Nanoformulated Materials from Citrus Wastes

Radwa Mahmoud Azmy

Abstract Citrus peels are a rich source of essential oils (EOs); these oils have efficient antioxidant and insecticidal properties. However, using these EOs is restricted because of technical obstacles such as their poor solubility in water and rapid rate of vaporization. Nanotechnology enables the formulation of the EOs into promising, efficient nanomaterials. These materials can be used in different fields such as water treatment, production of eco-friendly insecticides, and the food industry. Also, the citrus peels are a great source of nanocellulose, which is considered as a promising material used in water treatment and composite industry. This chapter sheds light on the employment of nanotechnology in the production of different nanomaterials from the agricultural wastes of citrus crops.

Keywords Citrus waste · Essential oils · Waste management · Recycling · Nanocellulose · Nanoemulsion · Eco-friendly insecticides · Food preservation · Antimicrobial

List of Abbreviations

EOs	Essential oils
C	Citrus
LC	Lethal concentration
NE	Nanoemulsion
NEs	Nanoemulsions
NPs	Nanoparticles

R. M. Azmy (✉)
Entomology Department, Faculty of Science, Ain Shams University, Cairo, Egypt
e-mail: radwa.azmy@yahoo.com; radwa.azmy@sci.asu.edu.eg

A. S. H. Makhlouf and G. A. M. Ali (eds.), *Waste Recycling Technologies for Nanomaterials Manufacturing*, Topics in Mining, Metallurgy and Materials Engineering, https://doi.org/10.1007/978-3-030-68031-2_22

1 Introduction

Agricultural wastes can be defined as the wastes produced through the different farming activities causing environmental pollution. The actual need for sustainable materials is directing the research focus towards the green biodegradable materials. Citrus fruits belong to Rutaceae and comprise around 140 genera and 1300 species, including *Citrus sinensis* (orange), *C. aurantifulia* (lime), *C. limonum* (lemon), and *C. reticulata* (mandarin). Citrus fruits are very common cultivated fruits throughout the world with increasing production every year [1, 2]. After consumption, about 40–60% of the citrus fruit is considered wastes [3]. Annually, about 110–120 million tons of wastes are produced worldwide from industries of citrus fruits producing great challenges of waste management [4]. For example, the industry of orange juice production leads to a significant quantity of liquid and solid wastes, up to 8–20 million tons every year [5]. Citrus wastes do not have commercial importance, and the accumulation of these wastes generates a serious problem to the environment, such as many leachates, heavy odour, moreover, attracting flies and rats [6]. However, these residues comprise rich materials (such as essential oils (EOs), insoluble and soluble carbohydrates, pectin, and cellulose); these components can be the base of many industrial practices [7–10]. Lately, several attempts have been made to develop new procedures to produce valuable materials from these wastes motivated by economic and environmental concerns [11–17].

Nanotechnology is growing rapidly and interacting with many other scientific fields creating new innovative applications. Green nanotechnology is a fruitful multidisciplinary field in the agricultural sector. The applications of the green nanotechnology attracted attention, especially in the formulation of new nanoinsecticides. A nanoinsecticide is a formulation that comprises components in the size of the nanometer range with unique characteristics [18].

This work aims to highlight the production of nanomaterials from citrus wastes such as the formulation of nanoinsecticides from EOs extracted from citrus wastes (peels of the fruits). In addition, this chapter discusses the extraction of

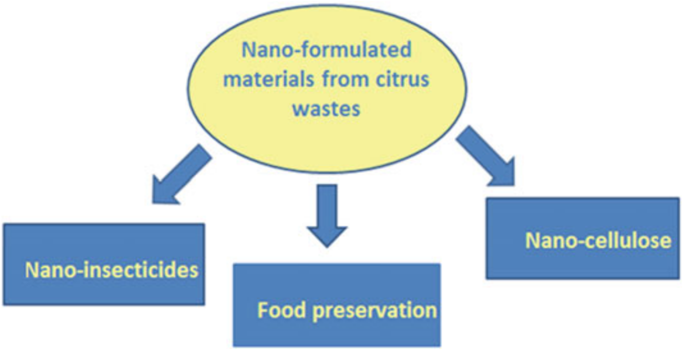

Fig. 1 Main fields for the recycled nanomaterials from citrus wastes

nanocellulose from citrus peels and its use in water treatment and different composite materials. Besides, this chapter enumerates the use of nanomaterials from citrus wastes in food products. These different nanomaterials present promising approaches to overcome pollution problems through the recycling of agricultural wastes and also present effective eco-friendly products. The main areas discussed in this chapter are shown in Fig. 1.

2 Nanoinsecticides Formulated from Citrus Essential Oils

Nanopesticide is a term used to describe a variety of formulations that include elements in the size range of nanometer, such as nanoparticles (NPs), nanocapsules, and nanoemulsions (NEs). The purpose of the nanoformulations is to increase the poor solubility and guarantee a constant slow release of the active ingredients. Citrus EOs are considered as by-products in the industry of juice; such EOs have been evaluated as insecticides to control several insect pests [19, 20]. EOs thought to be promising in insecticides industries. However, the use of EOs is often limited due to several reasons, such as high volatility and low water solubility [21]. The nanotechnology can solve the obstacles of EOs application as insecticides through the production of novel delivery systems. A promising approach to overcome those obstacles is to incorporate the EOs into the formulation of NEs, and the nanoencapsulation pokes to get NPs coating the EOs [20].

These new nanoformulations enhance the efficacy of EOs because of the greater surface area, the sustained release, the generation of systemic activity due to the smaller size of particles and the higher mobility. The nanoformulations also enable the avoiding of the organic solvents used in the application of conventional pesticides [22].

2.1 Nanoemulsions of Essential Oils

A nanoemulsion (NE) is an emulsion that contains tiny particles ranging in size from 10 to 100 nm [23, 24]. The small size of the particles related to the wavelength of light causes the NEs to tend to be slightly turbid or transparent. NEs can be formulated from the following major components:

i. The aqueous phase: This phase primarily consists of water.
ii. The oil phase: This phase includes various non-polar components such as EOs. The nature, stability, and properties of the NE are dependent on the physicochemical properties of the oil phase, such as solubility in water, chemical stability, polarity, density, viscosity, and interfacial tension [21].

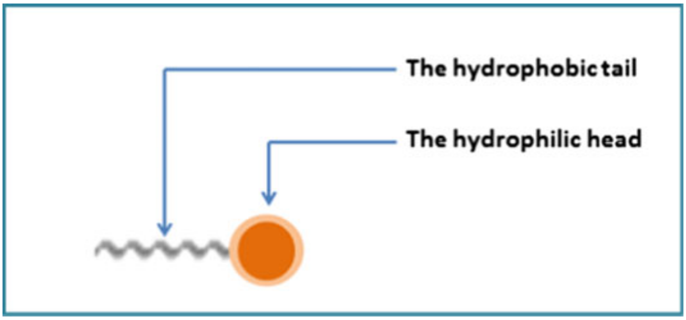

Fig. 2 Schematic representation of the emulsifier molecule

iii. The emulsifiers: It is a surface-active molecule that can adsorb to surfaces of droplets; it facilitates the partition of the oil droplets and prevents them from aggregation. The emulsifier molecule consists of a hydrophobic tail that faces the oil phase and a hydrophilic head that faces the aqueous phase, as shown schematically in Fig. 2.

The emulsifier molecules on the surface of the Nes particles act as a shell surrounding a core of lipophilic material. The selection of suitable emulsifier is very crucial for the appropriate design of the NE [25, 26]. The nature of emulsifier has a crucial impact on the kind of homogenization mechanism used to formulate the NE. The stability of the NE under the environmental pressures such as the pH, the ionic strength, cooling, heating or storage for a long time depends on the kind of the emulsifier used [27]. The emulsifier helps to prevent the system breakdown through various mechanisms, such as gravitational separation, droplet flocculation, and phase separation, as shown in Fig. 3.

