Bio-nanocomposites: A Next Generation Food Packaging Materials

Arati Dubey, S. Irudhayaraj, and Adhish Jaiswal

Abstract Bio-nanocomposites are next generation food packaging materials that promote better food quality. Bio-nanocomposites are the replacement for current non-biodegradable and non-renewable materials which are applied as food packaging materials. These nanocomposites are promising materials for human health, food storage and eco-system. Advantages of incorporating nanomaterials into the packaging materials include better physico-chemical, mechanical, antibacterial and antimicrobial properties. Several kinds of nanomaterials including metal, metal oxide and other inorganic and organic nanostructures have proven to be effective to increase the shelf life and reduce the spoilage of food by different mechanism of action. Incorporation of nanomaterials in biopolymer makes the production and application of food packaging material.

Keywords Food spoilage · Packaging materials · Antimicrobial properties · Polymer · Biodegradation

1 Introduction

Now a days, the fear of rising and spreading CORONA virus among the people increases which leads to the consumption of ready to eat food products globally. Recently, fresh packed food's sales in market have been raised more than 60% than the previous year. Specially in metro and tyre I city demands and sales of frozen foods like meat and fish products, fries, patties and products such as batter, paste, curries, and desserts continuously rising which shows that there will be a massive blow in ready to eat meals in the market. Due to COVID-19 outbreak, online shopping are also growing among the people which again accelerate this business. The

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current challenge in this sector is that ready to eat food is a pre-cooked food so it is important that packaging of these food should be such that it can protect food from surrounding contamination, dust, odors, temperature, physical damage during transport, light, microorganism and humidity. The factors which can deteriorate food are microbial contamination, chemical and physical reactions which affect the taste, odor and appearance of food. Here, Food packaging plays a important role to: ensure the safety, increase health consciousness, and shelf life of the food. In the modern age, the need for food packaging development is changing due to men's lifestyle. Over an extended period, people ate whatever they could collect from their local surroundings. When people changed their peripatetic lifestyle to staying in a sheltered area, they needed to store food items. There has been little sophistication in packaging materials until the 1800s. The people used various things found in nature like leaves, shells, and gourds to hold food items and bamboos, grasses, and wood used for the weave baskets and also for shaping into food containers, people used some materials such as paper, glass, and pottery. Egyptians formed the glass and pottery near about 7000 B.C., which was the first evidence; however, industrialization was not seen by Egyptians as long as around 1500 B.C. Figure 1 shows more details about the evolution of packaging materials growing demand for the ease of food products due to change in lifestyle [11, 50]. After early development, there was rising attention on food and food quality. There were several modifications for improving the quality of food. Plastics is one of the significant fields that has seen a considerable improvement in materials and their properties. Plastics have as food packaging materials in the last 50–60 years for a very long time. Presently, a wide range of plastic materials are employed for food packaging applications. These packaging application generate waste materials, such as metals, glass, and plastic, which causes pollution. In a record, 42% plastics produced enter into the world primarily as a packaging material. Global plastic waste per year is 275 million tones and world use 500 billion plastics every year. Furthermore, limitation of petroleum resources in our country pushed researchers to focus on different ecofriendly, safe and non-toxic packaging material without compromising the main features of the packaging such as strong mechanical properties, moisture barrier properties and extended product shelf life. Nanotechnology is considered as an essential tool for ensuring good quality and safety of food and food products during storage and transportation. It also help to extend the food product shelf life by avoiding the issues related to chemical contaminants, oxygen, damage microorganisms, light, moisture barriers, etc., as a food packaging materials [14]. Nanomaterials plays an vital role in the food packaging industry as fillers, nutrient carriers, and antimicrobial agents. Nano-food packaging is described as a novel food packaging because it has various properties like antimicrobial, antioxidant, optoelectronic that could assess the food quality and improving their barrier properties and mechanical strength. The main nanomaterials used in food packaging are silver nanoparticles, Zinc oxide, titanium dioxide, and silicon dioxide to develop strong light and heat resistance plastic with gas barrier properties to prevent food spoilage and improved the shelf-life of the packaging product [19]. Additionally, some active agents could use as functional food packaging in the food industry, shown in Fig. 2 [64].

