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COMPENDIUM ON PLASTIC FREE - SMART FOOD PACKAGING: A REVIEW

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Abstract:
This review provides a perspective on the development, application, and future prospects of biodegradable packaging, various biopolymers, and their advantages and disadvantages. Also, producers and customers alike are increasingly very concerned about smart packaging. Food safety must be assured, and suitable solutions to extend shelf life and reduce food waste must be considered. Smart packaging produced from bio-based materials is a viable option since it combines sustainability with real-time tracking of food quality, ensuring health safety while also delivering economic and environmental benefits. Smart packaging materials have sensors that can identify changes in food qualities including those in quality, maturity, and safety. In order to show quality of food decline, a smart sensor, for example, might cause a discernible color shift. This article looks at cutting-edge developments in biodegradable packaging that offer new hope for the food business. Also, the effectiveness of using these packaging materials to assess the safety and freshness of food goods, including meat, fish, dairy, vegetable, and fruit products, is evaluated.

Index Terms: biodegradable packaging, bio-polymers smart materials; active packaging; sensing components

1. INTRODUCTION:

Today's increasing packaging market is essential to the modern economy. Nowadays, the majority of synthetic polymers are created using petrochemicals, which are not naturally biodegradable. While being disseminated in nature, these polymers cause significant environmental contamination that is harmful to both humans and wildlife. As a result, developing alternatives to these materials is critical in order to protect the environment. In the recent years, biopolymers based biodegradable packaging have lifted up significant attention to food manufacturer for packaging, since the inflation of sustainable development policies with the dropping reserves of fossil fuel along with rising worry about the environment. As a result, Biodegradable polymers are a key area of research.

The preferred solution is smart packaging depending on bio-based materials that offers viability and tracking of food quality across time while also providing pecuniary and economic advantages. As the globe shifts towards more advanced technologies, packaging companies can rely on them and acclimatize to them, as well as incorporate them into their packaging strategies to gain the benefits of being ahead of the secure food and environment.

2. BIO-BASED PACKAGING

Biopolymers are composed of a continuous series of compound subunits derived from natural sources. They can be created from natural resources or from monomers derived from living organisms. It could also be made directly by microbes. Based on the source and last use purpose, this can be divided 1st, 2nd, and 3rd generations, our primary focus is with biodegradable materials, it can be categorized as follows.

2.1 Classification of Biopolymers

First Generation: This generation's materials for shopping containers included pro-oxidizing and auto-oxidizing chemicals as well as synthetic polymers like low density polyethylene (LDPE), which has a fraction between 5 to15% starch wadding. After that, these chemicals degrade or bio fracture into smaller, rarely biodegradable molecules. Yet, a great deal of goods has negatively impacted the image of bio-based products, especially for consumers who were urged to play by the rules of natural decomposition [14]. LDPE excels in withstanding bases, alcohols, acids, and esters. Moreover, it has excellent strength against to several aldehydes, ketones, and vegetable oils. It is stable in temperatures up to 80 °C. It can be either clear or opaque, and it can be quite soft in terms of flexibility and toughness [37]. On the other hand, it is brittle. It can be employed for a multitude of everyday purposes, such as juice packaging, as well as for industrial uses, such as those requiring corrosion-resistant materials, welding equipment, etc.

Second Generation: This generation materials consist combination of LDPE and around 40 to 70 % pre-gelatinized starch along with various hydrophilic copolymers like vinyl acetate and acrylic acid which are acted for compactness. Noticeably, total time taken for starch degradation is around 40 years while above mentioned film takes only approximately 2-3 years.

Third Generation: On the foundation of sources and manufacturing processes, the third generation of materials can indeed be categorized into three main categories:

I) Polymers extracted/isolated directly from biomass

These kinds of polymers are primarily derived from plants, marine life, and domesticated animals. To give an example, synthetic polyesters like polylactic acid can all be blended with polysaccharides like whey protein, chitin and starch, casein, cellulose, collagen, and so on.

