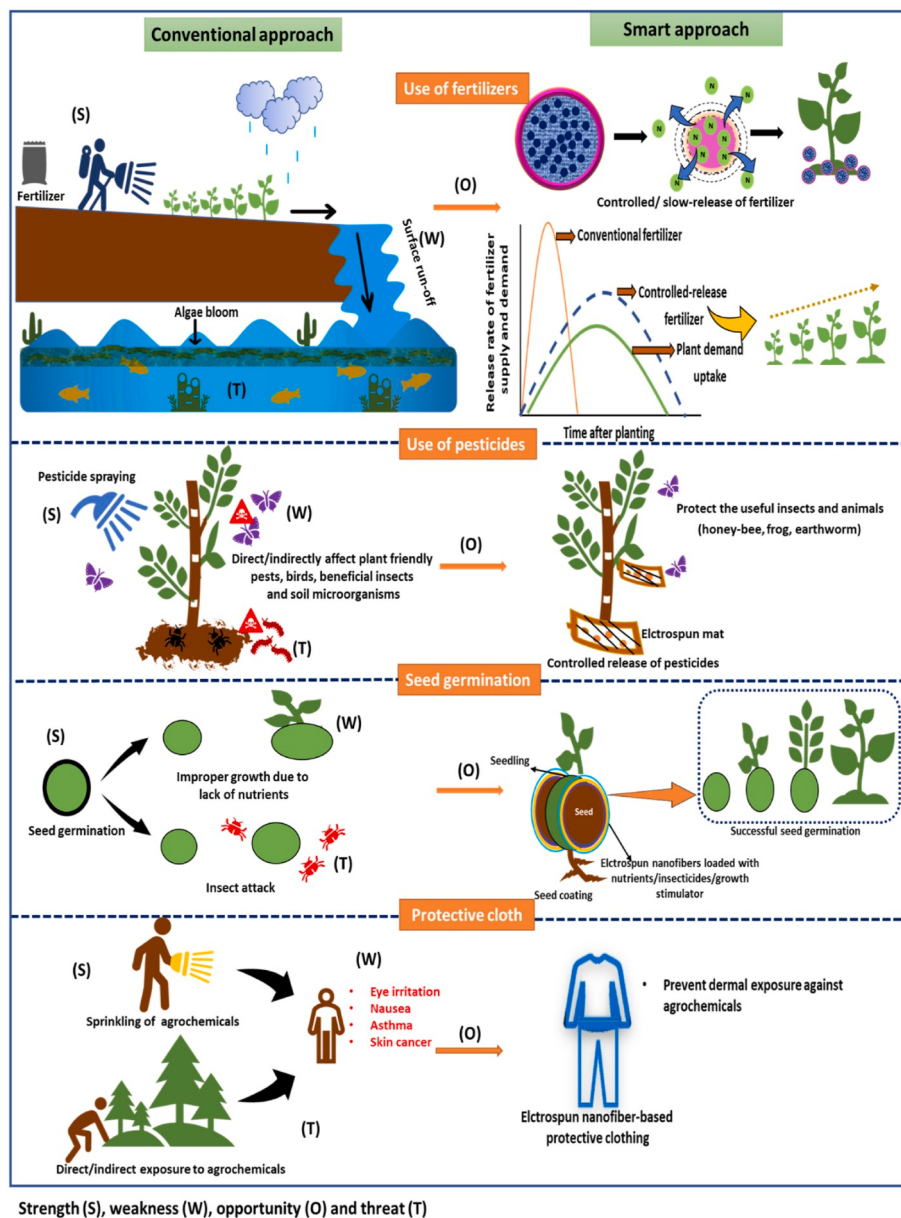


Fig. 13. Summative representation of conventional and smart adaptable and sustainable approaches highlighting the potential agricultural applications of electrospun fibrous assemblies while conforming to SWOT analysis.

