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REVIEW

Food preservation techniques and nanotechnology for increased shelf life of fruits, vegetables, beverages and spices: a review

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Abstract

Food wastage is a major issue impacting public health, the environment and the economy in the context of rising population and decreasing natural resources. Wastage occurs at all stages from harvesting to the consumer, calling for advanced techniques of food preservation. Wastage is mainly due to presence of moisture and microbial organisms present in food. Microbes can be killed or deactivated, and cross-contamination by microbes such as the coronavirus disease 2019 (COVID-19) should be avoided. Moisture removal may not be feasible in all cases. Preservation methods include thermal, electrical, chemical and radiation techniques. Here, we review the advanced food preservation techniques, with focus on fruits, vegetables, beverages and spices. We emphasize electrothermal, freezing and pulse electric field methods because they allow both pathogen reduction and improvement of nutritional and physicochemical properties. Ultrasound technology and ozone treatment are suitable to preserve heat sensitive foods. Finally, nanotechnology in food preservation is discussed.

Keywords Food preservation · Electrothermal · Freezing · Ultrasound · Ozone treatment · Pulse electric field · Nanotechnology

Abbreviations

ReFED	Rethink Food Waste Through Economics and Data
GAE	Gallic acid equivalent
TPC	Total phenolic content
FDA	Food and Drug Administration
GRAS	Generally recognized as safe
EFSA	European Food Safety Authority

Introduction

Food is vital for human survival and development. A recent review shows that food transmission of the coronavirus disease 2019 (COVID-19) is overlooked (Han et al. 2020). Food can be consumed in raw or processed form to obtain energy and sustain growth. Food wastage has become a major issue worldwide in the recent times. A considerable amount of food gets wasted at various stages of the food production and consumption chain. According to the report of Rethink Food Waste Through Economics and Data (ReFED), the data in Fig. 1 show the food wastage distribution for various types of food materials (ReFED 2016). Globally, due to inefficient supply chains, rising population and climate change, a large number of people are deprived of food on regular basis (Leisner 2020). Griffin et al. (2009) showed a detailed study about the waste generation of different food communities. Out of the food waste generated, 20% comprised production waste, 1% of processing waste, 19% of distribution and 60% of consumer generated waste. The major reasons for wastage were due to shrinkage of food while cooking, manufacturing issues, supply chain barriers, high consumer standards, changing climatic conditions, soil runoffs and

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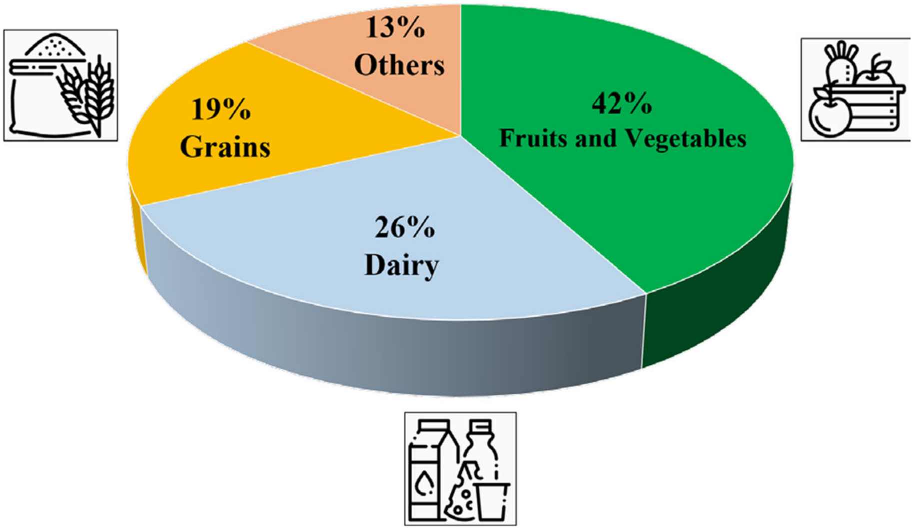

Fig. 1 Food wastage for different food materials based on weight percentage. The demand for variety and abundance as well as inefficient storage conditions increases the amount of overall food wastage. Fruits and vegetables are among the least expensive and fastest spoiling foods followed by milk and dairy products. Data from ReFED (2016)

policy constraints (Bräutigam et al. 2014; Silvennoinen et al. 2014; Filimonau and De Coteau 2019; Gomez-Zavaglia et al. 2020).

A recent analysis conducted in Finland in 2019 found more than 50% of the food waste is from households (Filimonau and De Coteau 2019). The decision between ‘best before’ or ‘use by’ was a tough call to take in determining shelf life of product for the customers.

However, with the increase in population, consumers demand food that is fresh, healthy and nutritious. Although enough food is produced every day to feed the world, the technology and food produced fails to reach those in need. Thus, food wastage has become a key challenge to in all food processing sectors.

Any kind of food when harvested begins to show spoilage responses. One of the sustainable solutions to counter the food wastage issues is food preservation. The idea of food preservation was introduced in the ancient times when our ancestors were finding ways to keep the food fresh and edible. Concepts like sun drying, salting and pasteurization were introduced depending on climatic and seasonal factors. Preservation enabled humans to form communities, stopped them from killing animals and brought about a leisure attitude keeping food for additional time.

Rapid industrialization and advent of lean methods paved the way for processes like thermal treatment, canning and freezing which gave a better shelf life extension by controlling the pathogens. However, food safety and security became a major concern due to the growing population and increasing consumer standards and demands providing healthy and nutritious food (Saravanan et al. 2020). Thus, the concept of preserving food grew rapidly with an aim to provide food to all. The goal of food preservation is to inhibit any biochemical reactions and to restrict entry of bacteria or fungi. The technique allows minimization of wastage with improved shelf life extension. Some of the popular conventional preservation techniques like heating, drying and freezing have been implemented in large industries (Pereira et al. 2018; Białkowska et al. 2020; Said 2020). However, it has been found that there are certain disadvantages in heat treatment and freezing methods such as food shrinkage, texture and nutrient loss and organic properties leading to a huge overall loss in the food product (Jayasena et al. 2015).

In the recent years, chemical and microbiological treatments have been carried out with additives, coatings and various polyphenolic plant extracts thus posing an effective solution to food preservation. There is a lack of research in bridging the gap between the food wastage and food preservation techniques. This review investigates the upcoming food preservation technologies which are likely to play a dominant role in the food preservation industry. Current trends and advancements in preservation techniques and their applications to foods including fruits, vegetables, liquid foods and spices are the key aspects discussed here. The review covers a wide range of changes brought in conventional technologies and current technologies in the above fields. Special focus is also given to nanotechnology with its application in foods, agriculture and packaging sectors. The data have been collected after an extensive literature search over the subject surveyed for the last 15 years taking into account the challenges faced in industry during preservation. This work could be a perfect platform for understanding the advancements in food preservation techniques and its relevance to industry. The advent of nanotechnology in research and a combination of various advanced technologies as discussed in the literature (Butnaru et al. 2019; Nile et al. 2020; Rech et al. 2020; Tsironi et al. 2020) as well as in this manuscript could be the “go-to” technologies in the future. Thus, positive steps need to be taken to narrow down on the enhancements of these technologies for having a sustainable and cost-effective lifestyle.