II) Polymers produced by conventional chemical synthesis of bio-monomers

Polylactic acid (PLA) is the well known example of this category. It is resemble to polystyrene in properties. It is obtained though fermentation of starch or glucose. Wheat, corn, otherwise Molasses or whey is the primary source [65]. Lactide and lactic acid are the two major monomers. PLA has excellent water vapor permeability; that which crucial for fresh food packaging [28]. For instance, it depicted good properties with "Panola" variety of raspberry with 24 or 40 micron's all combination of packaging which maintained Stable concentration of anthocynins during storage period resembling polypropylene box having holes along with card board boxes. It is maintained gas composition (average around 7% o_2 and 15% % CO_2) with thickness of PLA bags, 25 micrometers [55].

III) Polymers obtained directly from natural or genetically modified organisms

As a source of carbon stockpile and energy, many bacteria build these polymers. This category embraces bacterial cellulose and Poly Hydroxyl Alkanoates (PHAs). PHAs are hydrophobic and insoluble in water. PHA polymerase enzyme catalyzes the HA polymerization in the form of PHA. This entire pathway of reactions occurs within the cell by the terms of series of various enzymes reactions. Depending on the types of carbon source and bacteria such as *Bacillus, Halobacterium, Alcaligenus, Rhizobium Azetobacter* and many others; PHA can be produced from rigid brittle to plastic to rubber like polymer. PHA has resembled properties to polythene and polypropylene like thermoplastic and elastic [80]. It takes 5 to 6 weeks for biodegradation in favorable conditions [9]. Like renewable sources, biodegradable plastics can be generated by synthetic polymers by the use of micro organisms. Poly Hydroxyl Alkanoate (PHA), a biodegradable plastic can be produced by converting styrene using bacterium *Pseudomonas putida* , that have broad applications [14].

3. ADVANTAGES AND DISADVANTAGES OF BIO-BASED PACKAGING MATERIAL

Through studying the accessible prose can be set up squabbles for both affirmative and negative characteristics of bio-packaging. The energy consumption is lower for production of biodegradable plastics compare to traditional petroleum passed plastic. Some of these eco-friendly packaging can be reused in their native form while other can be decomposed in an eco-friendly environment. The main pros and cons of bio-based packaging substances are enlisted under.

Table 1: Advantages and Disadvantages of bio-based packaging material

Advantages	Disadvantages
Renewal	The lack of arable land (future)
Good for the environment	Transportation
Less energy to produce	Limited properties
Easier recycling	Less awareness of people
Non toxic	Installation cost
Reduced dependence on oil	Processing plants

Table 2: Miscellaneous applications of bio-based packaging films in food sector

Applications	Biopolymers	References
Baked items	PLA packs	Jager A., 2010
Beverages	PLA coated cups	
Curdled milk	PLA jars	
Potato chips	Cellulose sheet	Grumezescu *et al.*, 2017
Sweets	Cellulose films	
Chocolates	Cornstarch trays	
Organic crops	Cornstarch packs	
Kiwi	Cellulose-based trays	Kumar and Thakur, 2017
Chilled fries	PLA sheets	Nieburg *et al.*, 2010

4. BIODEGRADABLE SMART PACKAGING

Food manufacturer are always endeavor to improve the environmental influence and sustainability of their products, as their interest is surged up in development in smart biodegradable packaging materials. Smart packaging materials consists such elements that increase their functional behavior such as antioxidants, oxygen barriers or antimicrobials along with light blockers. These materials for smart packaging can be obtained from various sources of nature that are listed below.

- ✓ Macronutrients: specific protein and carbohydrate molecules
- ✓ Inorganic nanoparticles: Ag, TiO_2, ZnO and clay
- ✓ Organic nanoparticles: lipid, protein

And carbohydrate based nanoparticles

- ✓ Essential oils or other extracts from plants: thyme oil and tea extract
- ✓ Phytochemicals: curcumin, quercetin and anthocyanins

This smart packaging can be categorized in 2 various categories that which also further classified according major triggered action.

(i) Active Packaging: Contains additives, such as antioxidants, plant extracts or antimicrobials that can improve the quality, shelf-life and safety of foods by inhibiting chemical reactions or microbial growth.