- In order to meet the cost-effectiveness and easy processability, most of the polymeric materials being used for the delivery of agrochemicals are non-biodegradable (e.g., PAN, PP) and the solvents used are also toxic (e.g., DMF, DCM), hence the long-term fertility of soils may remain largely compromised. So, there is a need to encourage the use of green electrospinning materials, i.e., to promote the production of the electrospun mats/membranes using low concentrations of biodegradable polymers in water or hydrophilic solvents. Further, the use of deep eutectic solvents and solvent-free spinning (e.g. melt, supercritical CO₂-assisted, UV-curing, anion-curing, and thermo-curing electrospinning) could be better alternatives to replace the use of toxic solvents (Mouden et al., 2017).
- Fabrication of a diverse range of morphologies of electrospun polymeric nanofibers (such as core-shell, side-by-side, hollow, multi-layer, and sandwiched structured) may enable the modification and augmentation of the release profile to an adequate level.
- Reportedly, biochar and biofertilizers can be produced from various organic biomass waste such as animal manure, sludge, food waste,

green waste, agricultural waste, and crop residue. Organic biomass waste as biofertilizer has engrossed great interest owing to its ready applicability, availability, and smoother production. Furthermore, biochar as organic biomass has been used as a reinforcing filler in improving the physicochemical, thermal, electrical, and even water absorption characteristics of polymer composites. Therefore, synergetic encapsulation of biochar and biofertilizers amongst electrospun nanofibrous assemblies can potentially be used as pollutant adsorbent for the soil/water ecosystem."

- Micro/nanofibers have been successfully loaded with various metabolites for use in other disciplines, mainly in food and medicine. The effect of the use of such micro/nanostructured fibers on plant metabolism activity has not yet been studied.
- Some nanomaterials such as clays and zeolites upon encapsulation amongst the electrospun nanofibers tend to enhance the water retention capacity of soil and also may facilitate the slow-/controlled-release of agrochemicals/materials and plants nutrients.

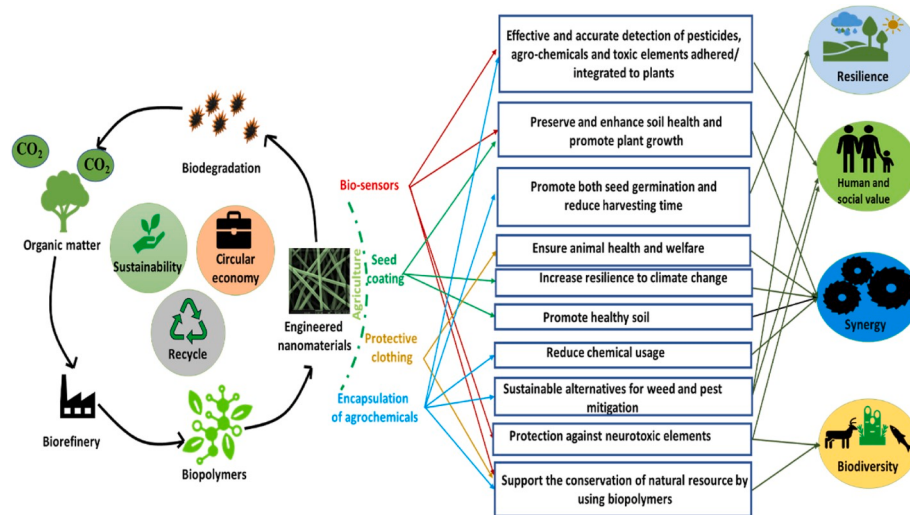


Fig. 14. Agroecological framework for promoting circular economy and designing sustainable engineered agro-devices.