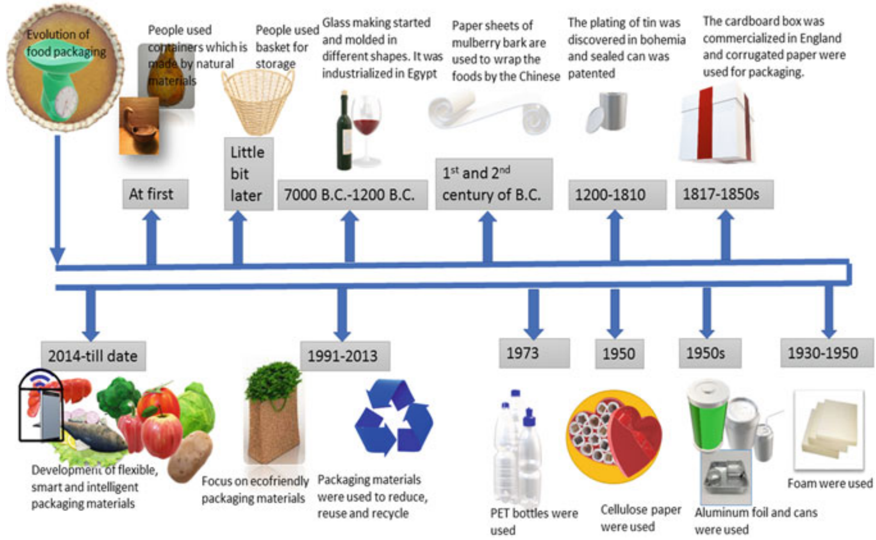


Fig. 1 Evolution of food packaging

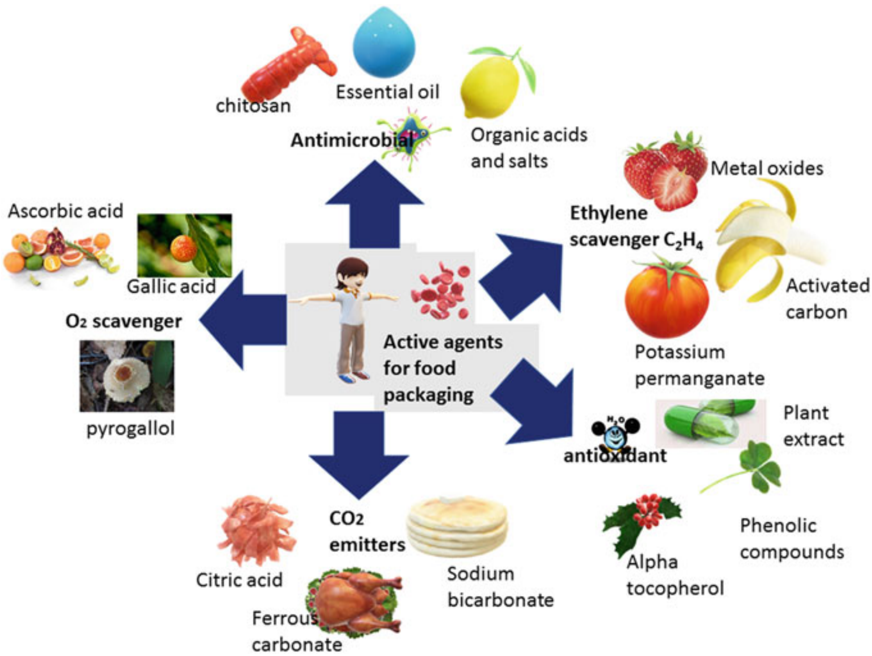


Fig. 2 Active agents for food packaging

Nanotechnology has recently focused on monitoring the spoilage and increasing the shelf life of food products. The incorporation of nanomaterials in food packaging makes it intelligent and active packaging. Food spoilage affects human health, has a tremendous economic impact globally, and raises medical care costs. The active packaging involves the coating of materials and sachet that releases antioxidants, flavors, antimicrobial agents and preservatives to improve or maintain the food quality. The new technology can reduce the wastage of food and food born illness via real-time food quality monitoring throughout the food supply chain. There is growing interest in specific types of biological and chemical sensors to analyze the quality of food. Active packaging can utilize as increasing demand for standard and traditional food packaging. An intelligent packaging system is a continuation of active packaging by improving the quality to provide information about food spoilage. There is a limited number of reports that are using nanotechnology for such kinds of applications. Innovative packaging aims to develop a new type of packaging system that can monitor packaged food quality to the surrounding environment by providing information related to the freshness of food via various signals. Different food quality indicators and devices are used in commercial places to detect food spoilage in intelligent packaging systems [68]. This chapter mainly cover the factors that are responsible for spoilage of food products and the various type of food packaging materials including biodegradable polymers and nanoparticles to control the barrier properties.

2 Type of Food and Factors Responsible for Spoilage of Food

Generally foods are categories into two sections: perishable food, having a short period of life and quickly spoils for example meat, fish, dairy, bread, fruits, and vegetables. Whereas, non-perishable foods which decompose after a long time for example canned food items which include meat, fish, peanut butter, jelly, tea bags, dry soups, stews, etc. All sorts of food can be affected mostly by microbial, chemical and physical reactions which results changing smell, taste and appearance of food. The physico-chemical properties of food changed after spoilage and it becomes unfit for consumption. The food spoilage from microorganism involves production of an enzyme that leads to the formation of unwanted products in the food which react together to change the food characteristics. Whereas in the chemical spoilage of food, chemical reaction e.g., oxidation, enzymatic browning, and non-enzymatic reaction occur in the food to change the smell or color of the food. In case of Physical spoilage of food, occurs when foods are physically damaged during harvesting, processing, packaging or distribution.

3 Microbial Food Spoilage

The microbial spoilage of food has a great concern and has always been problematic for human being. Microbial spoilage caused by large number of microorganisms like bacteria and fungi (molds, yeasts). The microorganisms that are responsible for the food spoilage are shown in Fig. 3.

3.1 Bacteria

Generally, the bacteria are considered as significant organisms for the spoilage of food. There are some non-pathogenic bacteria also that are responsible for food spoilage but they do not pose any threat to human health. However, some pathogenic bacteria may cause serious concern to human health. Proteinaceous food like milk, dairy product, meat, fish, shellfish and poultry are affected by the pathogenic species of microorganisms for example Bacillus cereus, have been found in a fluid milk product, responsible for spoilage and human illness. Clostridium perfringens are found in meat and poultry products that are stored under anaerobic conditions. Additionally, some Enterobacteriaceae include pathogenic species such as Escherichia coli and Salmonella, responsible for the spoilage of food aerobically and anaerobically. In the seafood products, obtained from hot atmospheric conditions, the Vibrio. Spp., species are dominant for the spoilage of marine food products at temperature above 20 °C.

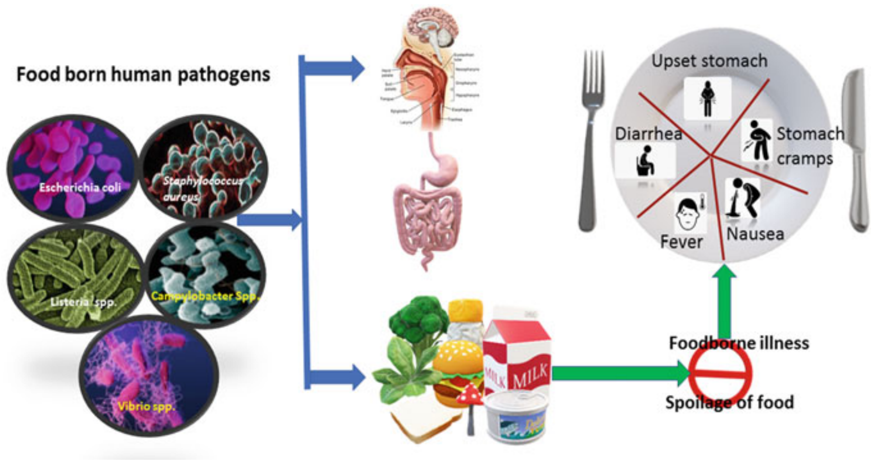


Fig. 3 Microorganisms for food spoilage

Furthermore, in fish and meat, the amine is produced by living organisms via several members of this group. The remaining species that are Obesumbacterium have disagreeable colors in beer and orders.

3.2 Yeast

The spoilage of Yeast generally occurs at pH 5.5 or lower. Generally, the products with high sugar and salt content, spoilage occur by the genera related to the Zygosaccharomyces species. Few species like Z. baillii, Z. bisporus, and Z. rouxii are responsible for the spoilage of foods and beverages. Candida species is one of the significant contributors to the spoilage of foods [45].

3.3 Molds

Molds are filamentous fungi that are responsible for food spoilage. Molds are found in wide varieties and number of genera. Usually, the Zygomycetes, termed as the "pin molds," are frequently considered fast producers. These species spoiled various kinds of food by a "hit and run" approach. Generally, at higher temperatures and lower water activities, Aspergilli and Penicillia, known as common molds, are responsible for the spoilage. Molds are responsible for the genesis of unwanted mycotoxins grow on numerous food stuff. Some fungi also produces small secondary metabolites belonging mainly to the genera Aspergillus, Penicillium, Fusarium, and Alternaria [45].

4 Chemical Food Spoilage

Chemical food spoilage refers to the chemical reactions that change the flavor and color of food during processing and storage. After harvesting the fruits and vegetables or slaughtering animals, chemical changes begin naturally within the foods and start degrading the quality. The breakdown of fats turns into rancid, and naturally—occurring enzymes develop which results extensive chemical changes in foods as they age [10]. Enzymatic and non-enzymatic browning is two different processes which are responsible for chemical spoilage.

4.1 Enzymatic Browning

Enzymatic browning is a naturally process that occurs in many fruits, vegetables, and seafood. Generally, the negative impact of enzymatic browning in fruits and vegetables are change in color, flavor, taste and nutritional value. Enzymatic browning occurs when they are cut, injured, peeled and diseased or exposed to any unusual conditions. On exposure to air the fruits and vegetables develop brown colored melanin pigment because of the oxidation of phenolic compounds. It became functional with the oxidation of phenols by polyphenol oxidase into quinones. It has been reported that polyphenol oxidase present in fruits, vegetables and some seafood is highly responsible for enzymatic browning [11].

4.2 Non-enzymatic Browning

Non-enzymatic browning is a strong chemical reaction responsible for the characteristic change in color during the heating or long-time storage of fruits and vegetables. It is attributed to a Maillard chemical reaction, where carbonyl group of reducing sugars reacts non-enzymatically with free amino groups of amino acids and proteins. In this chemical reaction, the brown coloration of food occurs without the activity of enzymes. Non-enzymatic browning can produce fluorescent, brown, and highly cross-linked pigments such as chromophores and melanoidins. It is commonly apparent that L-ascorbic acid degradation products and sugars, e.g., furfural, 5-(hydroxymethyl) furfural, or other carbonyl compounds are responsible for browning in juice and further, polymerize with each other or react with amino acids to yield browning materials [45].