Prevalent food preservation technologies

Thermal treatment

Heat or thermal treatment is considered as one of the novel techniques for food preservation. For many years, the technique is well proven in various food sectors: from bakery and dairy to fruits and vegetables (Wurlitzer et al. 2019; Gharibi et al. 2020; Prieto-Santiago et al. 2020; Christiansen et al. 2020). The process generally involves heating of foods at a temperature between 75 and 90 °C or higher with a holding time of 25–30 s. Study on preservation enhancement of apple juice beverage by pasteurization and thermal treatment of maize showed a great impact on the flavor, digestibility, glycemic index, aroma, color and sensory attributes (Charles-Rodríguez et al. 2007; Zou et al. 2020). A recent report also highlighted five different types of rice when undergoing hydrothermal treatment showing results in par with respect to the quality of market rice (Bhattacharyya and Pal 2020).

The heating of foods reduces the pathogens. However, extensive research has also concluded nutrient losses, energy wastages, flavor changes and reduction in the food matrix (Roselló-Soto et al. 2018). A study conducted on light and dark honey showed changes in physicochemical characteristics, antioxidant activities and nutrient variations post-treatment (Nayik and Nanda 2016; Zarei et al. 2019). Liquid foods, juices and beverages too have a negative impact causing gelatinization and browning reactions (Codina-Torrella et al. 2017; de Souza et al. 2020). Over the years, constant investigation has been done on optimization studies of heat on exposure of food to improve its shelf life. Adjustments and slight modification to former technologies have recently contributed to significant advances with a combination of electrical and thermal methods. Different processes like electroplasmolysis, ohmic heating, and microwave heating of foods have created a dramatic impact in the food industry advancements. Table 1 shows the advanced electrothermal treatment techniques applied to different foods.

Freezing

Cooling and freezing of products have been extensively applied for preservation of leafy vegetables, spices and milk products to maintain the sensorial attributes and nutrition qualities. Extensively used freezing techniques involve air blast, cryogenic, direct contact and immersion freezing, while advanced techniques involve high pressure freezing, ultrasound assisted freezing, electromagnetic disturbance freezing and dehydration freezing (Cheng et al. 2017; Barbosa de Lima et al. 2020). Cooling and freezing process mainly relies on the process of heat transfer. During cooling, there is a transfer of heat energy from the food and packaged container to the surrounding environment leading to an agreement of cooling. Thus, thermal conductivity and thermal diffusivity greatly affect the cooling or freezing rate. During the recent years, the storage technique has gained significant interest with the start of ready-to-eat foods catering to the needs of the consumer. The foods with their appropriate packaging material and cool temperature will always inhibit entry of microorganisms as well as maintain food safety. Although cooling and freezing are effective in their own terms, cooling time, uneven speed of ice crystal formation, storage expenses and specialized environments are concerning issues. In order to understand and overcome these challenges, technological tools like three-dimensional mathematical models and computational fluid dynamics models were evaluated to understand the heat transfer and fluid flow patterns with various food formulations thus showing an approach to minimize the issue (Zhu et al. 2019a, b; Barbosa de Lima et al. 2020; Brandão et al. 2020; Stebel et al. 2020). Table 2 shows a description of the various advanced freezing techniques applied to different foods.

Ultrasound

Ultrasound treatment involves use of high intensity and frequency sound waves which are passed into food materials. The efficient technology is chosen due to its simplicity in the equipment usage and being low cost as compared to other advanced instruments. The versatility of ultrasound is shown in its application in different fields ranging from medicine, healthcare to food industry (Dai and Mumper 2010).

Figure 2 illustrates a representation of different types of sonicators used for powdered and liquid foods. The process deals with ultrasonic radiation passing through the target solution. This action causes a disturbance in the solid particles in the solution leading to particles breaking and diffusing into the solvent (Cares et al. 2010). It should be noted that the intensity of the technique should be kept constant. This is because as intensity increases, intramolecular forces break the particle–particle bonding resulting in solvent penetrating between the molecules, a phenomenon termed as cavitation (Fu et al. 2020; Khan et al. 2020). Further enhancement of ultrasound extraction is dependent on factors like improved penetration, cell disruption, better swelling capacity and enhanced capillary effect (Huang et al 2020; Xu et al 2007). Table 3 shows the

Table 1 Advanced electrothermal treatment techniques used in the food industry

Advanced techniques	Technology involved	Application in food materials		References
		Sample(s) analyzed	Conclusions	
Electroplasmolysis	Involves effective destruction of cell membrane matrix of different food materials with help of high electric current Helpful in increasing the efficiency of extraction	Apple, cucumber, pear, carrot, banana (Pear, banana: 900–1100 V/cm Apple, cucumber, carrot: 200–400 V/cm)	Electric field strength depends on the type of tissue (Disintegration index < 0.5) Electric field higher for cells having secondary cell wall	Bazhal et al. (2003)
		Tomato Range of field strength test: 36–108 V/cm Treatment time: 5– 30 s	Enzyme inactivation of pectin methyl esterase and *Aspergillus niger* decreased with increased in treatment time at 108 V/cm Highest amount of pectin obtained was 3.56% at 36 V/cm for 80 s	Yildiz and Baysal(2006)
Microwave heating (post-pasteurization)	Involves absorption of electromagnetic energy leading to a temperature increase of the food (due to high dielectric capacity) thus improving the product quality Microwave heating is greatly influenced by shape, size, food matrix and equipment	Gurum *(Citrulluslanatus var. Colocynthoide)* Microwave power: 800 W Time: 6 min Frequency:2450 MHz	Increase in oil extraction yield from 27.6% to 35.4% Acid value increase from 0.68 mg to 0.95 mg KOH/g of oil Increase in polyphenol content from 22.6 to 25.3 mg Gallic acid equivalent (GAE)/kg oil Increase in antioxidant activity from 59.2–64.7%	Karrar et al. (2020)
		Saffron Temperature:45–125 °C Time:10–30 min Solvent concentration: Ethanol (0–100 v/v %)	Process conditions of 95.15 °C, 30 min and ethanol concentration of 59.5% was considered optimum for microwave heating	Sarfarazi et al. (2020)
		Apple juice Power: 270–900 W Frequency:2450 MHz Treatment time: 83 °C for 30 s	Reduction in microbes *(E coli)* post-microwave treatments Treatment between 720–900 W for 60–90 s showed 2 to 4 log population reduction in microbes	Cañumir et al. (2002)
Ohmic heating	Involves heating of the food by the passage of electric current. The food product acts as an electric resistance thus heating the whole matrix Higher the voltage applied, better the more the heat generated	Orange juice Temperature: 40–95 °C Time: 60 s	Comparison between conventional thermal heating and ohmic heating showed changes in the antioxidant activity (ascorbic acid) 7% decrease observed at 42 V/cm, 69 °C 11% decrease observed at 44 V/cm, 70 °C	Demirdöven and Baysal (2014); Salari and Jafari (2020)
		Tomato juice Conventional heating: 75–300 s Ohmic heating: 15–60 s	Lycopene presence observation and detection and comparison between conventional and ohmic heating Conventional: 20.5–23.3% increase observed Ohmic heating: 21.3–23.6%	Makroo et al. (2020); Salari and Jafari (2020)
		Orange juice Hot water treatment: 90 °C, 15–60 s	Cartenoids detection Hot water: 2.3–3.9% decrease in carotenoids	Funcia et al. (2020); Makroo et al. (2020)