- From the industrial point of view, innovative and cost-effective controlled-release fertilizer formulations for scaling-up the productivity and rapid commercialization of the CRFs products need to be explored on a pilot scale.
- Despite significant scientific and technological advances in agriculture, farmers throughout the world (particularly in developing regions) rely on traditional farming methods. Therefore, educating farmers and empowering them with smart agro-devices (such as IoT-based smart agriculture monitoring systems and nanofiber-based biosensors) not only helps the farmers in enhancing the soil fertility but also contributes toward sustainable and smart agricultural practices. For instance, intensive efforts have been made in the United States to develop educational interventions for sustainable agriculture, such as the ~ \$17.7 million Farmer and Rancher Development Program by USDA to educate and train the farmers toward sustainability (USDA, 2020).
- DNA extraction is known to be the most fundamental, crucial, and inevitable experiment in plant genetics to investigate and classify plants. However, conventional DNA extraction methods are not only tedious and time-consuming, but also follow a relatively large number of steps, thereby increasing the risk of DNA degradation, sample loss, and also DNA cross-contamination (Wallinger et al., 2017). Electrospun nanostructured devices can be successfully employed to facilitate successful plant DNA extraction and growth. For instance, Demirci et al. prepared poly[(ar-vinyl benzyl) trimethylammonium chloride] grafted CA-based positively charged electrospun nanofibers for successful adsorption of negatively charged biomolecules such as DNA (Demirci et al., 2014). Such nanostructured devices can potentially promote the purification and separation of DNA in plants.
- Nowadays, electrospun nanofibers have gained popularity in water filtration and desalination, mainly due to their excellent physicochemical attributes and diverse functionality. Since a large amount of water is being consumed in agriculture, resulting in a shortage of drinking water worldwide, therefore, managing the consumption of water in agriculture (as in drip or sprinkler irrigation) is of great importance. Electrospun nanofibers can be employed for the desalination of salty waters, purification of contaminated water (pesticides and fertilizers), and crop irrigation.
- In the near future, more and more electrospun nanofiber-based biosensors for a diverse range of applications (such as *in-situ* detection, and analysis of pollutants, diseases in crops and livestock, food processing parameters, animal fertility, therapeutic drugs in veterinary testing applications, etc.) with high sensitivity, selectivity,

stability, functionalization, integration, and long-life span may facilitate design and development of new-age agricultural devices for practical applications by farmers.

- A large amount (~5 billion tons) of crop-based organic waste is being carelessly disposed into the environment which may lead to irreversible health concerns. Contemporary literature highlights the valorization of various agricultural wastes such as quinoa scraps (Kavali et al., 2019), pomegranate scraps, pomegranate peels (Talekar et al., 2018), and pomegranate twig scraps in value-added products (e.g lignin, alginate) which in turn aligns with the objectives of the circular economy.

9. Conclusive remarks

Conventional agricultural approaches may not be effective in the coming decades, as it adversely affects plant growth, soil fertility, biodiversity, and agroecosystems. Considering the great challenges, such as the growing global population and climate change, the introduction of nano-structured agricultural devices, can potentially address the growing sustainability concerns and enhance agroecological resilience. The performance of engineered electrospun fibrous assemblies has revolutionized the world agriculture canvass dramatically and thereby attributing to their novelty, circular economy, and significant contribution to rapid production and enormity to meet the projection of global food demand. This article highlights the applicability of electrospun nanofibers in the controlled delivery of fertilizers, seed coating, sensors for surveillance and control of pests, safe pesticide delivery, and designing protective clothing. The paper puts forth a new vision from the conventional instinct-based agro-farming practices for enhancing agricultural crop output to smart, sustainable, and engineered approaches, promoting minimum polymeric material usage, agrochemical wastage, and exposure. Despite the known potential benefits of such fibrous materials, functionally efficient pathways for designing electrospun nanofiber-based agro-farming micro-devices need to be explored without compromising the ethos of sustainability and green norms while ensuring enhanced agro output and thereby promoting synergy between sustainable agriculture and food system. A systematic SWOT/TOWS-assisted qualitative analysis for parametric assessment of various scenarios and strategic conceptualization of path forward approaches, leveraging their strengths and mitigating their weaknesses against opportunities and threats has been proposed. The study demonstrates, based on the available scientific understanding and strategic assessment, the overall prospects of electrospun fibrous constructs as a potential solution to ensure clean and sustainable agriculture not only to

enhance the agro output but also to ensure resilient agricultural practices without inflicting secondary consequences on the soil-water ecosystem and human health and thereby meeting the provisions of the 2030 Agenda.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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