2.1.1 Formulation of the Nanoemulsion

Nanoemulsions can be formulated through different approaches classified into low-energy and high-energy approaches according to the underlying principle [21, 28].

Low-Energy Approaches

The formulation of nanoemulsions using the low-energy approaches depends on the formation of oil droplets spontaneously in mixtures of water, oil, and emulsifier when their environment is changed [27].

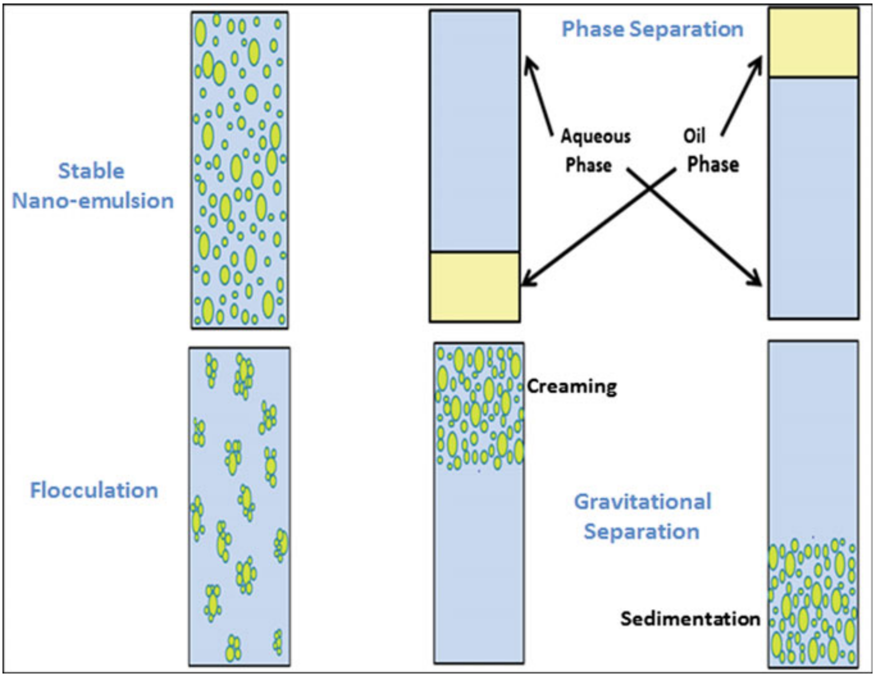

Fig. 3 Schematic representation of the stable nanoemulsion and breakdown of the system through various mechanisms, such as flocculation, gravitational separation, and phase separation. Adapted with permission from Ref. [27] Copyright 2017, Taylor and Francis Group

High-Energy Approaches

The formulation of NEs by high-energy approaches is done by using mechanical devices able to cause powerful forces that can disrupt the aqueous and oil phases into tiny oil droplets. These approaches include micro-fluidizers, sonication methods, and high-pressure valve homogenizers [28, 29].

2.1.2 Preparation of Essential Oils Nanoparticles

To prepare encapsulated NPs of EOs, polyethylene glycol is heated at 65 °C till it melts. Afterwards, EOs are mixed with polyethylene glycol; the mixture then has to be stirred heavily for 30 min to guarantee the dispersion of the EOs in the polyethylene glycol. Then, cooling of the mixture for 2 h at −4 °C to form the NPs spontaneously, then grinding in a refrigerated mortar (0 °C) and sieving by a sieve mesh 230. The powders have to be kept in sealed polyethylene pouches then stored at 27 ± 2 °C in a desiccator comprising calcium chloride to avoid absorption of moisture [22]. EOs in solid controlled-release NPs coated by polyethylene glycol prevent degradation and rapid evaporation of the EOs and enhance the insecticidal activities of them through ingestion and contact with the insect pest [22, 30].

2.2 *Control of Harmful Insects Using Nanoinsecticides Derived from Citrus Wastes*

Several nanoinsecticides have been studied to control the medically necessary insects which transmit dangerous diseases such as the disease-vector mosquitoes and the domestic cockroaches which live near human beings in the houses, hospitals, and restaurants. In addition to the insects that cause economic loss such as the pests of the stored grains and the pests of field plants.

2.2.1 Control of Disease-Vector Mosquito *Culex pipiens* Using Citrus Essential Oils Nanoemulsion

Mosquitoes transmit several dangerous human diseases, including malaria, rift valley fever, and encephalitis viruses. The control of disease-vector mosquitoes is facing ecological and economic challenges regarding the environmental consideration, besides the expansion of resistance of the mosquito species against the conventional chemical insecticides [31, 32]. There is a critical necessity for novel eco-friendly control tactics; the use of botanical-based insecticides is auspicious because they are more eco-friendly, while the synthetic insecticides pollute the environment and harm the non-target organisms.

The EOs of *C. sinensis* (Rutaceae) contain many constituents such as monoterpenes, limonene, pinene, octanal, and terpinolene [31]. Nanotechnology makes it possible to overcome the obstacles of EOs application as insecticides, such as poor water solubility and vaporization of volatile compounds. The formulation of NEs from EOs conserves the biological activity of the EOs; this formulation could be used effectively to control the aquatic larval stage of *Culex pipiens* [33].

Azmy et al. prepared NE from EOs extracted from peels of *C. sinensis* (agricultural wastes) by the high-energy ultrasonication method. This study contributed to nanobiotechnology presenting an effective larvicide against the disease-vector mosquito *C. pipiens with* LC_{50} equal to 27.4 ppm; the droplet size distribution of the NE is shown in Fig. 4; the mean droplet diameter of the nanoemulsion was calculated to be 78.8 ± 14.2 nm [26, 33]. The stabilization of the NE is due to the surfactant, as it acts as a mechanical barrier that prevents the accumulation of the NE droplets [34]. Larvicidal activity of the NE may be due to the primary component (limonene), which is reported to have insecticidal properties [34].

The high efficacy of the NE may be a result of the tiny size of droplets of the NE, which increases the surface area and facilitates the penetration of the active

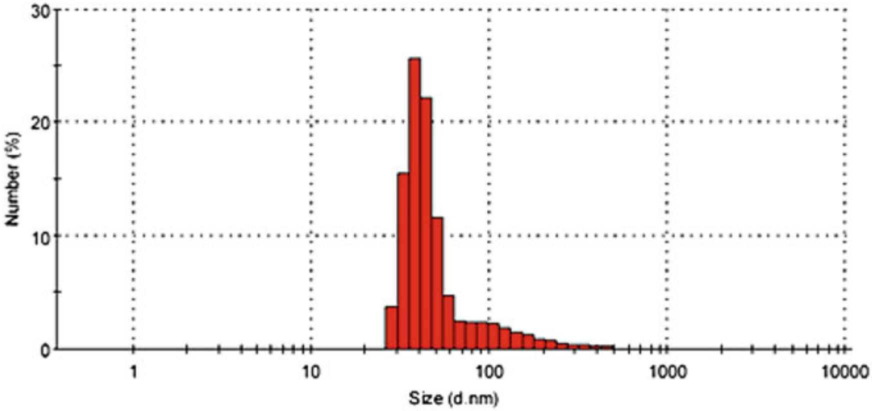

Fig. 4 Droplet size distribution of the nanoemulsion droplets. Adapted with permission from Ref. [33]

ingredients in the EOs into the mosquito larvae. The botanical molecules can interact with larval body enzymes and hormones, bind to cellular membranes, and thus interfere with the biochemical pathways of the mosquito larvae [35, 36]. In addition, NEs of EOs have various advantages, including long shelf life and biodegradation [37].