5 Physical Food Spoilage

Physical spoilage of food occurs during harvesting, processing, or distribution due to physical damage. Due to the physical deterioration of food, there is an increase in the chance of chemical or microbial spoilage and contamination because the outer covering of the food is injured or busted, and microorganisms can penetrate the foodstuff more easily [45].

6 Condition Required for Spoilage of Food

6.1 Nature of Food

Generally, liquid food like fruit juices, water, butter, sugar, soup broth, etc., spoil faster since the organisms can lay out all over the food through their movability or by convection currents. Some semi-solid foods like soup, tinned fruits, and meat stews can spoil more quickly than liquid foods. The solid food items to be more prone to tarnish from their outward appearance.

The growth of the most appropriate microorganisms can be controlled by food that is rich in nutrients. Proteinaceous foods like meat, eggs, and fish are more prone to be attacked by the organisms that can break down the proteins. On the other hand, various foods like bread, pasta, jams, and syrups rich in carbohydrates are more prone to be attacked by fermentative organisms. In contrast, fats are more prone to be attacked by lipolytic organisms. Enzymes can degrade the foods with lipids to produce free fatty acids, which have a putrid and annoying odor, and it is crucial in olive oil, meat, and dairy systems. Several foods have found naturally occurring antimicrobial and inhibitory substances. These substances can slow down the growth of microorganisms [42, 45].

Several yeasts grow very well in very high sugar or salt concentrations. Notably, Debaryomyces hansenii is tolerant to very high NaCl concentration and some strains are resistant even up to 24% (*w/v*) NaCl concentration. Furthermore, molds are tolerant to high concentrations of salt or sugar.

6.2 Activity of Water

The water activity (WA) of food is the ratio of vapor pressure of the food to the vapor pressure of pure water. WA has a dominant role in the growth of the microorganisms. The highest WA for most microorganisms is in the range 0.995–0.980. Since an aqueous phase is a principal requirement for the metabolism therefore any process like drying, curing by addition of sugar or salt will decrease the WA value. Decreasing the value of WA will slow down the microbiological growth which results longer shelf life of food. Various microorganisms have different requirements concerning WA; the composition of the microflora is impacted by the WA.

Bacteria need a high WA and therefore do not cause the spoilage of dry foods in dry condition. Usually, yeasts grow in a WA value above 0.87–0.94, however Osmotoler species grow in a low WA value of 0.60. Next, molds can grow in foods with the most insufficient WA of 0.70–0.80; notably Xeromyces can grow in WA value of 0.60 [45].

6.3 pH

The growth of different microorganisms requires different pH values of the food. Most natural habitat of microorganisms evolve around neutral pH, which is excellent for bacterial enzyme activities. Yet, few bacteria like Lactobacillus and Acetobacter are allow to grow at lower pH ranges (3.0–4.4).

Generally, Yeasts can be grown in the range of pH 4.5–7.0. Some yeasts such as P. membranifaciens and Z. bailii are more permissive to grow at low acidic pH value while, others such as S. cerevisiae and D. hansenii are more permissive towards higher pH values within 5.0–7.0 [45].

The stress response mechanisms by microorganisms enables them to sustain in certain pH conditions. There are two distinct processes with Salmonella Typhimurium are resistance response to more acidic pH and tolerance response between pH 4.5 to 6. A few proteolytic bacteria can soar at a higher pH because they produce amines to buffer the high pH at the time of soaring. Oxidative yeasts oxidize organic acids, sugar, and alcohol which raise the pH during the growing period; so, they favor to grow on the surface of liquors forming a film.

6.4 Temperature

Temperature conditions play an essential role in the spoilage process during processing, transportation and storage of foods. When the temperature increases, the lag phase decreases which increases the growth rate. Temperature also control enzyme activity, protein synthesis, solute uptake, and shelf life length. Various microorganisms can grow within a wide range of temperatures, but maximum growth occur at the optimum temperature.

Organisms are divided into mesophiles, psychrophiles, and thermophiles based on their temperature preferences. Several human and animal pathogens in the mesophiles category have food spoilage microorganisms. The minimum growth range of mesophiles occur at 5–15 °C, optimum 30–45 °C, and maximum 35–47 °C temperature range. Escherichia coli, Salmonella, Clostridium botulinum, and Staphylococcus aureus are the examples of these pathogens. Molds and yeasts grow at and below room temperature, therefore they are highly responsible for spoilage of food at cool temperatures [45].

6.5 Gaseous Conditions

The oxidation–reduction potential (ORP) of the food also have impact on the types of organisms that will grow. The spoilage occurs at the surfaces of foods by the aerobic organisms; maximum animal foods and fresh plants have a small ORP throughout.

Facultative microorganisms grow on the surface of the foods and within them, e.g. spoilage of canned foods by the members of the genus Bacillus. Anaerobic organisms can grow in foods stored in the absence of oxygen. Spoilage of food stored in vaccum packs occur due to the fermentation process of bacteria and yeasts. Yeasts grow under both aerobic and anaerobic condition. Generally, molds are aerobic, therefore spoilage occurs at the surface, but mycelium penetrates deep into the food [45].

6.6 Interaction Phenomena

All of the Physico-chemical parameters have a definite impact, but it is essential to study their mixed interaction concerning the growth of microorganisms. Depending on the microorganisms, the interactions may be positive or negative, and the permissible levels of food additives may support the growth of microorganisms if it is present in food. The bacteria will become dominant first; but at a later stage, if the food conditions permits then mold or yeast spoilage may occur. The waste products produced by the dominant organisms may act as stimulant or depressant in the growth of another organism's. For example, few molds of the Penicillium species may produce antibiotics during their development, blocking the growth of other microorganisms [45].

7 Basic Properties Required for Food Packaging Materials

7.1 Barrier properties

7.1.1 Mechanical Properties

The polymer architecture of food packaging material plays a crucial role in several polymer preparation process like injection molding, film forming, sheet extrusion, blow molding, etc., and further polymeric structure tailors the mechanical properties of the end product. Additionally, numerous packaging materials are employed for storage at below room temperature, so it is crucial to examine the mechanical performance under these storage conditions [13, 58].

The tensile strength, percent elongation and the elastic modulus are determined by performing the tensile test analyses. These values provide mechanical information of the biopolymer materials.

7.1.2 Chemical Resistance Properties

Chemical resistance is an essential property required for food packaging because it exhibits its behavior towards acid or base. Consequently, it is required to estimate the performance and the suitability of food packaging material towards acidic and basic condition as a function of time. Generally, the tensile stress elongation at break and modulus of elasticity of sample immersed in weak and strong acid solutions as a function of time, simulating actual conditions, at ambient temperature [58].

7.1.3 Biodegradation/Antimicrobial Properties

Novel bio-nano composites show unique properties such as biodegradability which should not be lost during practical applications. Physical properties of biodegradable polymers need to to improved to replace the current petroleum-based materials. Exploitation of the antimicrobial properties of metal nanocomposites has received great attention. The packaging films with metal nanocomposites are found to control the growth of harmful pathogenic and spoilage microorganisms. The nanocomposite films with antimicrobial activity are especially advantageous due to their admissible architectural integrity and barrier properties impregnated within [6].

8 Food Packaging Materials

Materials used for food packing include paper, paperboards, glass and metals (aluminum, foils, and tin-free steel). In addition, a wide range of plastics in both flexible and rigid forms are employed [13]. These days, food packaging materials combine various materials with peculiar functional or aesthetic properties.