Table 2 Advanced freezing techniques widely applied for different foods

Advanced freezing techniques	Technology involved	Application in foods		References
		Sample	Conclusions	
High-pressure freezing	Involves freezing water at high pressure below 0 °C so that it forms small ice crystals instantly once the pressure is released Process takes place with the absence of heat Crystallization occurs instantly once high pressure is released Preservation of original properties and quality improvements noticed	Comparison of sugar-rich dairy-based food foams (ice creams) and a non-aerated liquid system Maximum pressure applied: 360 MPa at −25 °C	Volume fraction of the air after treatment—78% Crystal size reduction—40 μm to 34 μm Overall improvements in sensorial properties	Volkert et al. (2012); You et al. (2020)
		Kombu seaweed *(Laminaria ochroleuca)* Process conditions: 5 °C, 400–600 MPa, 5 min followed by refrigeration at 5 °C or freezing at -24 °C	Comparison of salted and unsalted seaweed Detection of 103 volatile compounds found. Major compounds detected were aldehydes, alcohols, ketones, alkanes, alkenes, and acids Freezing lowered levels of hydrocarbons, alkanes and thiazoles Salting increased levels of acids, alcohols, pyranones, lactones and thiazoles	López-Pérez et al. (2020)
Ultrasound-assisted freezing	Involves passing of sound waves in between the food. Can be of low frequency (< 100 kHz) or high frequency (20–100 kHz) No destruction of food Intensity, frequency of ultrasound, position of samples, cooling medium temperature key parameters for the process Can be used to treat both solid and liquid samples	Cantaloupe melon juice *(Microcystis aeruginosa)*	Testing for probiotic substrate *Lactobacillus casei* Study done for a period of 42 days at 4 °C Reduced caloric value observed	Zendeboodi et al. (2020)
		Grape juice Amplitude of 50% and 70% with treatment times of 0, 2.5 and 5 min Temperature maintenance: 50–80 °C	Comparison of ultrasound and pasteurization treatment was done Total phenolic content (TPC) was same for both the treatments at 10 min with amplitude of 70% pH decreased and total soluble solids increased with amplitude and treatment time Results indicated usefulness of juice sonication to enhance inactivation of pathogens	Margean et al. (2020)
		Pomegranate juice	Results showed ultraviolet 5.1 W/cm^2 dosage, 3.5 L/min flow rate and 50 °C microbes were below the detection limits Lower temperatures could reduce the microbial activity preserving the bioactive compounds	Khan et al. (2020); Alabdali et al (2020)
Radioactive freezing	Not predominantly used in freezing Radio waves generate a turning force in the water molecule, and an ice cluster is created due to dielectric and dipolar properties of water	Onion, potato, ginger, carrot Dosage: 0.05–0.15 kGy	Inhibition of sprouting Shelf life enhancement	Prakash (2016)
		Cereals, fruits Dosage: 0.15–0.5 kGy	Phytosanitation Sterilization purposes Mycotoxin decontamination observed most effect with advantages in nutrient qualities	Ravindran and Jaiswal (2019); Mousavi Khaneghah et al. (2020)

Table 2 (continued)

Advanced freezing techniques	Technology involved	Application in foods		References
		Sample	Conclusions	
Dehydration freezing or osmodehydrofreezing	Involves osmotic dehydration and freezing techniques Food is first dehydrated (water removal) and immediately frozen Shelf life extension observed due to accelerated freezing process Low energy consumption, low cost of packaging	Mango *(Unripe vs Ripe "Kent" mangoes)* Treatment: 50 °C in 60 brix sugar solution with 2 g calcium lactate/ 100 g with pectin methyl esterase	Unripe mangoes showed two- to fivefold soluble solid gain as compared to ripe Unripe samples had lowest water loss with reduction in lightness. Ripe samples were stable Pectin methyl esterase improved rigidity in mangoes	Sulistyawati et al. (2018)
		Pineapple with sucrose syrup Treatment: 2 h at 40 °C	Changes in pH, total acidity, soluble solids, and water observed Dry matter content increase during multiple stage osmodehydrofreezingStudy conducted showed multistage osmodehydrofreezing gave better performance than single stage osmodehydrofreezing	Fernández et al. (2020)

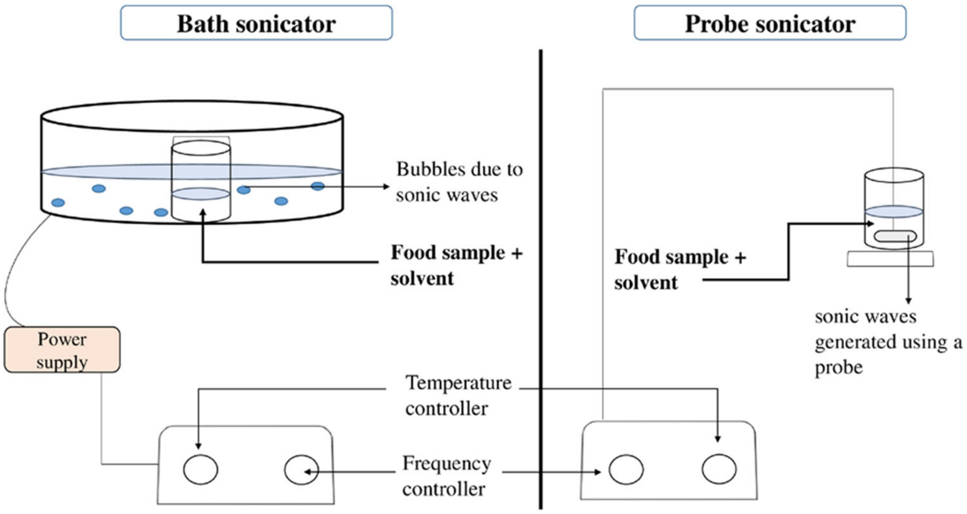

Fig. 2 Types of ultrasound treatments: bath sonicator and probe sonicator. The treatment works on the principle of cavitation in which there is an energy transfer among food particles leading to bubble formation and collapsing. The technique requires minimal power providing more efficiency than traditional drying methods. It is used for treating various powdered or liquid foods

types of ultrasound technologies available which have created paths for efficiency improvements.