2.2.2 Control of the German Cockroach Pest

Blattella germanica is a cockroach pest commonly found in urban environments as houses, hospitals, restaurants, and food production facilities [38]. This insect is a vector of several pathogens, such as bacteria, protozoa, viruses, and helminths [39, 40]. The development of resistance in the cockroach populations against synthetic insecticides as organophosphates, organochlorines, pyrethroid, and carbamates, and the concern about the environment demands new and safe control approaches [41–45]. Bio-insecticides made of EOs can be used as an alternative method for pest management [46–49]. The application of EOs is progressively considered for control programs because they are generally less toxic to human beings and the environment than the synthetic neurotoxic insecticides [50]. However, some obstacles related to EOs poor water solubility, volatility, lack of persistence, and a tendency to oxidation should be overcome before using them as an alternative control system [50]. Nanoformulation of the EOs could be the solution to the EOs limitations, and it also provides a controlled release of EOs.

Nanoformulations of EOs are more soluble, with higher surface area, smaller particle size, and lower toxicity because no organic solvents which are used as in conventional pesticides and their formulations [20]. Thus, this formulation is safe to be used in domestic places such as houses, schools, and restaurants, where the cockroach pest exists. González et al. used polyethylene glycol as a coating material for EOs extracted from fruit peels (agricultural waste) of bergamot, *Citrus reticulate*, EOs to control *B. germanica* [37]. Polyethylene glycol has a full scale of solubility and non-interference with enzymatic activities of the living organisms and the natural excretion from them [51]. This nanoformulation of the EOs causes a remarkable rise in the contact toxicity due to the persistent release of the terpenes in the EOs and improves the contact activity against the first instar and adults of *B. germanica*. González et al. assumed that the polyethylene glycol stabilizes the EOs and decreases the volatility of the terpenes. They noticed that the major components of EOs in the nanoformulation did not change chemically through the time of storage, so no hydrolytic or oxidized derivatives were found from the original compound. This is an indication of no breakdown of the active constituents [37]. The nanoformulation enables better penetration of EOs constituents into the insect tissues [52]. Faster penetration may occur by contact with the cuticle of the insect or through penetration of the digestive tract [52, 53]. The nanoformulation droplets exhibit a large surface area; they can increase the exposure time of the biologically active ingredients of the EOs to the insect tissues.

2.2.3 Control of Stored Grains Pests

Rhizopertha dominica is a common serious pest of stored grains such as rice, wheat and corn. At the same time, *Tribolium castaneum* is a common secondary pest in stored grains. Control of such pests depends on synthetic insecticides as pyrethroids, organophosphates, and fumigants [54, 55]. These insecticides are cost-effective, but cause problems like environmental pollution and resistant behaviour besides the negative effects on human health and the other organisms [56–58] . EOs display efficient repellent and toxic effects against several stored product insect pests [59–61]. Despite these promising effects, EOs have problems in the application concerning volatility, stability, and sustainability [37].

González et al. studied the incorporation of *C. reticulate* (bergamot) EOs in stable controlled-release NPs against both *R. dominica* and *T. castaneum*. They used polyethylene glycol as a carrier; it prevents fast evaporation and enhances the stability and insecticidal activities of these EOs [22]. The designed solid nanoformulation of the EOs is favourable for the control of pests in the stored grain, as it does not affect the humidity, which is a significant factor regarding the seed's quality [22]. Insect cuticle is produced by the epidermal cells, and it covers the whole body of the insect. The cuticle extends in the foregut, hindgut, and the tracheal system. It consists of various layers: wax, epicuticle, then exocuticle, and endocuticle. Exocuticle and endocuticular layers consist of crystalline chitin nanofibres in a matrix of polyphenols, protein, water, and minor quantities of lipids [62].

It is suggested that constituents of the EOs alone (non-polar or minimally polar) diffuse vertically and/or horizontally in the insect cuticle [22]. The horizontal diffusing occurs when these constituents reach the tracheal system; then, they carry on moving to the other tissues in the insect and finally reach their sites of action. At the same time, the vertical diffusing occurs when the EOs constituents enter through the tegument towards the epidermis and then enter into the organism [63, 64].

Terpenes of the EOs studied in González et al. work was polar; thus, the external layer of wax could facilitate the horizontal diffusion of this terpene to the detriment of their vertical diffusion through the hydrophilic endocuticle. In contrast, the diffusion of EOs NPs could occur through both the vertical and horizontal diffusion because the NPs had a matrix of polyethylene glycol 6000 with its amphiphilic nature (has both hydrophilic and hydrophobic properties); it is soluble in water and some polar organic solvents. This different uptake pathway between the EOs only and the NPs of EOs may be related to the improvement of the toxicological activity against the insect. Moreover, the nanoformulation has a large surface area resulting in more adhesiveness of bergamot EOs coated with polyethylene glycol to the tissues of the insect, extending the exposure time and contact with the active ingredients [22]. Giunti et al., 2019 developed NE containing sweet orange (*C. sinensis*) EOs and evaluated its repellence activity against two insect pests of stored grains: *Tribolium confusum* and *Cryptolestes ferrugineus*. The developed nanoformulation showed acute toxicity against both insects when tested as cold aerosol and fumigant. The NE was effective in repelling and controlling the target pests. Cold aerosol treatments with nanoformulations of EOs are promising alternatives for the sanitation of warehouses, production areas, and machinery [65].

2.2.4 Control of Tomato Crop Pest

The tomato crop has a great economic significance worldwide; it is threatened by the tomato borer *Tuta absoluta* [66]. This insect has a great reproductive potential reaching 13 generations in the year [67]. The larvae feed into the plant leaves, fruits, and stems, causing a serious loss in tomato yields. The high rate of growth and severe damage caused by this tomato crop pest forced the farmers to raise the times of insecticides application [67]. This misuse resulted in the resistance towards these insecticides [68] and also caused a negative impact on the non-target living organisms, such as the pollinators and natural enemies [69, 70]. As a result of these negative impacts, alternative safe insecticides are needed. Among the various plant-derived active materials, EOs showed efficacy in controlling insect pests [71]. Despite the promising properties of EOs, there are some drawbacks that can affect their application like environmental degradation, poor solubility in water, volatility, and tendency to oxidize [50].

The encapsulation of EOs into NPs with polyethylene glycol as a coating material could solve these problems and improve their efficacy due to the small size of the particles [22]. This formulation improves the solubility of the EOs in water and controls the release of the active ingredients [72]. Campolo et al. formulated polyethylene glycol NPs containing EOs of different citrus peels (lemon, mandarin, and sweet orange) to control these tomato borer (*T. absoluta*) larvae through contact and ingestion route. The results showed higher insecticidal activity of NPs on larvae through ingestion; NPs of the mandarin EOs had the highest efficacy through the ingestion toxicity [20]. NPs have more mobility than the bulk materials; this property enables the fast penetration of the active constituents into the insect tissues [73, 74]. In addition, NPs can release the active ingredients of the EOs gradually at the site of action [75].

3 Application of Nanomaterials of Citrus Wastes in the Food Industry

Currently, the preservation of foodstuff products is the most vital concern in the food industry [76]. Processed food products are exposed to contamination with microbes and spoilage by the enzymatic activity. As a result of cutting the food product, the inside nutrients are exposed to the enzymes and microorganisms that reduce the shelf life [77].

The chemical materials used to inhibit some enzymes and decrease the growth rate of microbes in the food products may have toxicological effects in the long run [78, 79]. So, new alternatives for these chemical treatments should be developed through new technologies [80]. The use of EOs is considered as an efficient alternative. EOs are botanical products which consist of a combination of constituents as terpenoids, terpenes, and aromatic phenol-derived constituents with high antioxidant and antimicrobial efficiency. EOs showed promising use for food application because of its ability to prolong the shelf lifetime of processed food by preventing lipid oxidation [67, 81, 82]. The antimicrobial impact of EOs is related to the dissolving of the bacterial cytoplasmic membrane [83]; some studies reported the ability of EOs to inhibit *Staphylococcus aureus* 10 and *Bacillus cereus* [84].