In the food industry, packaging is an essential component at each stage. Its permeability is the fundamental weakness therefore there is a need for innovative, cost-effective, environmentally safe, and intelligent food packaging material. Consequently, various major factors handle the continuous discovery of intelligent food packaging materials that promote transportation, handling, and storage. So far, the glass, plastics, and metals are employed in packaging applications but they face the problem of non-biodegradability. Bio-nanocomposite materials are promising candidate for food packaging applications. Green packaging materials, including biodegradable, edible materials, plant extracts, and nanocomposite materials characteristics, can reduce the negative environmental impacts.

8.1 Paper as Packaging Materials

The reedy plant papyrus was used by Egyptians to produce the world's first writing material. Later bamboo and mulberry barks were used in the development of paper-making process. Nowadays, paper are manufactured even from cottonseed hair, sunflower stalk, agricultural waste and leaves [52].

Based on grade the paper can be classified as processed and recycled paper. Further, paper for food packaging can be classified into two broad categories: (1) based on pulp or paper treatment (2) based on shape and combination of various materials. Wood pulp treatment effects the paper properties and its use significantly [15] (Table 1).

Advantage of using paper as a packaging material are cost-effectiveness, lightweight, printability, easy availability, and strong mechanical properties. But its major drawback is humidity and moisture absorption. The paper products were progressively combined with a layer of biopolymer coating to improve their barrier properties, functionality and hydrophobicity by the surface modification with the mixing of biopolymers [13].

Table 1 Different types, properties and uses of paper in food packaging application

Types of paper	Preparation and properties	Use in food packaging
Kraft paper	Unbleached pulp and bleached pulp Soft, expensive and White color	Flour, sugar, and fruits and vegetables
Tissues	Wrapping tissue is of two types Ordinary tissue and neutral tissue	Bakery products, and tea and coffee bags
Grease proof paper	Prolonged heating of wood pulp Translucent and impermeable to fats and oils	Oil/fat rich food, milk products and meat
Glassine paper	Extreme hydrationof grease proof paper High density, transparency, smooth and glassy surface	Liner for baked goods, biscuits and cooking fat rich food
Vegetable parchment paper	Acid treatment of pulp High wet-strength with poor gas barrier property	Oil/fat rich food and pastries,
Waxed paper	Wax coated on paper base Liquid and gas barrier properties	Fruit juices, milk, baked food and pastries
Sulfite paper	Light weight, glazed to improve appearance	Bakery and confectionary products
Paper board	Prepared from 100% virgin pulp or 100% bleached virgin pulp or 100% recycled paper	Milk and bakery products, fruit juices and dry fruits
Paper bags	Prepared from various types of paper and available in different forms	'Carry home' and 'grocery carry use' bags

Recycling of paper refers to reuse of recovered paper after proper processing in form of new paper or other paper based products [21]. But, recycled paper can never match the quality of virgin paper, however recycling of waste paper conserves raw materials such as wood, forest and biomass [65].

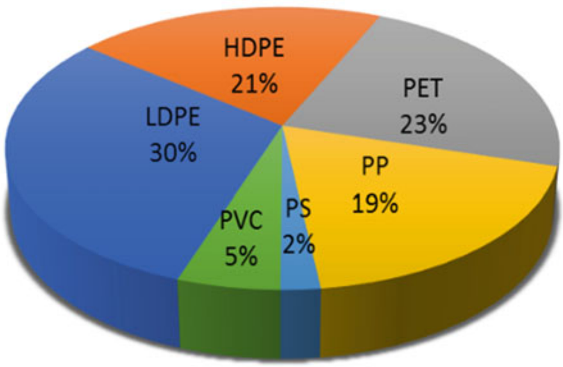
8.2 Glass and Metals Based Packaging Materials

Both glass and metals are totally resistant to vapors and gases, they act as an effective barrier between the external atmosphere and air inside the material. Glass containers are one of the oldest method and currently practiced method of packaging wide variety of materials (pharmaceuticals, nutraceutical, dietary supplements and several other food products) [59]. Glass is manufactured from silica precursor, in presence of sodium carbonate, limestone or calcium carbonate and alumina. For storing the pharmaceutical and biopharmaceutical specially designed glass of Type I, Type II, Type III and Type IV are employed, among these Type I and II are preferred for medical formulation [55].

Metal-based packaging is one of the most versatile and widely utilized method for packaging of different products. This packaging provides physical protection and recyclability [71]. Metals, such as aluminum and steel are durable for food products. Tin-plated steel are durable properties, such as recyclable, eco-friendly, provide physical protection, and thermal and chemical resistance (Figs. 4 and 5).

Bio-based packaging materials exhibit better barrier properties, including permeability of vapor and gases, while hydrophobic surface treatments should boost resistance to humidity. The barrier properties of bio-based packaging materials can have improved by coatings using deposition of atomic layers, while hydrophobic surface modifications should increase resistance to humidity [13].

Fig. 4 Global production of petroleum-based polymer



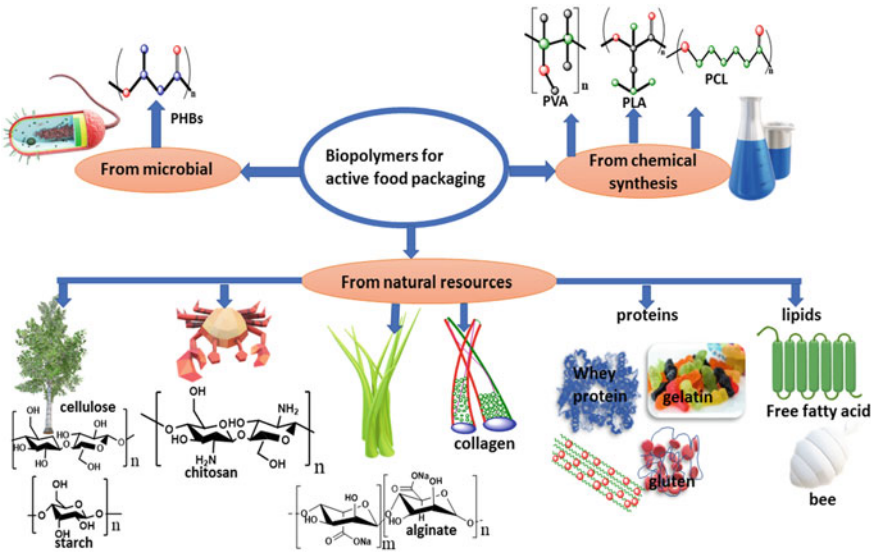


Fig. 5 Biopolymers for food packaging

9 Petroleum Polymers Based Packaging Material and Its Draw Back

In the middle of the twentieth century, petroleum-based polymer materials were widely used by human beings. These materials are advantageous in terms of cost-effectiveness, usability, aesthetic quality and physicochemical properties. Generally, plastics are employed as packaging materials, notably they are employed as food packaging materials. Major drawback of these plastic packages are non-biodegradability and use of petroleum polymer as source. Percentage of more often used petroleum-based polymer for food packaging are shown in Fig. 6. Blackberries packaged in snap-fit package made of poly(lactic acid) and poly(styrene) met the "US standard No 1" grade for commercialization for more than 12 days at 3 °C [33].

Consequently, nearly 80% of plastics used for landfills, less than 10% of plastics recycled, and around 10% incinerated. So far, above 6 billion metric tons of plastics waste in total has accumulated worldwide, and it is a matter of concern for the environment. Thus, the biodegradable packaging materials give more attention to the packaging industry [47, 73]. Few petroleum based polymers has been discussed here.