(A) Antioxidants
(B) Antimicrobials
(C) Gas Controllers

(A) Antioxidants

Several types of antioxidants are added to food packaging to prevent oxidation in the food, such as that do breakdown of proteins and fats [41] [18]. These antioxidants typically slow down food oxidation by dissipating oxygen and reducing hydrogen peroxide, even by squelching existing free radicals [72] [24]. Garlic, saffron, strawberries, and many more plants are used to extract the main natural antioxidants. They contain a variety of substances that can prevent food from oxidizing. For instance, epigallocatechin gallate as well as epigallocatechin, two crucial antioxidant molecules that are prevalent in green tea, have demonstrated excellent antioxidant activity [26].

Moreover, the antioxidant properties of several plant extracts such grape seed, ginger, and ginko leaf extract on gelatin films was investigated [29]. Anthocynins are the water-soluble pigments that are abundant in nature and have excellent antioxidant activity. They can be found in crops, florals, fruits, and vegetation [72]. Essential oils, consisting of terpene, phenolic, and terpenoid chemicals, are another class of these molecules and have stronger antibacterial and antioxidant activities [23] [16]. Many essential oils are produced by distilling natural sources such as carvacrol, thyme, and cinnamon [23]. These essential oils demonstrated improved mechanical and physicochemical qualities when they were included into the packaging materials. They also showed antioxidant and antibacterial capabilities. Moreover, these essential oils are employed to improve the characteristics of several nanoparticles, including titanium dioxide (TiO_2), zinc oxide (ZnO), and silver (Ag) [16].

(B) Antimicrobials

It is beneficial that adding of antimicrobial materials into the packaging materials, as it inhibits the growth of pathogenic microbes [10] [42] [72]. Various botanically derived extracts like saffron, garlic cabbage etc. and essential oils such as cloves, oregano, rosemary oils are could be added in packaging material[1] [4] [72] [5] [32] [65]. They either diffuses into the food while storage or as such retain in to the packaging materials [58] [72]. Noticeably, some antimicrobial substances are very sensitive to the heat and those may loss their efficiency while they contacted with heat during thermal processing. So, this problem can be solved by using electro spinning, casting or other solvent evaporation methods for preparation of packaging materials [25].

Anthocynin illustrates to have better antimicrobial properties that depicted in active packaging material [43]. It restricts extracellular enzymes and also cut down the microorganism's cytoplastic membranes. Other naturally derives antimicrobial compounds are also examined. To demonstrates, when eugenol have been incorporated in to gelatin film, film depicted boosted antibacterial activity , as 2.5 log units of *S. aureus* and 3 log unit of *E. coli* reduced compare to control [30]. Furthermore, one another study also revealed its antibacterial activity against *P. aeruginisa* when tomato extract combined with itaconic acid were added in chitosan and poly(vinyl alcohol) films [60].

Active packaging materials also assist to cut down the contamination occurred through various fungi and viruses [51]. One study has shown that tea extract added in the chitosan based film depicted antiviral effect against the *Murine norovirus* (MNV-1) [6]. In another study silver incorporated into the polylactic acid film demonstrated boosted activity against *Felin vir*us (FCV) [38]. Fungal resistant packaging materials have also been developed. To exemplify, augmentation of *Aspergillus niger* as well as *Penicillium expansum* on bread were trimmed down when cinnamaldehyde was inserted into film containing of gliadin [8].

(D) **Gas Controllers**

Various gases can easily penetrate to food packing materials, but oxygen is the main issue since it accelerates food oxidation and reaction that causes discoloration [15]. Thus, it is vital to keep the oxygen level in the food packaging constant. Several oxygen-scavenging compounds, including palladium, ascorbic acid, and ferrous acids, are used to regulate different oxygen concentrations. Sulfites, tocopherols, and unsaturated hydrocarbons can all be applied [15]. Moreover, the enzyme glucose oxidase is quite effective in scavenging oxygen. Herbal compounds such phenolics, salicylic acid, flavonoids, and gallic acid are also very effective at reducing the detrimental effects of oxygen on food [23] [54]. It is easier for hydroxyl groups to develop easily in substances with pleasant structural textures such double bonds between carbon-oxygen and carbon-carbon, and these substances function better [15] [44] [72].