Although EOs thought to be promising in food industries, the use of EOs is often limited as a result of many factors such as rapid volatility, strong odour, and low solubility in water. On the other hand, it is challenging to mix oily compounds in aqueous products due to the chemical and physical instability when applying in the food systems [83]. Thus, the formation of new innovative delivery methods to enhance the effectiveness of EOs is a demand in the foodstuff industries. A promising approach to overcome such obstacles is to incorporate the EOs in the formulation of NEs. The NE is composed of two immiscible phases, the EOs, and the aqueous phase, with droplets of size from 10 to 100 nm [85]. NEs are stable emulsions in which the surfactant is used to stabilize EOs and water phases by decreasing their surface tension [21]. The application of NEs in beverages and drinks is growing due to the small droplet size and transparency or only slight turbidly in the product [86]. Citrus EOs are generally recognized as safe by the United States food and drug administration [87]; they can be used with edible coatings and films to provide protection without significant impact on the sensory properties of the food (Fig. 5).

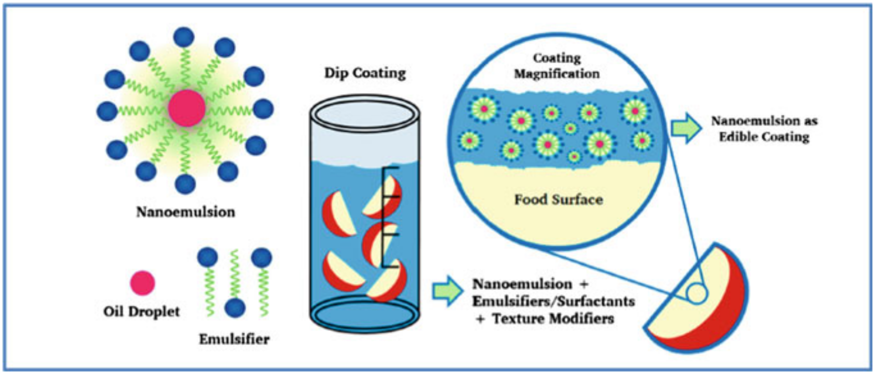

Fig. 5 Schematic demonstration of using nanoemulsion as food coatings. Adapted with permission from Ref. [88] Copyright 2018, MDPI

3.1 Preservation of Fish Products

Wu et al. designed NE coating from EOs extracted from citrus peels to preserve silvery pomfret fish (*Pampus argenteus*); this nanoemulsion coating was formed through the incorporation of the EOs to chitosan coating (biopolymer-based edible coating) onto the fish surface. They studied the preservation effect of the NE coating compared to the coating with conventional emulsions; the NE coating showed potential antimicrobial activities and acted as a barrier to oxidative reaction and gas exchange during the refrigerated storage process. The NE coating was efficient in preventing the growth of microorganisms and the changes in the product chemistry during the storage. As a result, the NE coating extended the shelf life of the fish product from 12 to 16 days [85]. This work showed that the NE coating containing citrus EOs could be used efficiently in seafood preservation.

Severino et al. and Donsì et al. used coating based on chitosan containing NE of EOs extracted from the citrus agricultural wastes, mandarin peels, on green beans. Their experiments were associated with several non-thermal treatments against *Listeria innocua*; the results revealed a promising application of this type of NE in the food industry [86, 88].

3.2 Increasing the Shelf Life of the Cake

Citrus wastes principally the peels are a rich source of dietary fibres and antioxidants; they can be used in processing healthy food products. The shelf life of foodstuff products is limited; manufacturers of foods need to prevent the oxidation process for the sake of shelf life prolongation of such products. Therefore, antioxidants became essential food additives [89].

Synthetic antioxidants may cause toxic or carcinogenic effects. So, natural resources gained attention, especially, by-products of several juice factories [85]. The extract of dried peels of lemon and orange could be potential antioxidants in foodstuff products. Mahmoud et al. encapsulated lemon and orange extract studied its efficiency on the shelf life of the cake. They applied this nano formulated antioxidants on the cake and then evaluated its influence on the cake sensory and stability properties [90]. The results showed strong antioxidant activity and extension of the storage time of the cake at room temperature. The influence of the nanoencapsulation was estimated and then compared with butylhydroxytoluene, which is a common synthetic antioxidant. There was no notable change in the taste, colour, odour, texture foodstuff industries whole acceptability of the cake samples. Encapsulation empowers the entrapment of active ingredients inside a carrier, then transport, and discharges these active ingredients through a controlled system [86].

3.3 Processed Cheese Supplemented with Nanoliposomes

Processed cheese is widely consumed and has a high nutritional value, but it requires efficient preservation during the long shelf life [90]. Phenolic compounds are known for their antimicrobial and antioxidant activity; the use of EOs containing phenolic compounds improves the nutritional value and reduces the spoilage rate of the processed cheese [91]. These compounds can be extracted from natural sources, such as citrus fruits, and the consumers are more concerned with the compounds from natural resources. However, the interaction between the proteins in milk and the phenolic compounds causes the loss of phenolic compounds activity and reduces the nutritional value of the cheese [92].

El-Messery et al. prepared nanoliposomes as encapsulation technique of mandarin peel extract to be added to the processed cheese as an alternative to bioactive phenolic compounds. These nanoliposomes can help in the conservation of phenolic compounds from the mandarin peel and protect these phenolic compounds from interaction with milk proteins [93]. They found that the encapsulation efficiency of the nanoliposomes during the cold storage of the processed cheese was stable for three months. In addition, they noticed no change in the phenolic content, the physical and chemical properties of the cheese samples. This study reveals that nanoliposomes of EOs is a promising technique to produce processed cheese with a high content of phenolics and prevent the phenolics from interaction and retain their efficiency.

3.4 Mechanism of Antimicrobial Activity of the Essential Oils Nanoformulations

Hydrophobicity is the important characteristic of EOs, and the lipophilic nature of their constituents permits them to interact with the fatty acids of the microbial cell membrane [94]. It is well known that gram-positive bacteria are susceptible to EOs in comparison to gram-negative bacteria [95]. This may be due that gram-negative bacteria have complex and rigid membrane rich in lipopolysaccharide that limits the diffusion of hydrophobic constituents through it. On the other hand, gram-positive is surrounded by a thick peptidoglycan wall. It is not sufficiently dense to resist the small antimicrobial molecules which facilitate access to the cellular membrane [96, 97]. Numerous reports support that the bioactive constituents in EOs might attach to the cell surface and penetrate the phospholipid bilayer of the cell membrane. Therefore, their accumulation disturbs the structure of the cell membrane and influences the cell metabolism leading to cell death, as shown in Fig. 6 [98, 99]. The antimicrobial efficiency of EOs can be enriched by encapsulating with several nanomaterials such as liposomes, NEs, and polymeric NPs. The nanoencapsulation of the EOs control the release of the active constituents, decrease the volatility, and protect it from the environmental pressure [100].