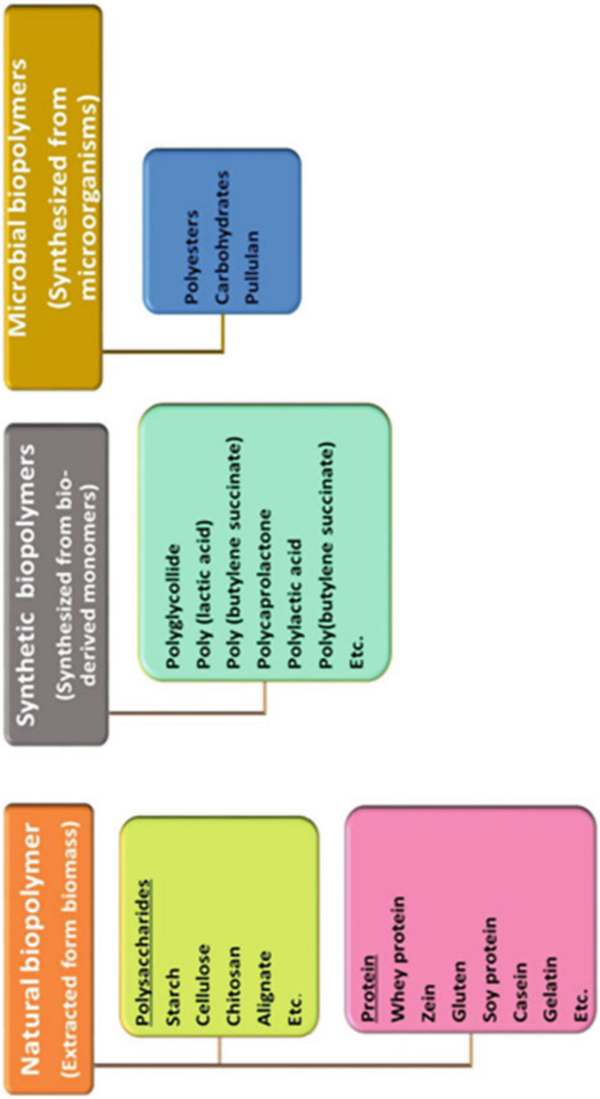


Fig. 6 Different types of biopolymers

9.1 Polyethylene (PE)

PE is one of the most common plastics produced in the world and has a wide range of physical properties. PE are rigid, hard or soft and malleable. The large varieties of products stored and packaged made by soft and malleable films in the packaging industry. Polyethylene has a low cost in comparison with many other plastics. The lower softening point favors lower processing energy costs. The packaging industry used two types of polyethylene: high-density polyethylene (HDPE), low-density polyethylene (LDPE) [6]. LDPE film incorporated with gallic acid and potassium chloride exhibited excellent oxygen-scavenging potential [2]. LDPE/(clay/carvacrol) films exhibited excellent antibacterial activity against *Escherichia coli* and *Listeria innocua* [57]. LDPE/ethylene vinyl acetate active packaging films shown controlled release of ferulic acid as natural antioxidant, which was 635 times higher than that of LDPE film [26]. HDPE/copper nanofiber nanocomposites exhibited enhanced tensile strength, oxygen barrier and antibacterial properties [8].

9.2 Polypropylene (PP)

Polypropylene is a rigid, rugged, and transparent glossy film with high strength and puncture resistance. It acts as an excellent barrier to moisture, odors and gases. Oriented PP is a clear glossy film with better optical properties, high tensile strength and puncture resistance. It exhibits moderate permeability to gases and odors while higher barrier property towards water vapor. It is used mainly to pack snack foods, biscuits, and dry foods [6]. Plasticized protein coatings on polypropylene film exhibited significant bacterial growth inhibition against Lactobacillus plantarum [35]. Corn zein nanocomposite coating of polypropylene films demonstrated reduced oxygen permeability and water permeablility [35].

9.3 PET Poly (Ethylene Terephthalate)

In the packaging industry PET is one of the most widely used polymers. It increases the barrier properties of soft drinks packages and several other rigid and flexible packaging applications. Incorporation of nanocomposite is an unique way to improve the properties of this material [6]. Olive leaf extract impregnated PET/PP films exhibited significant lipid oxidation of sunflower seeds [12]. Supercritical carbon dioxide impregnated PET/PP exhibited adsorption of α-tocopherol (TOC), a natural antioxidant [24].

9.4 PVC (Polyvinyl Chloride)

It is a thermoplastic material produced via free radical polymerization of vinyl chloride. It withstands high temperatures and shows excellent resistance to oil and fat. PVC are used in the form of blow-molded bottles. PVC based film is tough, high elongation, relatively low tensile and tear strength. It is appropriate for the packaging of mineral water, fruit drinks, and fruit juice in bottles. Generally, in the food packaging application, the use of PVC is decreasing because of its toxicity and environmental issues [6] (Table 2).

10 Biopolymers Based Packaging Material and Its Benefit

Polymers have played an essential role in packaging materials for a long time because they possess various desired features like softness, lightness, and transparency. Although, synthetic packaging films can cause some severe environmental problems because of their total non-biodegradability. The complete replacement of synthetic film with an eco-friendly packaging film is exclusively difficult for particular applications like food packaging. Biopolymers are natural polymer which has introduced as sustainable packaging materials. There is another possibility for non-petroleum-based polymers including polysaccharides, proteins, lipids, poly hydroxyl butyrate (PHB), polylactic acid (PLA), polyvinyl alcohol (PVA), poly butylene succinate (PBS), poly caprolactone (PCL) and their biopolymer blends. Biopolymers possess different properties such as non-toxicity and biodegradability that can be boosting their application in food packaging.

In the packaging industry, several natural and synthetic biodegradable polymers are used. The polymers can classify as natural, artificial, and modified natural polymers based on their origin and an environmental point of view Fig. 6. These polymers with excellent physicochemical properties are promising candidate for food packaging [6].

Table 2 Different petroleum based product and their respective packaging applications

Petroleum based product based	Packaging applications
LDPE	Carrier bags, bin bags
HDPE	Milk and fruit juice bottles
PP	Drink bottle, juice bottles
PET	Carbonated drink bottles and other transparent drink bottles
PVC	Chemical bottles, trays and cups

10.1 Natural Polymers

Natural polymers play an essential function in the food packaging business. They have excellent properties, nutritional food value, antioxidant and inclusive antimicrobial properties, cost-effective, renewable origin, spreading, and the fact that are environment friendly. Different types of biodegradable polymers occur in nature. A brief explanation of few of them described below.

10.2 Starch

Starch is a natural polymeric carbohydrate present in many green plants (potato, rice, corn, wheat, barley, soybean and oat). The molecules of starch are composed of two types of polymers of d-glucose that is amylopectin (70–80%) and amylose (20–30%). Additionally, it is considered one of the promising alternative biopolymer materials. The advantages include nontoxicity, biodegradability, easy availability, and renewability. Starch-based films showed excellent barrier to oxygen at relatively low humidity. The brittleness nature of the starch film can be improved by adding few common plasticizers viz. glycerol, xylitol and sorbitol in the food packaging materials. It can also be plasticized using materials like poly (ε-caprolactone) (PCL), poly (vinyl alcohol) (PVA), and others. Starch blended with thermoplastic were used for cups, food wrapping, plates and other food containers. Yet, the blending technique do not show improve film properties, such as barrier properties and mechanical properties as compare to plain starch film. The sugar palm starch, combined with various plasticizer can be used for preparation of biodegradable films [53].