Ultrasound is slowly paving way into two most thriving sectors in the food industry, namely wine making and dairy production. Figure 3 shows the thermosonication process widely used in processing of milk and wine.

Milk is generally pasteurized in various industries to prevent spoilage and kill the microorganisms present. The utilization of a low-frequency ultrasound or combination of thermosonication (to 11.1 s) or manothermosonication could enhance the safety, quality and functional properties of product by 5 log times (Bermúdez-Aguirre et al. 2009; Deshpande and Walsh 2020; Gammoh et al. 2020). Low-frequency ultrasound alone has also played a significant role in improving the textural and homogenization effects of yoghurt, cheese and skimmed milk (Yang et al. 2020). With a shorter time interval, and thermosonication-applied (20 kHz, 480 W, 55 °C) production was improved to 40% and also had a positive impact on its organoleptic properties (Tribst et al. 2020).

Production of wine fermentation and alcoholic drinks always faces an issue in tackling microorganisms or yeast. Conventional methods generally involve use of chemical preservatives like sulfur oxide to prevent spoilage or

Table 3 Ultrasound technologies for efficiency improvements in the food industry

Type of ultrasound technology	Features	Sample	Frequency (kHz)	Time (min)	Power (W)	Temperature (°C)	Conclusion	References
Ultrasonication	Low temperature used for isolation of enzymes Proven to improve efficiency of proteins and functional foods Applicable for heat sensible products Recently used in wine fermentation to decrease the ageing time	Spices of tangerine peels, parsley, red pepper	–	30	–	40	Tangerine peels: special fragrance due to limonene and citral flavor substance Parsley: slight bitterness due to phenolic ether Red pepper: slightly sweet and spicy due to capsaicin and radish	Teng et al. (2019)
		Quince fruit	28	15	50	–	Yeast growth inhibition observed Low enzymatic activity and browning Lowest off odor obtained when treated with ultrasound	Yildiz et al. (2020)
Manosonication	Involves a combination of ultrasound and pressure applied together Inactivates enzymes at low temperature and moderate pressures Efficiency higher than ultrasonication Effective in maintaining taste, nutrient qualities and sensorial attributes in liquid foods, fruits, vegetables and recently in nanofoods	Apple, cranberry and blueberry juice	20	3,6,9	–	20,40,60	Complete inactivation of bacteria at 60 °C in 6 and 9 min. No change observed in 20 °C, 40 °C Change of 3.5–5.9 log units observed as per the conventional treatment	Režek Jambrak et al. (2018)
		Citrus waste	40% amplitude, 250 kPa	20	–	42	Analysis using Box-Behnken design Highest extractability of pectin: 27.83% Ultrasound: 22.83% Heat: 24.71%	Hu et al. (2020)
Thermosonication	Involves a combination of ultrasound and heat applied together Used for sterilization or pasteurization purposes Better to use as compared to any other thermal treatment due to its high precision Found to improve the physicochemical and sensorial characteristics of fruits, beer, dairy, rice and mixed juices	Orange juice		12 days		4	Bioactive compounds decreased during storage, while pectin methyl esterase values increased Changes observed from the 12th day of storage. Storage at 4 °C proved increase in shelf life	Wahia et al. (2020)
		Milk	–	4	–	60	Central composite rotatable design used for determining the effect 53.7 °C and 52 °C showed removal of pathogens from milk	Deshpande and Walsh (2020); Parreiras et al. (2020)

Table 3 (continued)

Type of ultrasound technology	Features	Sample	Frequency (kHz)	Time (min)	Power (W)	Temperature (°C)	Conclusion	References
							Combination of pasteurization and thermosonication (11.1 s) increase shelf life by 2 weeks Retinol levels remained stable after processing	
		Red pitaya juice	–	1.5	–	83	Degradation and isomerism of betanin and phyllocactin More than 92.97% retention of polyphenols in the juice	Liao et al. (2020)
		Mung bean protein	20	5, 10, 20, 30		30, 50, 70	Particle size reduction and free sulfhydryl content with time Increase of hydrophobicity and exposure of non-polar groups Twofold increase in protein solubility, clarity at 70 °C No change observed at 30 °C and 50 °C	Zhong and Xiong (2020)
Manothermosonication	Involves a combination of heat, ultrasound and pressure Isolation of enzymes or bioactive compounds at a shorter time interval Maximum cavitation as compared to other types Generally used for isolation of lipids and proteins Recently used for improving shelf life and food safety in citrus foods and dairy products	Wine	24	–	400	30, 40	Significant reduction of brettanomyces (89.1–99.7%) and lactic acid bacteria (71.8–99.3%) Results indicate great potential for treatment in continuous flow system for decreasing preservatives	Gracin et al. (2016)
		Modified pectin	400	5	–	45	Lower activation energy observed during kinetics Lowered degree of methoxylation and galacturonic acid Higher antioxidant activity as compared to citrus pectin	Wang et al. (2020a)
		Ferritin	200 kPa	40 s	–	50	Reduced content of alpha helix structure. Steady maintenance of spherical morphology (12 nm) Increase in iron release activity pH changes observed and tested in encapsulation of tea polyphenol epigallocatechin Increase in water solubility and encapsulation efficiency	Meng et al. (2019)