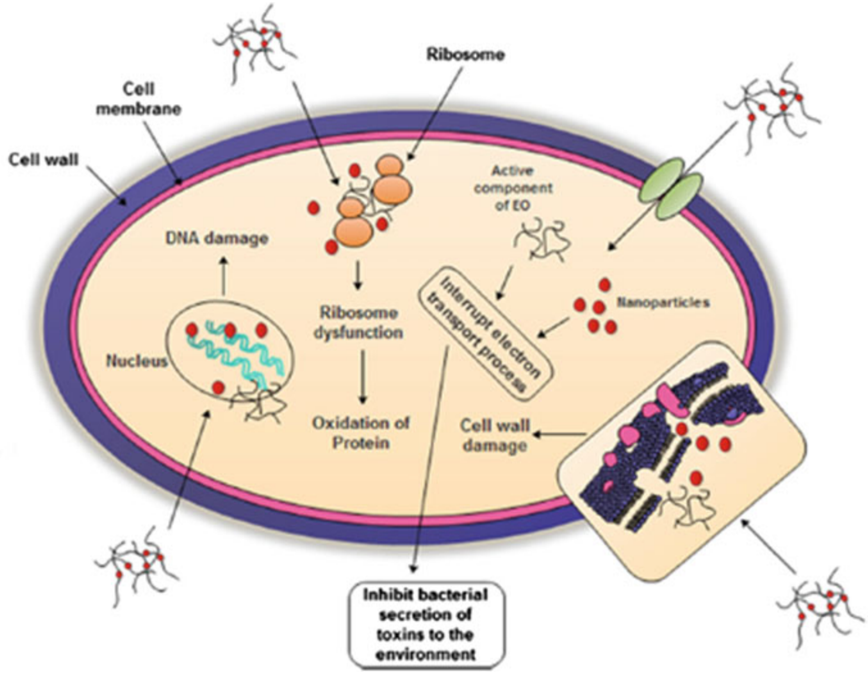

Fig. 6 Schematic demonstration of possible nanoencapsulated EOs mechanism of actions. Adapted with permission from Ref. [94] Copyright 2017, Elsevier

4 Nanocellulose Derived from Citrus Wastes

Cellulose, in the form of nanostructures, is known as nanocellulose; it is one of the most noticeable green materials. Nanocellulose gained increasing interests due to its attractive characteristics such as biocompatibility, nontoxicity, abundance, and renewability [101]. Several applications of nanocellulose attracted attention, such as the water treatment to remove pollutants and the manufacturing of high-performance composites. Owing to the low cost and energy, the extraction of nanocellulose from the agricultural wastes is a smart alternative for waste treatment [102].

4.1 Water Treatment Using Nanocellulose Derived from Citrus Wastes

Nonhazardous adsorption materials like nanocellulose are an important source for the elimination of the water pollutants without a dangerous effect on human health and the environment. Nanocellulose can be produced from agricultural wastes through different methods; bacterial, chemical, and physical, depending on the fibre content [103–105]. Several studies reported citrus peels as one of the best sources of nanocellulose [102, 106, 107]. Nanocellulose affords an alternative to the conventional adsorbent materials as zeolite or activated carbon. The use of nanocellulose in water treatment was effectively reported for the removal of heavy metal and organic pollutants [108]. High adsorption achieved by the nanocelluloses is due to its several reactive groups and large surface areas.

Several studies were reported concerning with use of modified nanocellulose in the removal of heavy metals from polluted water. The modification of the nanocellulose surface was done by adding groups to cellulose surfaces such as amine [109] carboxyl [110, 111], xanthate, and ammonium [112]. Modified nanocellulose was used to adsorb lead and cadmium ions from the wastewater with much higher adsorption capacities compared to the raw cellulose [113–115].

4.2 Materials Prepared from Nanocellulose for Production of Composite Materials

The application of nanocellulose as a composite material brought attention to the brilliant properties of nanocellulose. These properties include lightweight, high strength, and biodegradability [12, 15], in addition to its high rigidity as supporting material, which makes it ideally used in composite materials [27]. Such biomaterial has high applicability in numerous industries such as plastics and polymer composites, films, gels, foams, cosmetics, and implant material, concrete, coatings, screens. Nanocelluloses have a much larger surface area than cellulose, so it is an eco-friendly source for paper production with considerable quality. Nanocellulose can be used in high strength and lightweight material for electronics, coatings, and latex paints [116]. Moreover, nanocellulose can be applied in drug delivery as a biodegradable tissue scaffold and the production of filter paper used in the treatment of water and oil recovery [117].

5 Conclusion

This chapter summarizes the use of nanotechnology to convert citrus wastes into innovative nanomaterials through different formulations such as NEs and nanocapsules. These materials have excellent properties such as biodegradability and high efficiency and can be used in various fields. The nanoinsecticides can be applied to control disease-vector mosquitoes, the domestic cockroach pest, the stored gain pests, and the plant cop pests as a tomato. Also, these innovative nanomaterials can be used in the food industry to prolong the shelf life of many products, such as processed cheese, cake, and fish products. Finally, the chapter mentioned the application of the nanomaterials of the citrus waste in water treatment and their great application in various composite materials. However, there is still a significant gap in knowledge about the whole lifecycles of the nanomaterials in general. It is crucial to assess the consequences of using nanomaterials on the environment. Along with the determination of the optimum dose and safe limits and the interactions with the food matrices, other packaging materials, and antimicrobial compounds.

6 Future Perspectives

Despite reducing pollution through recycling of the citrus wastes and the production of a new type of promising materials, more studies are mandatory to estimate the effect of these new nanomaterials on the living organisms, especially the human beings and the environment, including the water sources and the soil. Environmental issues have to be taken into consideration when applying the nanomaterials in different products such as coatings, latex paints, plastics, foams, and cosmetics because these products can be frequently touched and handled by people. The excellent penetration power of NPs due to their tiny size requires excellent attention. Generally, NPs can enter organisms during inhalation or ingestion and can accumulate within the body to various tissues and organs due to long exposure. Moreover, the use of nanomaterials in packaging and food processing may cause a new collection of risks. Consumers are noticed to be accepting of nanomaterials in the out packaging more than in food processing. There is a need for safety assessments with an increasing number of food products containing nanomaterials. For example, studying the migration of NPs from food packaging into the foodstuff and the problem of accumulation of these particles in the living organisms. In addition, the various reaction factors such as pressure, pH, temperature, and time have to be evaluated as it may affect the nature of the properties of the nanomaterials.

References

1. Okwu DE, Emenike IN (2006) Evaluation of the phytonutrients and vitamin contents of Citrus fruits. Int J Mol Med Adv Sci 2(1):1–6
2. de Castro MDL (2014) Towards a comprehensive exploitation of agrofood residues: olive tree–olive oil as example. Comptes Rendus Chim 17(3):252–260
3. Martín M, Siles J, El Bari H, Chica A, Martin A (2010) Orange peel: organic waste or energetic resource. Technol Syst Differ Manure Org Waste Treat Opt 1:25–28
4. Sharma K, Mahato N, Cho MH, Lee YR (2017) Converting citrus wastes into value-added products: economic and environmently friendly approaches. Nutrition 34:29–46
5. Awan AT, Tsukamoto J, Tasic L (2013) Orange waste as a biomass for 2G-ethanol production using low cost enzymes and co-culture fermentation. Rsc Adv 3(47):25071–25078
6. Lin J, Zuo J, Gan L, Li P, Liu F, Wang K, Chen L, Gan H. (2011) Effects of mixture ratio on anaerobic co-digestion with fruit and vegetable waste and food waste of China. J Environ Sci 23(8):1403–1408
7. Sharma K, Mahato N, Lee YR (2019) Extraction, characterization and biological activity of citrus flavonoids. Rev Chem Eng 35(2):265–284
8. Mahato N, Sharma K, Koteswararao R, Sinha M, Baral E, Cho MH (2019) Citrus essential oils: extraction, authentication and application in food preservation. Crit Rev Food Sci Nutr 59(4):611–625
9. Mahato N, Sharma K, Sinha M, Cho MH (2018) Citrus waste derived nutra-/pharmaceuticals for health benefits: current trends and future perspectives. J Funct Foods 40:307–316
10. Mahato N, Sharma K, Nabybaccus F, Cho MH (2016) Citrus waste reuse for health benefits and pharma-/neutraceutical applications. Era's J Med Res 3(1):20–32
11. Su H, Tan F, Xu Y (2016) Enhancement of biogas and methanization of citrus waste via biodegradation pretreatment and subsequent optimized fermentation. Fuel 181:843–851
12. Negro V, Mancini G, Ruggeri B, Fino D (2016) Citrus waste as feedstock for bio-based products recovery: review on limonene case study and energy valorization. Bioresour Technol 214:806–815
13. Mamma D, Christakopoulos P (2014) Biotechnological potential of citrus peels. Springer, Dordrecht, pp 273-291
14. Zema DA, Calabrò PS, Folino A, Tamburino V, Zappia G, Zimbone SM (2018) Valorisation of citrus processing waste: a review. Waste Manag 80:252–273
15. Fagbohungbe MO, Herbert BMJ, Hurst L, Li H, Usmani SQ, Semple KT (2016) Impact of biochar on the anaerobic digestion of citrus peel waste. Bioresour Technol 216:142–149
16. Kah M, Beulke S, Tiede K, Hofmann T (2013) Nanopesticides: state of knowledge, environmental fate, and exposure modeling. Crit Rev Environ Sci Technol
17. Mahato N, Sinha M, Sharma K, Koteswararao R, Cho MH (2019) Modern extraction and purification techniques for obtaining high purity food-grade bioactive compounds and value-added co-products from citrus wastes. Foods 8(11):523
18. Campolo O, Malacrinò A, Zappalà L, Laudani F, Chiera E, Serra D, Russo M, Palmeri V. (2014) Fumigant bioactivity of five Citrus essential oils against Tribolium confusum. Phytoparasitica 42(2):223–233
19. Song J-E, Kim J-M, Lee N-H, Yang J-Y, Lee H-S (2016) Acaricidal and insecticidal activities of essential oils against a stored-food mite and stored-grain insects. J Food Prot 79 (1):174–178