10.3 Cellulose

Cellulose is a biopolymers in found in all plant materials, algae, fungi, bacteria and made up of a chain of β-(1 → 4)-linked glucose residues. Due to their poor solubility, hydrophilic nature and a highly crystalline structure faces some difficulties in food packaging.

Cellulose has the potential to conserve water loss from dry areas and it can absorb undesirable liquids. These properties sharpen the treatment of deep ulcers and as an antimicrobial agents in wound dressings. Surface improved wood cellulose fibers, like taurine cellulose, α-hydroxysulfonic acid cellulose (HSAC) are used to prepare environmentally friendly film. The film made by HSAC showed excellent mechanical properties. Improved cellulose fiber blended with PVA played vital role in improving the tensile strength of the composites and can be used as a packaging material [53].

10.4 Chitosan

Chitosan (CS) is a nontoxic linear polycationic polysaccharide composed of randomly distributed β-(1 → 4)-linked 2-amino-2-deoxy-d-glucose (d-glucosamine) and 2-acetamido-2-deoxy-d-glucose (N-acetyl-d-glucosamine) units. Commercially it is produced by chemical N-deacetylation of chitin shells of shrimp and other crustaceans. The molar mass of the polymer and the extent of deacetylation is one of its most important chemical characteristics which dictate its use. Additionally, it showed different properties, biodegradability and biological roles, depending on the relative proportions of d-glucosamine and N-acetyl-d-glucosamine residues. CS showed many valuable features as a packaging material because of partially or well enough solubility in the water, films forming nature without the use of other additive and heat resistance. Further, CS has excellent barrier properties towards oxygen and carbon dioxide and shown excellent antimicrobial activity. The membrane of chitosan is used for coating fresh fruit, in particularly, strawberries, berries, and grapes. The addition of antioxidant and preservative like garlic extract, lysozyme, nisin allow for longer storage of products [53].

10.5 Protein-Whey Protein

Whey protein (WP) is a combination of alpha lactalbumin, beta-lactoglobulin and immunoglobulin. They are adequate of forming flexible films, and they are used as raw materials because they have good oxygen barriers, average moisture permeability, and good biodegradability. WP are one of the cost-effective raw materials used in the manufacute of edible films. The WP with Plastic films is used as biodegradable and showed high barrier to oxygen. The commercial biodegradable Bio-Flex, blended with WP to form coatings films which is used as biodegradable packaging material [53].

10.6 Zein

Zein is a mixture of proteins from corn and is classified as a prolamin, which contains 44%-79% of the endosperm protein. It has both hydrophilic and hydrophobic properties. Although is shown poor mechanical properties, it can be employed as food packaging material, mainly as an impermeable protective coating because of its good gas barrier, biocompatibility, and biodegradation properties. Zein-based films with glycerol, nanocarbonate, oleic acid and nanocarbonate show the possibility to pack food products [53].

10.7 Gluten

Wheat gluten (WG) is a main protein of wheat. It is a water-insoluble protein consisting of more than 60 different polymeric polypeptides. It has a molar mass of 30,000–100,000 g/mol. WG has been widely modified chemically or enzymatically because of its low solubility. The laminated film of WG with glycerol as a plasticizer and polylactic acid (PLA) as a reinforcing component has higher strength than the gluten films and it shows good barrier properties [53].

10.8 Microbial Polymer

Microbial polymers, also indicated to as biopolymers and have been employed in food, pharmaceutical, cosmetics and other industries applications. The controlled microbial fermentation has admitted the use of these significant components as coating, packaging, stabilizing, thickening or gelling ingredients in the food industry. As an additive, these polymers can act as an antioxidant, antimicrobial, sweetener preservative, antioxidant material and can be used to boost properties of modern functional food. In the last decades, these natural polymers have garnered boost interest due to their biodegradable, nontoxic, eco-friendly, nontoxic, and modifiable features, along with decreased production costs [53].

10.9 Polyhydroxyalkanoates (PHA)

PHA are naturally occurring biodegradable polymers which are produced by bacterial fermentation of lipid and sugars. Depending on the monomer it can be thermoplastic or elastomeric materials. These polymers produce excellent packaging films either alone or in combination with synthetic plastic or starch. Though these polymers are currently too much expensive than petrochemically based plastics. Few modifications of PHA have been developed to expand the range of its packaging applications. For the food packaging applications polymer must illustrate a high purity level. The obtained material involves minor impurities like lipids and proteins during the microbial production of PHA. The small amount of impurities may cause a significant odor problem when using PHA as a package [53].

10.10 Synthetic/Artificial Polymers

Man-made biodegradable polymers and polymers from renewable resources have found applications in the packaging industry. These polymers are found to be advantageous over natural polymers because they can be tailored to provide a wider range of properties for specific applications [53].

10.11 Polyglycolide

Polyglycolide (PGA) or polyglycolic acid is the linear, simple, rigid, aliphatic hydrolyzable polyester. It exhibits high crystallinity and barrier properties against CO_2 and O_2. PGA is use as protective layer in multilayer packaging systems, for carbonated soft drinks and beer bottle for packaging applications [53].

10.12 Polylactic Acid (PLA)

Polylactic acid (PLA) derived from biodegradable and renewable resources like corn, fermentation of sugar feedstock, etc., which has excellent physical and chemical properties. PLA is recyclable, biocompatible, biodegradable and compostable, non-toxic, renewable, hydrophilic and highly transparent. Generally, commercial PLA is a copolymer synthesized form poly (D-lactic acid) and poly (L-lactic acid) monomers. The properties of PLA can vary from semi crystalline to amorphous nature depending on the D-lactide/L-lactide enantiomers ratio. It also has a high heat distortion temperature, good gas barrier properties and mechanical properties. Concerning the optical, physical, and mechanical performance of the oriented PLA polymer (OPLA) in food application, the comparative study has achieved two of the commonly used materials used for new food packaging applications, which are polyethylene terephthalate (PET) and oriented polystyrene (OPS) [53].

10.13 Polybutylene Succinate (PBS)

PBS is a commercially available aliphatic polyester having succinic acid as one of the monomers. It is principally manufactured through polycondensation of 1, 4-butanediol and succinic acid. These polymers give a wide range of environmentally friendly thermoplastics. When PBS mixes with other polymers such as poly (ethylene succinate) (PES) and thermoplastic starch, the materials' cost reduces [53].

10.14 Polycaprolactone (PCL)

Poly- ε-caprolactone is a biodegradable polyester obtained by the ring-opening polymerization of ε-caprolactone. It is soluble in a broad range of solvents. It has a low glass transition temperature and exist as semi-rigid material at room temperature. It is readily biodegradable by Enzymes and fungi. Various copolymers with lactide or glycoside developed to improve the degradation rate. It uses for packaging materials with composite films [53] (Table 3).

11 Nanomaterials Used in Food Packaging

In recent years nanomaterials have drawn much attention due to their extraordinary properties and mainly used to impart antimicrobial function and improve the gas barrier, mechanical and thermal properties to extend the shelf life and freshness of packaged food items. The different types of nanomaterials used in food packaging are discussed below-

11.1 Silver NPs (AgNPs)

Generally, AgNPs is widely used as an antimicrobial agent for food and beverage safety. AgNPs possess a larger surface area at a nano-scale as compared to micro-scale or bulk. In addition, AgNPs interact with the surface of the cell via different mechanism. AgNPs is incorporated into the plastic polymers by different methods for food packaging. It has been reported that AgNPs and ZnO-NPs containing LDPE can protect and elongate the shelf life of orange juice. The active-nanocomposite of this material has proven to be highly efficient for antimicrobial nanomaterial in combination with heat treatment [13] (Table 4).