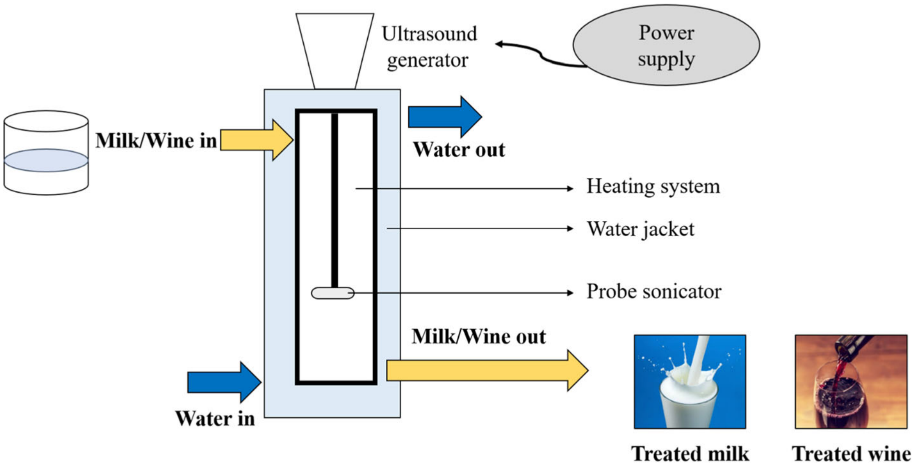

Fig. 3 Thermosonication processing generally used for treating milk and wine samples for improving the shelf life. The treatment can prove to be cost-effective with reduced processing temperature due to the use of sonication as compared to conventional heat treatment or addition of synthetic preservatives

thermal pasteurization followed by filtration to get the pure beverage. A recent study reported significant reduction of about 85–90% lactic acid bacteria with high power ultrasound at 24 kHz for 20 min for treatment of wine (Luo et al. 2012; Gracin et al. 2016). However, careful handling should be carried out in order to maintain the flavor and texture (Izquierdo-Cañas et al. 2020; Xiong et al. 2020).

Ultrasound studies have also found applications in isolation of bioactive compounds and processing pastes and juices in many fruits and vegetables. Recently, the technique was used to find the total phenolic content in spices like saffron (Teng et al. 2019; Azam et al. 2020; Yildiz et al. 2020). Table 4 shows the application of ultrasound technologies for various food crops. Thus, it can be concluded that ultrasound is a more sustainable technique than other traditional drying treatments.

Ozone treatment

With the growing demands of consumer slowly moving towards healthy meals and sustainable lifestyle, the demand for organic foods have increased rapidly. Consumers need a functional food that is free from additives, preservatives with a decent shelf life span. Thus, the concept of ozone treatment technology has risen in recent years. The reason for choosing ozone is due to its diverse properties and quick disintegration.

In simple words, ozone is an allotrope of oxygen. The molecule is formed when oxygen splits into a single oxygen or nascent oxygen in the presence of light or ultraviolent radiation. Ozone formation is described by chemical equations as mentioned below (Eqs. 1 and 2) (Brodowska et al. 2018).

$$O_2 + e^- \rightarrow 2O \tag{1}$$

$$O_2 + O \rightarrow O_3 \tag{2}$$

The compound quickly decomposes into oxygen molecule and possess a high oxidation potential (2.07 V) making it a good antimicrobial and antiviral agent (Fisher et al. 2000; Nakamura et al. 2017) as compared to chemical preservatives like chlorine (1.35 V), hydrogen peroxide (1.78 V) and hypochlorous acid (1.79 V) (Pandiselvam et al. 2019; Afsah-Hejri et al. 2020). Apart from this, ozone removes the necessity to store harmful chemicals as the gas can be made instantly. The energy required is also minimal as compared to thermal treatment giving more importance to the shelf life (Pandiselvam et al. 2019).

Over the recent years, ozone has been listed by the Food and Drug Administration (FDA) as a generally recognized as safe (GRAS) solvent. This has led to a demanding choice in food processing and preservation sectors to ensure safety and standards in products. When in comparison with chlorine, its degradation leaves negligible residue when treated with solid foods or beverages. The technology in combination with ultrasound was also shown to enhance the bacterial safety without any damage in cabbages (Mamadou et al. 2019). Consumer grade ozone was recently proven effective in disinfecting plastic boxes for storage (Dennis et al. 2020).

Table 5 shows the effect of ozone treatment on pesticide degradation in various fruits and vegetables production. The effect of ozone treatment depends on the type of pesticide and food material, environmental conditions, time interval and the strength of pesticide. When horticulture crops were compared, tomato and lettuce had the best pesticide removal efficiency while apple and chili were the least. It was seen that the type of food matrix and structure also play a key role in preventing the growth of pathogens. Ozone can thus be considered as an advanced emerging method for multiple sectors due to its feasibility, easiness and less time consumption.

Table 4 Ultrasound technologies for various food crops

Food matrix	Method	Frequency (KHz)	Time (min)	Temperature (°C)	Power (W)	Conclusion	References
Onion	Ultrasound with blanching	20	1,3,5	70 in hot water	200	Retention of quercetin and other bioactive compounds observed Posed as a better method as compared to drying treatment and in terms of sustainable approaches	Ren et al. (2018); Ruivo Da Silva et al. (2020); Santiago et al. (2020)
Tomato paste processing waste	Ultrasound	–	1.5–18	–	–	Lycopene extraction using sunflower oil (2.18–36.8%) as green solvent 87.25% yield contrast as compared to conventional organic solvents (at 70 W/m^2 at 10 min) Reductions in peroxide and p-anisidine values observed	Rahimi and Mikani (2019); Sengar et al. (2020)
Pomegranate	Ultra violet radiation sterilization and ultrasound	–	10 at 3.5 L/min flow	50	59	Microbial activity (at 200 W) with ultraviolet and ultrasound was limited as compared to traditional pasteurization process preserving bioactive compounds	Alabdali et al. (2020)
Soursop nectar	Thermosonication	24	10	51	–	Inactivation of *E. coli* and *S. aureus* for maintaining quality and stability of nectar using acoustic energy density of 1.3–1.4 W/mL 4.5–5 log (colony forming unit per mL) reduction in pathogens Inactivation of polyphenol oxidase found Thermosonication nectar mainly contained 85% ascorbic acid	(Anaya-Esparza et al. 2017)
Saffron	Ultrasound, microwave assisted extraction and ohmic heating assisted extraction	30	–	–	45–225	Highest total phenolic content (928 mg/100 g) was found for ohmic heating assisted extraction Extracts showed inhibition in lipase enzyme Presence of kaempferol and anthocyanins found in all extracts	Sarfarazi et al. (2020); Hashemi et al. (2020)

Pulse electric field

Pulse electric field technology is an advanced pre drying treatment involving shorter residence time for treatment of foods. The method was widely recognized due to its continuous operation and low requirement of electric fields (1–5 kV/cm). The method could be considered as a substitute for thermal drying and could enhance the food drying as it requires a very low temperature of 40 °C for functioning (Barba et al. 2015; Wiktor et al. 2016). Figure 4 shows the representative diagram of the process involved in treatment of liquid foods and paste using pulse electric field.

The methodology of pulse electric field involves placing the food (fruit, vegetable, milk or any juices) between two electrodes after which a pulse is applied with high voltage (50 kV/cm) for short time intervals. The principle is a combination of electroporation and electropermeabilization (Barba et al. 2015). The electric field breaks the cell membrane matrix of the food thus enhancing the nutritive qualities, safety and increasing shelf life. The factors affecting pulse electric field involve field strength, pulse width, frequency, treatment time, polarity and temperature used (Odriozola-Serrano et al. 2013; Wiktor et al. 2016).