20. Campolo O, Cherif A, Ricupero M, Siscaro G, Grissa-Lebdi K, Russo A, Cucci LM, Di Pietro P, Satriano C, Desneux N, Biondi A (2017) Citrus peel essential oil nanoformulations to control the tomato borer, Tuta absoluta: chemical properties and biological activity. Sci Rep 7(1):1–10
21. McClements DJ (2015) Food emulsions: principles, practices, and techniques. CRC press
22. González JOW, Gutiérrez MM, Ferrero AA, Band BF (2014) Essential oils nanoformulations for stored-product pest control–characterization and biological properties. Chemosphere 100:130–138
23. Mason TG, Wilking JN, Meleson K, Chang CB, Graves SM (2006) Nanoemulsions: formation, structure, and physical properties. J Phys: Condens Matter 18:635–666. https://doi.org/10.1088/0953-8984/18/41/r01
24. Tadros T, Izquierdo P, Esquena J, Solans C (2004) Formation and stability of nano-emulsions. Adv Colloid Interface Sci 108:303–318
25. Anton N, Gayet P, Benoit J-P, Saulnier P (2007) Nano-emulsions and nanocapsules by the PIT method: an investigation on the role of the temperature cycling on the emulsion phase inversion. Int J Pharm 344(1–2):44–52
26. Kralova I, Sjöblom J (2009) Surfactants used in food industry: a review. J Dispers Sci Technol 30(9):1363–1383
27. McClements DJ, Rao J (2011) Food-grade nanoemulsions: formulation, fabrication, properties, performance, biological fate, and potential toxicity. Crit Rev Food Sci Nutr 51 (4):285–330
28. Leong TSH, Wooster TJ, Kentish SE, Ashokkumar M (2009) Minimising oil droplet size using ultrasonic emulsification. Ultrason Sonochem 16(6):721–727
29. Gutiérrez JM, González C, Maestro A, Solè I, Pey CM, Nolla J (2008) Nano-emulsions: new applications and optimization of their preparation. Curr Opin Colloid Interface Sci 13 514 (4):245–251
30. Velikov KP, Pelan E (2008) Colloidal delivery systems for micronutrients and nutraceuticals. Soft Matter 4(10):1964–1980
31. Akono PN, Dongmo PM, Tonga C, Kouotou S, Kekeunou S, Magne GT, Lehman LG, Menut C (2015) Larvicidal activity of essential oils from pericarps of ripe Citrus fruits cultivated in Cameroon on pyrethroids sensitive and resistant strains of Anopheles gambiae Giles, 1902. J Entomol Zool Stud 3:334–339
32. Anjali CH, Khan SS, Margulis-Goshen K, Magdassi S, Mukherjee A, Chandrasekaran N (2010) Formulation of water-dispersible nanopermethrin for larvicidal applications. Ecotoxicol Environ Saf 73(8):1932–1936
33. Azmy RM, El Gohary EGE, Mahmoud DM, Salem DAM, Abdou MA, Salama MS (2019) Assessment of larvicidal activity of nanoemulsion from Citrus sinensis essential oil on Culex pipiens L. (Diptera: Culicidae). Egypt J Aquat Biol Fish 23(3):61–67
34. Saad MMG (2013) Chemical composition and biological activities of four Citrus essential oils. J Plant Prot Pathol 4(9):767–780
35. Fallatah SA (2010) Histopathological effects of fenugreek (Trigonella foenumgraceum) extracts on the larvae of the mosquito Culex quinquefasciatus. J Arab Soc Med Res 5 (2):123–130
36. Mishra P, Tyagi BK, Chandrasekaran N, Mukherjee A (2018) Biological nanopesticides: a greener approach towards the mosquito vector control. Environ Sci Pollut Res 25 (11):10151–10163
37. González JOW, Stefanazzi N, Murray AP, Ferrero AA, Band BF (2004) Novel nanoinsecticides based on essential oils to control the German cockroach. J Pest Sci 88 (2):393–404, 2015
38. Fotedar R, Shriniwas UB, Verma A (1991) Cockroaches (Blattella germanica) as carriers of microorganisms of medical importance in hospitals. Epidemiol Infect 107(1):181–187
39. Pai H-H, Ko YC, Chen ER (2003) Cockroaches (Periplaneta americana and Blattella germanica) as potential mechanical disseminators of Entamoeba histolytica. Acta Trop 87 (3):355–359