11.2 Nanoclay

Nano clay was the most demanding material in the food packaging industry because it was the first emerging material in the market among the other polymer nanocomposites. It is used for enhancing the physical of plastic and barrier properties of packaging material. Montmorillonite (MMT) is an example of nano clay. These polymer composites is extensively used because of their magnificent cation exchange efficiency, good swelling behavior, and wide surface area. Naturally, it is readily available because it derived from volcanic ash and rocks. Depending on the degree of nanoparticles distribution in the polymer matrix, the nano clay composites have

Table 3 Literature report of some examples of biopolymers used for food packaging

Polymer	Matrix	Properties	Applications	References
Starch	Cassava starch based foams incorporated with grape stalks	Biodegradable	Suitable for storage of food with low moisture content	[20]
	cassava starch based films incorporated with cinnamon essential oil and sodium bentonite clay nanoparticles	Biodegradable	Packaging of meat balls	[32]
Cellulose	Carboxymethyl cellulose (CMC) based films containing Chinese chives root extract (CRE)	Improved moisture content, water-solubility, swelling degree and thickness by the addition of CRE	Good antioxidant and antimicrobial activity	[48]
	Lysozyme and lactoferrin were incorporated into paper containing CMC	CMC improves the protein payload of paper	Lysozyme was most effective in preventing growth of microbiota	[7, 46]
Chitosan	Grapefruit seed (GFSE) extract incorporated chitosan film	GFSE made the films more amorphous and decrease the tensile strength	Inhibited the proliferation of fungal growth	[61]
	CRE incorporated chitosan based film	Optical properties were improved	Good antioxidant and antimicrobial activity	[49]
Whey protein (WP)	Lysozyme with Polyacrylic acid incorporated WP isolate films	Incorporating lysozyme into the film in complexed form extended its release time	Good anti-bacterial film	[43]
	WP incorporated with *Fucus vesiculosus* extract	Strengthened the mechanical properties	Inhibited the chicken breasts lipid oxidation	[4]
Zein protein (ZP)	Chilto fruit extract incorporated ZP	Zein fibers improved coating integrity upon water contact	Zein fibers delayed the release of phenolic compounds, hence suitable for food packaging	[35]
	Glycerol and polyethers added zein films	Excellent elongation and UV barrier properties	Promising for food packaging	[31]

(continued)

Table 3 (continued)

Polymer	Matrix	Properties	Applications	References
Soy protein	Bilayer of soy protein and poly(lactic acid)	Improved mechanical properties	Inhibition of mold, yeast and two strains of bacteria	[28]
	Soy protein isolate: bees wax edible coating	High O2 modified atmosphere did not extend shelf life	Antioxidant capacity of cut artichoke was maintained	[25]
Microbial	PLA films coated with a cellulose derivative/cocoa butter	Coatings decreased the water vapour permeability of PLA	Reduced the number of bacterial strains	[40]

Table 4 Ag NPs based composite food packaging materials reported in literature

Polymer matrix	Tested food	Tested microorganism	Shelf life	References
Ag/LDPE nanocomposite film	Chicken breast fillets	Psychotropic bacteria	8 days	[5]
Ag NPs/regenerated cellulose film	Cherry tomatoes	E.coli and S.aureus	9 days	[30]
Ag NPs/Alignate	Cheese	B.cereus, S.aureus, E.coli and S. typhi	14 days	[41]
Ag NPs/PE packages	Olivier salad	Coliform, mold and yeast	15 days	[63]
Silver and clay nanocomposite	Shrimp	V.parahaemolyticus, S. aureus and E.coli	6 days	[44]

either an intercalated or exfoliated pattern. It helps in the dispersion of the nanoparticles in the matrix of the polymer. In general, nano clay acknowledges as a vital filler for polymer, which is bio-based reinforcements. Therefore, the reinforced polymeric material reduces the barrier properties and gives mechanical strength to the biopolymer. It is used for packaging, carbonated drinks, beer bottles, and thermoformed containers for industrial purposes. Reportedly, the nano clay in plastic bottles keeps the juice fresh and prolongs the shelf life up to 30 weeks. The use of nano clay-based hybrid materials will provide sustainability and reduce environmental risks associated with dumping synthetic polymer-based packaging materials [38].

11.3 ZnO

It is extensively used in various applications like medical devices, cosmetics, medical devices, medication, atmospheric processed (MAP) packaging, and delivery. ZnO-NPs is specifically more attractive for packaging applications than AgNPs because

Table 5 ZnO NPs based composite food packaging materials reported in the literature

Polymer matrix	Tested food	Tested microorganism	Shelf life	References
ZnO NPs/PVA/Spathodea campanulata bud fluid matix	Black grapes	E.coli, P. aeruginosa and E.aerogenosa	7 days	[29]
Chitosan/potato/protein/linseed oil/ZnO NPs	Raw meat	Total bacterial count reduced	7 days	[66]
Betanin nanoliposomes incorporated gelatin/chitosan nanofiber/ZnO NPs	Fresh beef	E. coli and S.aureus	16 days	[3]
ZnO NPs/Chitosan	Poultry meat	Total aerobic mesophilic and psychotrophic, and Enterobacteriaceae	11 days	[60]
ZnO NPs/ Pullulan/chitosan	Meat	E.coli and L. monocytogenes	15 days	[51]

its cost-effectiveness and less toxicity. Also, ZnO can produce a large amount of hydrogen peroxide under UV irradiation that can cause oxidative stress in bacteria cells. Zinc ions play a crucial role in blocking the growth of bacteria. ZnO-NPs can oxidize ethylene into carbon dioxide and water under UV irradiation and decrease the accumulation of malondialdehyde (MDA) and pyrogallol peroxidase (POD) activity. PVC–ZnO-nano-composite films can use this mechanism to extend the shelf life of food products [13] (Table 5).

11.4 Titanium NPs (TiO_2-NPs)

TiO_2-NPs consider as most crucial metal oxide nanomaterials with inertia and thermo-stability which can improve the properties of biodegradable films. US-FDA can approve it in 1996 as a food additive. In the food packaging industry, it is frequently used as a whitener, photocatalyst, air and water purification, self-cleaning structures, water filtering, and antimicrobial. Many studies carried out on the antimicrobial effects of TiO_2, which indicated that, under ultraviolet light or sunlight, it could produce reactive oxygen species which directly destroy microbial cell walls. The particles of white TiO_2 efficiently scatter the visible light, therefore giving the coated object power, brightness, and whiteness. The TiO_2 in the form of thin coated solid is non-flammable, non-volatile, totally inert, and completely insoluble in all foods and food materials [13] (Table 6).