Over the years, demand for pulse electric field has grown drastically in all food sector areas. It can be used for destruction of bacteria *(E coli)* in milk. The treated milk

Table 5 Effect of ozone treatment on pesticide degradation in horticulture production

Food material	Type of pesticide	Concentration of pesticide	Time kept under ozone (min)	Level of reduction (%)	References
Apple fruit	Boscalid	3 ppm in ozonized water	15–20	42	Sadło et al. (2017)
Cabbages	Chlorothalonil	250 mg/h ozone gas	15	77	Chen et al. (2013)
Carrots	Difenoconazole	5 mg/L ozone gas	10–15	95.3	Souza et al. (2018)
Chili	Chlorpyrifos	Ozone fumigation with constant flow rate of 5.5 g/h	30	68	Sintuya et al. (2018)
Lettuce	Chlorpyrifos	5 ppm ozone gas	15	97.15	Wu et al. (2019)
Spinach	Chlorpyrifos Acetamiprid	Ozone wash with water (0.4 mg/L)	30	53	Wu et al. (2019)
Tomato	Fenitrothion	Ozone wash with water (2 ppm) in a microbubble format	20	98.32	Pandiselvam et al. (2020)

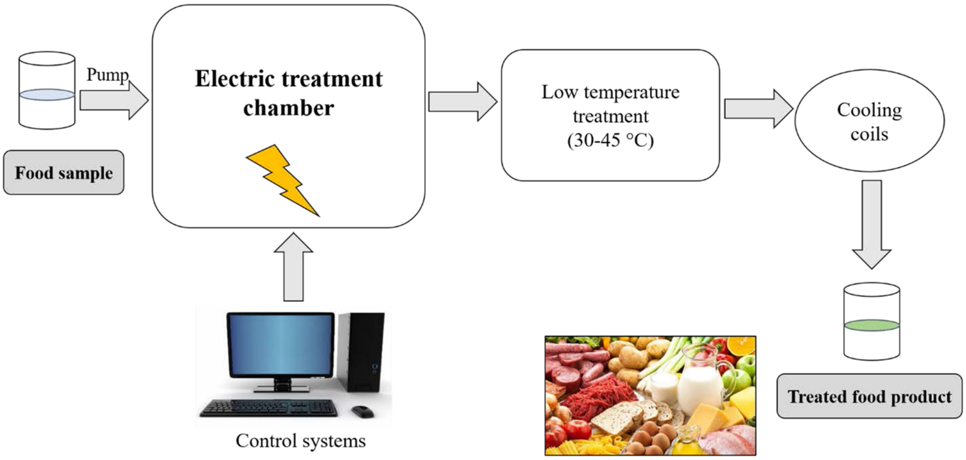

Fig. 4 Application of pulse electric field generally used for treating liquid foods and pastes. The technique is a nonthermal food preservation method involving usage of pulses of electricity into the food material. The treatment gives high quality food with almost no change in texture or quality thus maintaining the original taste of food

was found to be high in quality and possessed an increased shelf life. A recent investigation was also carried out on watermelon and citrus juices which showed changes in physicochemical and antimicrobial properties (Aghajanzadeh and Ziaiifar 2018; Bhattacharjee et al. 2019). Table 6 summarizes the outcomes of application of pulse electric field treatment on various food materials.

Nanotechnology for food preservation

Nanotechnology has become a huge breakthrough with great potential to promote sustainability. It integrates branches of applied sciences such as physics, biology, food technology, environmental engineering, medicine and materials processing. In simple terms, nanotechnology involves any material or nanoparticle having one or more dimensions to the order 100 nm or less (Auffan et al. 2009; He et al. 2019). The technology is preferred as they possess different properties like slow release action, target specific nature, precise action on active sites and high surface area (Joshi et al. 2019). The reason for the success of nanotechnology is due to its promising results, no pollutant release, energy efficient and less space requirements. Apart from these success factors, nanotechnology has also shown versatile applications in terms of safety, toxicity and risk assessment in areas of agriculture, food and environment (Kaphle et al. 2018). Figure 5 shows the different avenues of nanotechnology development in the food sector.

Nanomaterials are broadly classified into two types, namely organic and inorganic, depending on their nature and functionalities (Table 7).

Nanotechnology has been regarded as a promising tool for growing the economy in near future as well as maintaining the plant growth and nutritional qualities of the food commodity. Use of nanofertilizers and precision farming has posed several benefits in weed control and decrease in chemical pesticide thus enhancing shelf life. Growing use of nanotechnology in agro-food system industry may even pose as a solution to solve challenges in

Table 6 Effect of pulse electric field treatment on food materials

Food material	Process conditions	Outcomes	References
Blueberries	2 kV/cm, 30 µs for 4–6 h at 40 °C, 60 °C, 75 °C	Least impact on the nutritive qualities post-treatment till 75 °C Process saved the drying time by 2–30 h	Yu et al. (2017)
Date palm fruit	1,2,3 kV/cm, 30 pulses, 100 µs	Positive impact and increase in carotenoids, anthocyanins, flavonoids and phenolic Increase in the volatile and bioactive compounds at 3 kV/cm Better feasibility as compared to solvent extraction	Yeom et al. (2004); Siddeeg et al. (2019)
Apple juice	12.5 kV/cm, 27.6 L/h flow at 76.4 kJ 72 °C for 15 s 85 °C for 30 s	Huge variations in peroxidase activities and change in polyphenol oxidase	Wibowo et al. (2019); Salehi (2020)
Red beet	2–6 kV/cm, 10–80 µs	Betanin concentration in red beet increased by 6.7–7.2 times post-treatment	Luengo et al. (2016)
Olive paste	16 kV, 145 A, 30 °C, 200 µs, 75 Hz, 30 min	Extractability increase from 79.5% to 85.5% Enhancement of elenolic acid and tyrosol Overall olive oil extraction and quality found	Tamborrino et al. (2020)
Clover sprouts	1,2.5,5 kV/cm, 21 °C and 80% humidity, 12 h for 7 days	Dominant carotenoid was lutein during light exposure Increase of 6–8% beta-carotene found in red clovers Decrease of 3.3% zeaxanthin observed	Gałązka-Czarnecka et al. (2020)