40. Cochran DG (1995) Insecticide resistance. Understanding and controlling the German cockroach. Oxford University Press, New York, pp 171–192
41. Hemingway J, Small GJ, Monro AG (1993) Possible mechanisms of organophosphorus and carbamate insecticide resistance in German cockroaches (Dictyoptera: Blattelidae) from different geographical areas. J Econ Entomol 86(6):1623–1630
42. Valles SM, Yu SJ (1996) Detection and biochemical characterization of insecticide resistance in the German cockroach (Dictyoptera: Blattellidae). J Econ Entomol 89(1):21–26
43. Wei Y, Appel AG, Moar WJ, Liu N (2001) Pyrethroid resistance and cross-resistance in the German cockroach, Blattella germanica (L). Pest Manag Sci Former Pestic Sci 57(11):1055–1059
44. Casida JE, Durkin KA (2013) Neuroactive insecticides: targets, selectivity, resistance, and secondary effects. Annu Rev Entomol 58:99–117
45. Köhler H-R, Triebskorn R (2013) Wildlife ecotoxicology of pesticides: can we track effects to the population level and beyond? Science (80-) 341(6147):759–765
46. Tripathi AK, Upadhyay S, Bhuiyan M, Bhattacharya PR (2009) A review on prospects of essential oils as biopesticide in insect-pest management. J Pharmacogn Phyther 1(5):52–63
47. Talbert R, Wall R (2012) Toxicity of essential and non-essential oils against the chewing louse, Bovicola (Werneckiella) ocellatus. Res Vet Sci 93(2):831–835
48. Athanassiou CG, Kavallieratos NG, Evergetis E, Katsoula A-M, Haroutounian SA (2013) Insecticidal efficacy of silica gel with Juniperus oxycedrus ssp. oxycedrus (Pinales: Cupressaceae) essential oil against Sitophilus oryzae (Coleoptera: Curculionidae) and Tribolium confusum (Coleoptera: Tenebrionidae). J Econ Entomol 106(4):1902–1910
49. Isman MB, Miresmailli S, Machial C (2011) Commercial opportunities for pesticides based on plant essential oils in agriculture, industry and consumer products. Phytochem Rev 10 (2):197–204
50. Moretti MDL, Sanna-Passino G, Demontis S, Bazzoni E (2002) Essential oil formulations useful as a new tool for insect pest control. AAPS PharmSciTech 3(2):64–74
51. Danprasert K, Kumar R, Ming H, Gupta P, Shakil NA, Prasad AK, Parmar VS, Kumar J, Samuelson LA, Watterson AC. (2003) Synthesis of novel poly (ethylene glycol) based amphiphilic polymers. Eur Polym J 39(10):1983–1990
52. Nel AE, Mädler L, Velegol D, Xia T, Hoek EM, Somasundaran P, Klaessig F, Castranova V, Thompson M. (2009) Understanding biophysicochemical interactions at the nano–biointerface. Nat Mater 8(7):543–557
53. Margulis-Goshen K, Magdassi S (2013) Nanotechnology: an advanced approach to the development of potent insecticides. In: Advanced Technologies for Managing Insect Pests. Springer, Berlin, pp 295–314
54. Saroukolai AT, Moharramipour S, Meshkatalsadat MH (2004) Insecticidal properties of Thymus persicus essential oil against Tribolium castaneum and Sitophilus oryzae. J Pest Sci 83(1):3–8, 2010
55. Edde PA (2012) A review of the biology and control of Rhyzopertha dominica (F.) the lesser grain borer. J Stored Prod Res 48:1–18
56. Kljajić P, Perić I (2006) Susceptibility to contact insecticides of granary weevil Sitophilus granarius (L.) (Coleoptera: Curculionidae) originating from different locations in the former Yugoslavia. J Stored Prod Res 42(2):149–161
57. Islam MS, Hasan MM, Lei C, Mucha-Pelzer T, Mewis I, Ulrichs C (2004) Direct and admixture toxicity of diatomaceous earth and monoterpenoids against the storage pests Callosobruchusmaculatus (F.) and Sitophilus oryzae (L.). J Pest Sci 83(2):105–112, 2010
58. Pimentel MAG, LRD'A F, Guedes RNC, Sousa AH, Tótola MR (2009) Phosphine resistance in Brazilian populations of Sitophilus zeamais motschulsky (Coleoptera: Curculionidae). J Stored Prod Res 45(1):71–74
59. Ali A, Ahmad F, Biondi A, Wang Y, Desneux N (2004) Potential for using Datura alba leaf extracts against two major stored grain pests, the khapra beetle Trogoderma granarium and the rice weevil Sitophillus oryzae. J Pest Sci 85(3):359–366, 2012

60. Isman MB (2006) Botanical insecticides, deterrents, and repellents in modern agriculture and an increasingly regulated world. Annu Rev Entomol 51:45–66
61. Regnault-Roger C (2013) Essential oils in insect control. Nat Prod Berlin, Ger. Springer, Berlin, pp 4087–4102
62. Vincent JFV, Wegst UGK (2004) Design and mechanical properties of insect cuticle. Arthropod Struct Dev 33(3):187–199
63. Sfara V, Zerba EN, Alzogaray RA (2009) Fumigant insecticidal activity and repellent effect of five essential oils and seven monoterpenes on first-instar nymphs of Rhodnius prolixus. J Med Entomol 46(3):511–515
64. Tarelli G, Zerba EN, Alzogaray RA (2009) Toxicity to vapor exposure and topical application of essential oils and monoterpenes on Musca domestica (Diptera: Muscidae). J Econ Entomol 102(3):1383–1388
65. Giunti G, Palermo D, Laudani F, Algeri GM, Campolo O, Palmeri V (2019) Repellence and acute toxicity of a nano-emulsion of sweet orange essential oil toward two major stored grain insect pests. Ind Crops Prod 142:111869
66. Desneux N, Luna MG, Guillemaud T, Urbaneja A (2011) The invasive South American tomato pinworm, Tuta absoluta, continues to spread in Afro-Eurasia and beyond: the new threat to tomato world production. J Pest Sci 84(4):403–408
67. Garzia GT, Siscaro G, Biondi A, Zappalà L (2012) Tuta absoluta, a South American pest of tomato now in the EPPO region: biology, distribution and damage. EPPO Bull 42(2):205–210
68. Haddi K, Berger M, Bielza P, Cifuentes D, Field LM, Gorman K, Rapisarda C, Williamson MS, Bass C. (2012) Identification of mutations associated with pyrethroid resistance in the voltage-gated sodium channel of the tomato leaf miner (Tuta absoluta). Insect Biochem Mol Biol 42(7):506–513
69. Biondi A, Zappalà L, Stark JD, Desneux N (2013) Do biopesticides affect the demographic traits of a parasitoid wasp and its biocontrol services through sublethal effects? PLoS One 8 (9):e76548
70. Abbes K, Biondi A, Kurtulus A, Ricupero M, Russo A, Siscaro G, Chermiti B, Zappalà L (2015) Combined non-target effects of insecticide and high temperature on the parasitoid Bracon nigricans. PLoS One 18;10(9):e0138411
71. Cardiet G, Fuzeau B, Barreau C, Fleurat-Lessard F (2004) Contact and fumigant toxicity of some essential oil constituents against a grain insect pest Sitophilus oryzae and two fungi, Aspergillus westerdijkiae and Fusarium graminearum. J Pest Sci 85(3):351–358
72. Sasson Y, Levy-Ruso G, Toledano O, Ishaaya I (2007) Nanosuspensions: emerging novel agrochemical formulations. In: Insecticides Design Using Advanced Technologies. Springer, Berlin, pp 1–39
73. Gogos A, Knauer K, Bucheli TD (2012) Nanomaterials in plant protection and fertilization: current state, foreseen applications, and research priorities. J Agric Food Chem 60 (39):9781–9792
74. de Oliveira JL, Campos EVR, Bakshi M, Abhilash PC, Fraceto LF (2014) Application of nanotechnology for the encapsulation of botanical insecticides for sustainable agriculture: prospects and promises. Biotechnol Adv 32(8):1550–1561
75. Rasooli I (2007) Food preservation–a biopreservative approach. Food 1(2):111–136
76. Madden JM (1992) Microbial pathogens in fresh produce–the regulatory perspective. J Food Prot 55(10):821–823
77. Madden JM (1992) Microbial pathogens in fresh produce–The regulatory perspective. J Food Prot 55(10):821–823
78. Beuchat LR (1998) World Health Organization. Surface decontamination of fruits and vegetables eaten raw: a review.
79. Hansen FT, Sørensen JL, Giese H, Sondergaard TE, Frandsen RJN (2012) Quick guide to polyketide synthase and nonribosomal synthetase genes in Fusarium. Int J Food Microbiol 155(3):128–136
80. Giatrakou V, Ntzimani A, Savvaidis IN (2010) Effect of chitosan and thyme oil on a ready to cook chicken product. Food Microbiol 27(1):132–136