It is a well-known fact that the ethylene gas released by fruits and vegetables during natural respiration negatively affects the way they ripen, feel, look, and taste. It is crucial to maintain a steady ethylene gas level in packaged foods throughout storage. Compounds in effective ethylene regulators have the potential to oxidize, absorb, or even annihilate the gases [52]. Clay, titanium dioxide, palladium, potassium permanganate ($KMnO_4$), and activated carbon are some of the best examples [17]. This can be used both independently and in conjunction with other things. According to one study, even a film built from two distinct bases, such as chitosan and TiO_2 nanoparticles, in to which extract of black plum peel was added, had an impressive capacity to scavenge ethylene. The materials used for packing must also be designed so that they have the proper functional and physicochemical properties, such as mechanical, sensory, barrier, and many others [77].

(ii) Intelligent Packaging:

Act in respond to an identifiable trigger, for instance, an alteration in pH, temperature, moisture content, gas levels, light exposure or chemical constitution.

(A) pH Indicators
(B) Gas Indicators
(C) Time-Temperature Indicators

(A) pH Indicators

When the pH of a packaged product significantly alters, this type of indicator depicts a discernible change. pH sensors can able to provide a signal of variation in food quality or safety since these pH fluctuations which may be generated by enzyme activity, chemical interactions, or microbial development in foods [59]. When the pH of the immediate medium varies, several different varieties of natural pigments exhibit distinct color variations. This halochromic pH-sensor, also known as a colorimetric pH-sensor. It is chiefly based on a barter of protons (H+) between the pigments and their surroundings [40]. This kind of some colorimetric indicators can also change color when certain volatile substances are present, which can also be a sign of changes in food quality [35] [40] [68] [74]. These pH sensitive materials mainly work on anthocynin base. The Anthocyanins can be acquired from diverse plant sources, such as saffron petals [4], black rice bran [70], hibiscus [46]. Moreover, anthocynins can also obtain from various botanical resources like purple corn [50], black soybean seed coat [67], purple onion peel [31], and roselle [21] [76]. Along with these, red barberry, blueberry, purple sweet potato, red cabbage as well as carotenoids, betalains are major source of anthocynins.

Changing of pH responded by these expected pigments rely on their molecular structure, along with various surrounding parameters such as oxygen level, temperature, and light exposure [11]. Anthocynins are nowadays broadly applicable pigment in smart packaging of food, since, they depicts color change in broad spectrum of pH values [3]. It, changes from red (strongly acidic) to (mildly acidic) for purple color. Furthermore, it shows violet color for neutral pH and blue color for mildly alkaline pH. As pH increases, it illustrates green color for moderately alkaline pH and for strong alkaline pH, yellow color [11] [64]. So, these anthocynins could be well applicable for pH sensors as they demonstrate various colors under different pH range. Therefore, these anthocynins are the best options to incorporate into the smart packaging materials based on biopolymers; to track the variations in the quality of foods.

Many foods, including shrimp [70], milk [63] [75] [49], fish [22] [72], and pork [76], are packaged using this kind of intelligent packaging material as a quality indicator. In addition to this, a lot of natural ingredients are employed as food quality indicators. For instance, when added to polylactide, beta-carotene or bixin cause color changes and, when oxidized, provide a sign of the quality of the oil. Furthermore, adding betacyanins from dragon fruit peels to polyvinyl alcohol/glucomammam film for packaging fish results in a noticeable color change [7]. It indicated acidic circumstances with a purple tint and alkaline conditions with a yellow color.

(B) Gas Indicators

Various gases like ethylene and more are produced by the fruits and vegetables through natural respiration, which gives measures of their quality. Furthermore, such gases like oxygen can transfer inside and outside of the packaging and can change the characteristics of foods through chemical deterioration (such as oxidation). To add Further, various kinds of gases are also generated by the microbial action. Hence, it is very crucial for need-to smart bio degradable film to inform presence of gases [2] [57]. Smart packaging is already existed that are combined with these sensors and work on principle; when they get exposure of different gases it would change color according to type of gases. To cite an example, as the ammonia (NH_3) gas concentration rise, anthocynins depicts purple/violet to green/yellow [32]. Similarly, in the presence of oxygen, betalains shows measurable color variation [20].