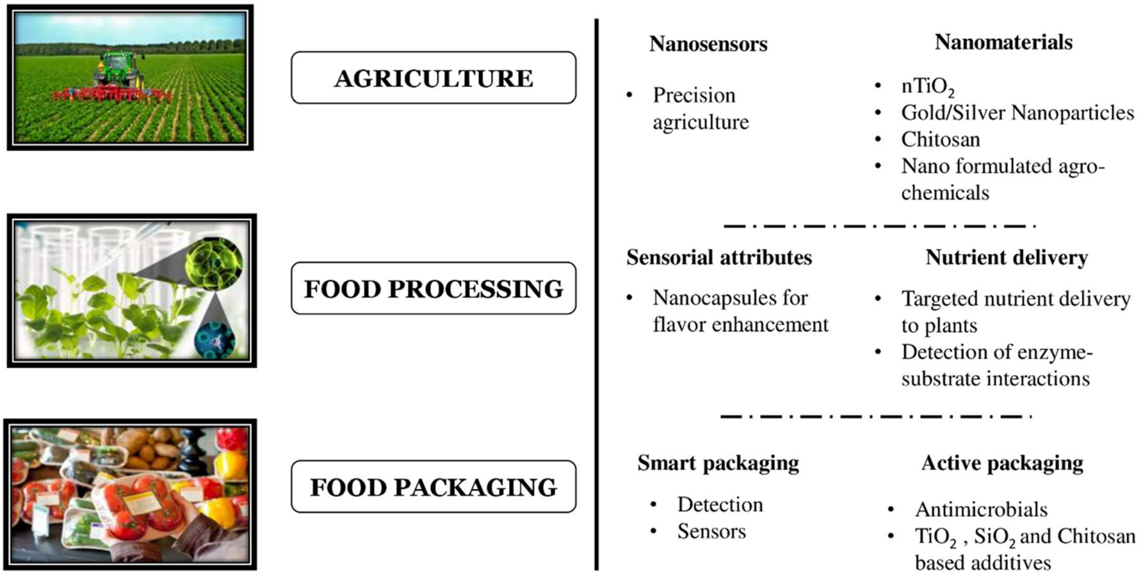

Fig. 5 Applications for nanotechnology in agriculture, food processing and packaging. Nanotechnology has gained a lot of interest with versatile applications and unique properties enabling efficient processes and quality products. The use of nanomaterials, nanosensors, precision agriculture and advanced packaging can play a promising role in improving the food sector

food security and agriculture (Yata et al. 2018; Ghouri et al. 2020). The three primary avenues where the technology could grow include food processing, agriculture and packaging.

Nanotechnology in food processing

The concept of nanotechnology has paved the way in processing and formulation of colorants, sensors, flavors, additives, preservatives and food supplements (nanoencapsulation and nanoemulsion) in both animal and plant

Table 7 Types and functionalities of nanomaterials

Category	Nanomaterial	Use of nanomaterial	Application in foods	References
Inorganic nanoparticles	Silver nanoparticles	Generally used as antimicrobial agents in food packaging and storage containers Recently used as a stabilizing agent in nanofillers	Effective food packaging solution preventing entry of pathogens Crop yield variations seen in chili, radish, lettuce	Li et al. (2020); Zorraquín-Peña et al. (2020); Seray et al. (2020)
	ZnO nanoparticles	Considered a biocompatible material Nanomaterial found positive in control of food borne pathogens	Increase in quality of cucumber by 36% Carotene, zinc and iron increase in cucumber observed	(Venkatasubbu et al. 2016; Seray et al. 2020)
	Se nanoparticles	Combination of Cu + Se nanoparticles increased the overall yield and chlorophyll content of tomato	Modification in the enzymatic activity of tomato plant Tomato yield increased by 21% with 10 mg/L Se nanoparticles	(Hernández-Hernández et al. 2019)
	TiO_2 nanoparticles	Photo activities shown on food contact surfaces Dual usage found in cosmetic (in sunscreens)	Packaging film of TiO_2 proved better for storage of green lettuce	(Weir et al. 2012; Peter et al. 2015; Yemmireddy and Hung 2015)
	SiO_2 nanoparticles	Anti-caking agent in certain powdered foods Abiotic stress resistant in plants and crops	Reduced the development stages of grapes (dosage: 0.5 g/L)	Lim et al. (2015); Zahedi et al. (2020)
Organic nanoparticles	Lipid nanoparticles	Used as oral delivery systems in drugs and active ingredients	Nutraceutical and drug delivery systems	Severino et al. (2012); Ban et al. (2020); Paliwal et al. (2020)
	Protein nanoparticles	Great potential in catalysis, synthesis, bio imaging Found in foods in the form of casein	Bovine milk and other dairy foods	Samadarsi et al. (2020)
	Carbohydrate nanoparticles	They are digestible or indigestible polysaccharides like sodium, alginate, pectin and cellulose. Physicochemical stability and solubility over algal oil nanoparticles showing high efficiency of 98.57% in the system	Encapsulation of oil	Verma et al. (2020); Wang et al. (2020b)

based products (He et al. 2019). The diversity of nanotechnology in various fields has led to introduction of nanosensors in food processing industries. Nanomaterials have shown several electrochemical and optical properties in different sauces, beverages, oils and juices. Table 8 shows the different nanomaterials used as sensors in food industry.

Distinctive characteristics have shown great qualities in the area of food processing as ingredients and supplements. Oxide chemicals such as magnesium oxide and silicon dioxide can act as a food flavor, food color and a baking agent. The use of titanium dioxide has also been certified as an additive in gums, sauces and cakes (Weir et al. 2012). Additionally, copper oxide, iron oxide and zinc oxide have been categorized as GRAS materials by European Food Safety Authority (EFSA) for animal and plant products (He et al. 2019).

Nanotechnology in agriculture

The use of nanotechnology in agriculture and the concept of precision agriculture has gained a lot of interest in the recent years. The main goal of agriculture is to reduce the volume of chemicals, minimize nutrient losses and increase the overall performance of crops. Although chemical fertilizers are added for increasing the crop yields, it pollutes and harms the soil, water, food and environment (Riah et al. 2014). Precision agriculture is one of the green ways to tackle this issue. It is a system based on artificial intelligence that understands crop quality, soil quality and