Table 6 TiO_2 NPs based composite food packaging materials reported in the literature

Polymer matrix	Tested food	Tested microorganism	Experimental findings	References
k-carrageenan/konjac glucomnann/TiO_2 film	Strawberry	Penicilliumm viridicatum	Irradiated for 6 h	[17]
Polylactic acid/TiO_2/GO film	Green peppers	E.coli and S.aureus	High antibacterial activity after 24 h of UV irradiation	[16]
CMC/Arabic gum/gelatin/garlic extract/TiO_2 NPs	Fresh Nile tilapia fish fillets	S. aureus, B.cereus, L. monoctogenes, S. typhmium, P. aeruginosa, E. coli and yeast C. albicans	Delayed bacteriological development, lost less water during cold storage for 21 days	[70]
Chitosan/whey protein/TiO2 NPs and Zataria multiflora essential oil	Cheese	Coliforms, spore-forming bacteria and lacotose-fermenting yeasts	Inhibit the growth of Listeria monocytogenes on the surface of cheese	[27]
SiO, ZnO and CuO/4A zeolite	Shrimp	Staphylococcus aureus, Listeria monocytogenes, Escherichia coli, Pseudomonas fluorescens, Vibrio parahaemolyticus *and* Aeromonas caviae	Reduced the total viable, Enterobacteriaceae, *Pseudomonas* spp. and *Shewanella putrefaciens*, in raw shrimp and *S. aureus*, *L. monocytogenes*, and *E. coli* count in inoculated shrimp	[56]

Table 7 Metal/metal oxide NPs based composite food packaging materials reported in the literature

Polymer matrix	Tested food	Tested microorganism	Shelf life	References
LDPE/Cu NPs	Peda (sweet)	E. coli and S.aureus	8 days	[37]
(Ag–Cu) NPs/polylactide films	Chicken samples	S. typhi, C. jejuni and L. monocytogenes	21 days	[1]
CuO/ZnO NPs	Guava fruit	E. coli and S.aureus	7 days	[34]
CMC/PVA/CuO	Processed cheese	Total bacteria count, coliforms, moulds and yeasts, and pscychrotropics	28 days	[69]
SiO, ZnO and CuO/4A zeolite	Shrimp	Staphylococcus aureus, Listeria monocytogenes, Escherichia coli, Pseudomonas fluorescens, Vibrio parahaemolyticus *and* Aeromonas caviae		[56]

11.5 Copper and Copper Oxide (Cu/CuO)

Copper nanoparticles have relatively Cu^0/Cu^{2+} low reduction potential hence it is quickly oxidized. It is used as an antimicrobial agent because it can reduce the growth of few microorganisms such as bacteria, fungi, and viruses. CuO nanoparticles increase the shelf life of food packaging materials [19] (Table 7).

11.6 Magnetic Nanoparticles (Fe_3O_4)

Magnetic nanoparticles may come into different shapes, sizes, and crystalline forms that might alter their toxicity. They were used in food packaging by utilizing a nanofiller. Several studies have found that the food packaging applications related to magnetic nanoparticles show better characteristics as a composites film [22].

11.7 Nano-starch

Starch is the cheapest, biodegradable, renewable, and non-toxic polysaccharide. It is used in food, pharmaceuticals, paper-making, plastic, rubber, and packaging materials because of its effectiveness, environmentally friendly, and ample supply. Generally, starch can be found in discrete and partially crystalline granules and mainly made up of two glycosidic macromolecules: branched amylopectin and linear amylose. It is vital to separate crystalline starch from the amorphous and crystalline complexes for the production of nano-starch. Flexible food packaging uses starch nanocrystals as a promising nanofiller. The starch nanocrystals improved barrier properties and mechanical properties since it is highly susceptible to hydration. The molecular structure of starch possesses hydrophilic functional groups; hence it is not applicable in a humid environment. The film of starch is appropriate as an antimicrobial packaging material [13].

11.8 Carbon Nanotubes (CNTs)

Carbon nanotubes are hollow tubes with a diameter of a nanometer in range. The two types of CNTs are single-wall CNTs and multiwall CNTs. It provides an outstanding high tensile strength and elastic modulus when combined with the polymer matrix. In recent times, CNTs have been composed of polymers and employed for packaging purposes and intelligent antimicrobial sensors. The carbon nanotube-based sensor could be producing a transparent, thin-film embedded with wireless chips which communicate to the market manager and customer about the spoilage of fruit and meal [13].

11.9 Nano-silica

The nano-silica mainly use at the time of hydrophobic coatings, especially for self-cleaning materials. Inside the container, the non-hydrophobic coating can allow food to be free-flowing material inside the containers or jars. There are various products such as wine, beer, and powdered soup that benefitted from this technology [13].

12 US and Indian Safety Guidelines in Food Packaging

The packaging and labeling of food is regulated by the U.S. food and drug administration (FDA). These regulations aim to aware the consumers about the food and increase the safety of food given out all over the United States. The center for food safety and applied nutrition (CFSAN) and the office of food additive safety can ascertain the protection from harmful food contact substances. The guidelines of FDAs also need that the labeling of the package involves the expiration, nutrition guidelines and best before used by dates, preparation instruction and handling, and the packaging company's contact information. The labeling of allergen has also been necessary since 2006. The labeling of food allergen and consumer act requires the disclosure when the product contains potential allergens like cereals, crustaceans, mollusks, eggs, fish, lupin and milk soybeans, peanuts. Also, a notification for the packaging of a product is made using any of the allergens mentioned earlier (U.S. FDA Administration) (Table 8).

13 Obstacles in Commercialization

There are several issues in the commercialization of nanopackaging films. First, the production and studies of nanopackaging materials are still in the laboratory level and is not yet scaled up to industrial level due to their high cost of production. Second, poor barrier and mechanical propertied as compared to that of the synthetic plastics. Third, leaching of NPs into the food materials. Fifth, lack of awareness. Sixth, cost of nanopackaging films are higher than currently available synthetic plastics packaging materials. Finally, it is essential for to emphasize manufacturers to label the nanopackaging packaging materials with requisite information or label.

14 Future Trends

Presently we focus the bio-based packaging materials. It is necessary to transformed bioplastic research to address industrial application via academic and industrial collaborations. The growth of the bioplastic market can reduce petroleum-based polymers. Currently, we are crossing active and intelligent packaging materials. Innovative packaging reduces the wasting of food to check the spoilage of food products in real-time. Bioplastics will become a core part of the bioplastics market. There are many types of research needed to improve the quality of bioplastic for food packaging applications. Still, much research is required to overcome the next generation of innovative and intelligent packaging that can improve the shelf life of food products and know the spoilage of food products by incorporating various materials and devices. The researcher can create an intelligent barcode by installing the sensors on the food packaging and scanned to clarify the freshness of packaged items.

Table 8 Different other nanocomposites with promising packaging applications

Nanocomposite	Method	Properties	References
Starch NPs/poly(dimethylsiloxane)	Super hydrophobic coating	Excellent water resistance, self-cleaning, and liquid-food residue reduction	[67]
Water chestnut starch composite films	Acid hydrolysis method	Starch NPs decrease moisture content, water vapour transmission rate and solubility, while increase thickness and burst strength	[18]
Polylactic acid/CNTs/chitosan	Electrospinning	Exhibited better antimicrobial activity against S. aureus than E.coli	[36]
Pectin-CNTs films	Physical mixing or chemical bonding	Improvement of properties of pectin-CNTs films by chemical bonding as compared to physical mixing	[23]
Nanoclay/cinnamon oil/ Cassava starch films	Green technology	Exhibited significant antibacterial potential against E.coli, S. typhi and S. aureus	[32]
LDPE/nano clay composite films	Twin-screw extrusion	Beef color maintained for up to 4 days and native micro flora was suppressed	[62]
Cellulose nanofibrils and nano clay	Spray technique	Higher clay content increased the barrier properties	[39]
Silica–carbon/Ag NPs	One-step ball milling process	Exhibited bacteriostatic effect	[9]
Nisin/nano silica/chitosan	Coating	Provided longer storage life for mushroom	[54]
Mesoporous silica NPs/potato starch films	Casting	Better antibacterial protection for mushrooms against M. circinelloids and mucur sp.	[72]

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