In addition to these, carotenoids also possess color changing nature in the presence of oxygen, so they can be used as oxygen sensor [26]. These gas sensors can be employed in the packaging film by various modes like adhesives, printed layers, and labels or as inside the film. The most important advantage is that these sensors provide information much cheaply than many other analytical instruments like chromatography, mass spectrometry or spectrophotometry [57]. A number of studies successfully examined presence of volatile compounds and various gases by biodegradable smart packaging including CO_2 [48] [53] [79], O_2 [69], volatile ammonia [71] [79] and H_2S [27] [75]. For instance, freshness of green bell peppers was examined by using colorimetric gas sensing indicators [13]. In this, film altered color green to orange as it gets spoil. In another study, produced NH_3 was measured during storage of shrimps by using tara gum/Polyvinyl alcohol film containing curcumin [34]. As result, film depicted color yellow to brown as concentration of NH_3 increased.

(C) Time-Temperature Indicators

Time – Temperature indicators, in short, TTIs are mainly used to track the temperature of packaged foods to maintain quality and safety of food during storage period. Natural pigments are widely used as indicators when smart packaging materials are formed with TTIs [19] [33] [73] [39]. The level of color transition of this particular indicator relies on Time-temperature contour that with packaged foods are rendered. The main advantages of TTIs; they are not only cheap but also simple in design. Moreover, they are being very simple and easy to read through consumers. These TTIs are classified into various groups based on temperature-detection method such as polymerization, diffusion, thermochromic and enzymatic reactions. Along with these, they are also dependant on photochromic reaction, electronics and microbial growth [66] [78].

To add further, these temperature based indicators are also categorized by their mode of operation. (i) Critical temperature indicators, also referred as CTI, depict whether the food is heated more or cool down lesser than some particular temperature during its life span. (ii) critical temperature/time integrators, (CTTIs) reports either the food is heated or cooled below than some particular temperature for longer than some specified time period. (iii) Temperature- time integrators, indicated as TTIs; that report the entire time versus temperature profile of food throughout its whole life. These sensors are dependent on an Arrhenius temperature and its activation energy should be between 10 and 40 kcal/mol.

Different types of vegetable extracts isolated from pomegranate juice, blue flowers [56] and fruit purees [45] illustrate discoloration when the temperature exceeds about 30℃. For instance, a study examined changing in color from violet to yellow when temperature rose 40 to 70℃ by incorporating temperature sensitive anthocynoins in chitosan/cellulose film [36]. Moreover, various other indicators for time temperature detection are produced depending on various another mechanism of sensor such as microbial based (green to red), diffusion based (yellow to pink). Enzymatic based indicators also shows alteration in color from green to yellow to red [57].

Table 3: Examples of the application of active packaging materials in the food industry

Film Matrix	Active Additives	Remarks	Reference
Chitosan	Pine needle extract	Films showed high antioxidant activity and protected oxygen-sensitive foods	Kadam *et al.*, 2021
Polylactic acid	Essential Oils (thymol, carvacrol)	A PLA film impregnated with thymol and carvacrol had the best antioxidant activity	Lukic *et al.*, 2020
Whey protein isolate	Lysozyme, Lactoperoxidase	Films extended shelf-life by inhibiting bacterial growth	Min *et al.*, 2005
Polylactic acid	Essential Oils (thymol, kesum, curry)	Films inhibited bacterial growth and extended shelf life of meats, fruits and vegetable products	Mohamad *et al.*, 2020
Chitosan	ZnO nanoparticles	Films had good activity against gram-positive bacteria and fungi	Youssef *et al.*, 2016

Table 4: Examples of the application of intelligent packaging materials in the food industry

Film Matrix	Active Additives	Remarks	Reference
Polylactide	Chlorophyll, Curcumin, Lutein	Color changes in film in response to changes in temperature or light exposure	Latos and Masek , 2020
Bacterial Cellulose film	Anthocyanin/Black carrot	Film changed color in response to gas production	Moradi *et al.*, 2019
Chitosan	Chlorophyll	Film changed color when exposed to elevated temperatures (>50℃)	Maciel *et al.*, 2012

5. CONCLUSIONS

Bio-based food packaging will be one answer to the global challenges related to environmental security, food saving and safety, as well as for renewable materials and technologies.

In this content, concern has been kept on plastic free smart packaging materials including;

(i) The packaging materials themselves degrade in nature after providing a safe envelope for the products

(i) Advanced coatings and additives to help preserving foodstuff

(ii) Renewable indicator materials with enabling technologies that can detect the quality of foods and are potentially feasible for industrial scale-up

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