81. López-Malo A, Alzamora SM, Guerrero S (2000) Natural antimicrobials from plants. In: Minimally processed fruits and vegetables. Fundamentals aspects and applications. Aspen Publishers, Gaithersburg, MD, p 237
82. Ghosh V, Mukherjee A, Chandrasekaran N (2014) Eugenol-loaded antimicrobial nanoemulsion preserves fruit juice against, microbial spoilage. Colloids Surfaces B Biointerfaces 114:392–397
83. Prakash A, Baskaran R, Paramasivam N, Vadivel V (2018) Essential oil based nanoemulsions to improve the microbial quality of minimally processed fruits and vegetables: a review. Food Res Int 111:509–523
84. Chang Y, McLandsborough L, McClements DJ (2012) Physical properties and antimicrobial efficacy of thyme oil nanoemulsions: influence of ripening inhibitors. J Agric Food Chem 60 (48):12056–12063
85. Wu C, Wang L, Hu Y, Chen S, Liu D, Ye X (2016) Edible coating from citrus essential oil-loaded nanoemulsions: physicochemical characterization and preservation performance. RSC Adv 6(25):20892–20900
86. Severino R, Vu KD, Donsì F, Salmieri S, Ferrari G, Lacroix M (2014) Antibacterial and physical effects of modified chitosan based-coating containing nanoemulsion of mandarin essential oil and three non-thermal treatments against Listeria innocua in green beans. Int J Food Microbiol 191:82–88
87. Persico P, Ambrogi V, Carfagna C, Cerruti P, Ferrocino I, Mauriello G (2009) Nanocomposite polymer films containing carvacrol for antimicrobial active packaging. Polym Eng Sci 49(7):1447–1455
88. Zambrano-Zaragoza ML, González-Reza R, Mendoza-Muñoz N, Miranda-Linares V, Bernal-Couoh TF, Mendoza-Elvira S, Quintanar-Guerrero D (2018) Nanosystems in edible coatings: a novel strategy for food preservation. Int J Mol Sci 19:705
89. Donsì F, Marchese E, Maresca P, Pataro G, Vu KD, Salmieri S, Lacroix M, Ferrari G (2015) Green beans preservation by combination of a modified chitosan based-coating containing nanoemulsion of mandarin essential oil with high pressure or pulsed light processing. Postharvest Biol Technol 106:21–32
90. Buňka F, Hrabě J, Kráčmar S (2004) The effect of sterilisation on amino acid contents in processed cheese. Int Dairy J 14(9):829–831
91. Martillanes S, Rocha-Pimienta J, Cabrera-Bañegil M, Martín-Vertedor D, Delgado-Adámez J (2017) Application of phenolic compounds for food preservation: food additive and active packaging. Phenolic Compd Act London, UK IntechOpen, pp 39–58
92. Mehanna NS, Hassan ZMR, El-Din HMF, Ali AA-E, Amarowicz R, El-Messery TM (2014) Effect of interaction phenolic compounds with milk proteins on cell line. Food Nutr Sci 5 (22):2130
93. El-Messery TM, El-Said MM, Farahat ESA (2019) Production of functional processed cheese supplemented with nanoliposomes of mandarin peel extract. Sciences (New York) 22 (5):247–256
94. Rai M, Paralikar P, Jogee P, Agarkar G, Ingle AP, Derita M, Zacchino S (2017) Synergistic antimicrobial potential of essential oils in combination with nanoparticles: emerging trends and future perspectives. Int J Pharm 519(1–2):67–78
95. Azhdarzadeh F, Hojjati M (2016) Chemical composition and antimicrobial activity of leaf, ripe and unripe peel of bitter orange (Citrus aurantium) essential oils. Nutr Food Sci Res 3 (1):43–50
96. Holley RA, Patel D (2005) Improvement in shelf-life and safety of perishable foods by plant essential oils and smoke antimicrobials. Food Microbiol 22(4):273–292
97. Hyldgaard M, Mygind T, Meyer RL (2012) Essential oils in food preservation: mode of action, synergies, and interactions with food matrix components. Front Microbiol 3:12
98. Bajpai VK, Sharma A, Baek K-H (2013) Antibacterial mode of action of Cudrania tricuspidata fruit essential oil, affecting membrane permeability and surface characteristics of food-borne pathogens. Food Control 32(2):582–590

99. Lv F, Liang H, Yuan Q, Li C (2011) In vitro antimicrobial effects and mechanism of action of selected plant essential oil combinations against four food-related microorganisms. Food Res Int 44(9):3057–3064
100. Bilia AR, Guccione C, Isacchi B, Righeschi C, Firenzuoli F, Bergonzi MC (2014) Essential oils loaded in nanosystems: a developing strategy for a successful therapeutic approach. Evidence-based complement. Altern Med 2014
101. Trache D, Tarchoun AF, Derradji M, Hamidon TS, Masruchin N, Brosse N, Hussin MH (2020) Nanocellulose: from fundamentals to advanced applications. Front Chem 8
102. Mariño M, Lopes da Silva L, Durán N, Tasic L (2015) Enhanced materials from nature: nanocellulose from citrus waste. Molecules 20(4):5908–5923
103. Kardam A, Raj KR, Srivastava S, Srivastava MM (2014) Nanocellulose fibers for biosorption of cadmium, nickel, and lead ions from aqueous solution. Clean Technol Environ Policy 16(2):385–393
104. Moon RJ, Martini A, Nairn J, Simonsen J, Youngblood J (2011) Cellulose anomaterials review: structure, properties and nanocomposites. Chem Soc Rev 40(7):3941–3994
105. Aspler JJ, Bouchard J, Hamad W, Berry R, Beck S, Drolet F, Zou X. (2013) Review of nanocellulosic products and their applications. Biopolym Nanocomposites Process Prop Appl 461–508
106. Thygesen LG, Hidayat BJ, Johansen KS, Felby C (2011) Role of supramolecular cellulose structures in enzymatic hydrolysis of plant cell walls. J Ind Microbiol Biotechnol 38(8):975–983
107. Zain M, Fazelin N, Yusop M, Ahmad I (2015) Preparation and characterization of cellulose and nanocellulose from pomelo (Citrus grandis) albedo. Nutr Food Sci
108. Kalia S, Boufi S, Celli A, Kango S (2014) Nanofibrillated cellulose: surface modification and potential applications. Colloid Polym Sci 292(1):5–31
109. Shivakumar Singh P, Vidyasagar GM (2014) Biosynthesis, characterization, and antidermatophytic activity of silver nanoparticles using Raamphal plant (Annona reticulata) aqueous leaves extract. Indian J Mater Sci 2014
110. Donia AM, Atia AA, Abouzayed FI (2012) Preparation and characterization of nano-magnetic cellulose with fast kinetic properties towards the adsorption of some metal ions. Chem Eng J 191:22–30
111. Yu X, Tong S, Ge M, Wu L, Zuo J, Cao C, Song W (2013) Adsorption of heavy metal ions from aqueous solution by carboxylated cellulose nanocrystals. J Environ Sci 25(5):933–943
112. Pillai SS, Deepa B, Abraham E, Girija N, Geetha P, Jacob L, Koshy M. (2013) Biosorption of Cd (II) from aqueous solution using xanthated nano banana cellulose: equilibrium and kinetic studies. Ecotoxicol Environ Saf 98:352–360
113. Stephen M, Catherine N, Brenda M, Andrew K, Leslie P, Corrine G (2011) Oxolane-2, 5-dione modified electrospun cellulose nanofibers for heavy metals adsorption. J Hazard Mater 192(2):922–927
114. Boufi S (2014) Nanofibrillated cellulose: sustainable nanofiller with broad potentials use. In: Biomass and Bioenergy. Springer, Berlin, pp 267–305
115. Hokkanen S, Repo E, Sillanpää M (2013) Removal of heavy metals from aqueous solutions by succinic anhydride modified mercerized nanocellulose. Chem Eng J 223:40–47
116. Mandal A, Chakrabarty D (2011) Isolation of nanocellulose from waste sugarcane bagasse (SCB) and its characterization. Carbohydr Polym 86(3):1291–1299
117. Tsukamoto J, Durán N, Tasic L (2013) Nanocellulose and bioethanol production from orange waste using isolated microorganisms. J Braz Chem Soc 24(9):1537–1543
118. Mahmoud KF, Ibrahim MA, Mervat E-D, Shaaban HA, Kamil MM, Hegazy NA (2016) Nano-encapsulation efficiency of lemon and orange peels extracts on cake shelf life. Am J Food Technol 11(3):63–75