Table 8 Use of nanomaterials as sensors in the food industry

Food sensor type	Material Detection	Sample chosen	Nanomaterial	Functions and outcomes	References
Electrochemical	Tert-butylhydroquinine	Edible oils in bakery industry	Au nanoparticles electrodeposited on graphene ribbons	Conductivity improvements due to increase in surface area on the target sites	Delfino et al. (2020)
	Antioxidants	Mixed fruit juices	Graphene nanoribbons	Enhanced surface and electrochemical properties seen	Ye et al. (2020)
	Glucose, sucrose and toxins	Soft drinks	Cu nanoparticles based inks	Carbohydrate oxidation	Pradela-Filho et al. (2020)
	Melamine	Milk	Carbon nanoparticles	Conductive and functional layer for detection of *Salmonella* strains	Nguyen et al. (2020)
	Adulterants	Chili sauce	Pd/Au nanocrystals	Enhanced catalytic activity and high surface area	Zou et al. (2020)
	Residual pesticides	Potato, onion and cabbage	TiO_2/Pd nanostructure	Improved electrochemical properties and conductivity	Naser-Sadrabadi et al. (2020)
	Pathogens (*Salmonella* species)	Skimmed milk	Au Nanoparticles	Electrochemical generation of signals	Echegoyen et al. (2016); Nguyen et al. (2020)
	Heavy metals (Hg^+)	Water	Au Nanoparticles	Higher surface area for thiophenol modified species	Tian et al. (2020)
Optical	Mycotoxins	Milk	CeO_2 nanoparticles	Catalytic activity	Goud et al. (2020)
	Gallic acid	Clove and green tea extracts	Au nanotubes bismuth based	Physical and morphological changes	Madhusudhana et al. (2020)
	Antibiotics (Sulfonamides)	Honey	Au nanoparticles	Surface plasmon resonance properties	Ye et al. (2020)

detects weed controls generally through drones. The area has recently gained interest in nutritional management and various optical properties to address food wastage and to feed the growing population (Duhan et al. 2017). Majority of plant species (cereal grains like wheat, rice, barley, tobacco, soybean, rye) follow the biophysical process of photosynthetically active radiation and electron transport. These targets have been identified to improve photosynthesis activity.

There has been many discussions and investigation on the concept of plant nanobionics and photosynthesis. Plant nanobionics deals with appropriate insertion of nanoparticles into the chloroplast of the plant cell for improving the plant productivity. It has been proven that titanium dioxide nanoparticles ($nTiO_2$) have become the “go-to” nanoparticles for efficient photosynthesis process (Hong et al. 2005; Gao et al. 2006, 2008). The application of $nTiO_2$ with spinach and tomato leaves under mild heat stress improved the overall photosynthesis process showing significant improvement in the transpiration and conductance rates (Gao et al. 2008; Qi et al. 2013).

Nanomaterials like silver ions, polymeric compounds and gold nanoparticles are also being investigated for use in pesticides. Usage of gold and silver nanoparticles has also had a positive effect to restrict the pest and improve plant growth (Ndlovu et al. 2020). Studies have also investigated on sulfur-based nanoparticle (35 nm) for organic farming which prevent fungal growth from apple tomatoes and grapes (Joshi et al. 2019).

Nanotechnology in food packaging

Many fresh fruits and vegetables are sensitive to oxygen, water permeability and ethylene leading to deterioration of food quality (Gaikwad et al. 2018, 2020). Thus, food packaging plays a critical role in addressing this issue. Nanoparticles and polymer-based composites have proven to be the best solutions (Auffan et al. 2009; Joshi et al. 2019). The application of a natural polymer or a biopolymer and coating it on the food surface has recently shown promise in preserving foods (Luo et al. 2020). Table 9 shows the different applications of nanomaterials used in food packaging. Although the application of nanomaterials in smart packaging is in its early stage, rapid advancements have been carried out through the years as it offers safe and sustainable approach (Rai et al. 2019).

Table 9 Applications of nanomaterials in food packaging

Nanomaterial	Packaging material	Food samples	Application of nanomaterial	References
Ag	Cellulose films	Tomatoes	Antibacterial properties	Gu et al. (2020)
TiO_2	Chitosan	Grapes	Preservative possessing antimicrobial activity	Zhang et al. (2017)
TiO_2	Polyacrylonitrile	Tomatoes	Ethylene scavenging property	Zhu et al. (2019b)
ZnO	Chitosan	Black grape, apple, mango, tomato	Antioxidant and antibacterial properties	Yadav et al. (2021)

The usage of chitosan and chitosan-based additives and films has been recently explored with multiple functionalities with positive outcomes. Chitosan-based films, in general, possess antioxidant, antimicrobial and antifungal properties making it a good replacement for synthetic chemicals (Yuan et al. 2016; Yousuf et al. 2018). The use of chitosan-based derivatives offer a promising solution towards maintaining the shelf life of foods without disturbing its sensorial properties (Kulawik et al. 2020). A recent study proved that chitosan-based matrices can also be used for clarification, preservation and encapsulation of different beverages (alcoholic, non-alcoholic as well as dairy based), fruit juices, tea and coffee (Morin-Crini et al. 2019). Apart from this, nanocomposites (combination of different nanomaterials) have shown efficient thermal and barrier properties at a low cost. Researchers evaluated the concept of the nanocomposites membranes and concluded that it decreased the water permeability in foods by a value of 46 (Jose et al. 2014). An increase in corrosion resistance was evaluated with use of clay and epoxy composites (Gabr et al. 2015).

Edible coatings with nanomaterials have also shown increasing potential towards food storage of fruits and vegetables. These coatings hold useful while transportation from factory to retailers and also maintain the nutritional qualities without causing any physical damage. Edible coatings are generally prepared from fats, proteins and polysaccharides which have been shown to block gases. Nanoclays and nanolaminates have also shown promising results to improve their barrier properties to gases for efficient food packaging (Echegoyen et al. 2016). Nanolaminates involve layer-by-layer deposition of a special coating where the charged surface is applied on food. The application of carbon nanotubes as nanofillers in gelatin films has also been successfully demonstrated (Rai et al. 2019). The biofilms are found to have improved tensile strength, mechanical, thermal and antimicrobial properties (Jamróz et al. 2020; Zubair and Ullah 2020). Thus, nanomaterials have emerged as an integral part while addressing nanotechnology in food packaging.

Conclusion

With tons of foods being wasted every single day, food preservation has been the need of the hour for extending the shelf life to help feed millions of people globally. Although plenty of advanced technologies have been introduced, major strides need to be taken to have a sustainable food system. Availability, access and proper utilization of food should be well balanced in order to understand the value of food security. It is important to maintain a correct and precise balance of technology with respect to design and cost effectiveness. Constant investigation is also being carried out in the area of finding more natural preservatives with excellent antioxidant and antimicrobial properties as they are safe to consume and eliminate processed food. The concept of hurdle technology, which combines multiple techniques to measure different variables like temperature, water activity, pH, moisture content and enzyme activities has also been explored to meet the consumer demands for an efficient food system. Another growing solution is in the area of nanotechnology in foods which has been discussed in this article. However, research on different nanomaterials, its toxicity, its safety to consumers and genetic factors is still under debates and discussions. The concept of bioencapsulation and nanoencapsulation in food supplements and drug developments is also growing at a fast pace keeping in mind the health and environmental effects. Further work needs to be done in data visualization and artificial intelligence, internet of things and machine learning. This would help changing the food and agricultural industry in the area of functional foods and crops through digitalization.

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