Biotechnological Innovations in Packaging and Sensors in the Food Processing

Pooja P. Thul[1*]; Dr. D. N. Jagtap[2]; Rinkesh A. Gosavi[3]; Manjit M. Khatal[4]; Prajakta Labade[5]; A. A. Sawant[6]

[*1,3]PhD Scholar, Department of Processing and Food Engineering, CAET, Dr. BSKKV, Dapoli, Ratnagiri, M. S. (India)
[2]Assistant Professor, Department of Agronomy, COA, Dr. BSKKV, Dapoli, Ratnagiri, M. S. (India)
[4]Young Professional, ICAR-Directorate of Onion and Garlic Research, Pune, Maharashtra, India
[5]PhD Scholar, Department of Soil and Conservation Engineering, CAET, Dr. BSKKV, Dapoli, Ratnagiri, M. S. (India)
[6]Professor and Head, Department of Processing and Food Engineering, CAET, Dr. BSKKV, Dapoli, Ratnagiri, M. S. (India)
*Corresponding Author

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Abstract— *The global bioplastics and biopolymers market size is expected to grow from USD 10.5 billion in 2020 to USD 27.9 billion by 2025, Bioplastics and Biopolymers Market by Type (Non-Biodegradable/Bio-Based, Biodegradable), End-Use Industry (Packaging, Consumer Goods, Automotive and Transportation, Textiles, Agriculture and Horticulture), and this high growth is driven primarily by the growth of the global packaging end-use industry. Food packaging has a crucial function in the modern food industry. New food packaging technologies seek to meet consumers' and industrial demands. Changes related to food production, sale practices and consumers' lifestyles, along with environmental awareness and an advance in new areas of knowledge such as biotechnology, act as driving forces to develop smart packages that can extend food shelf-life. Food producers gradually demand effective quality control procedures to satisfy and regulate consumer requirements to enhance production feasibility, automation, quality sorting and decrease the time and cost of production. Biosensors can be used to identify food allergens and pathogens rapidly and efficiently. It can also overcome all these disadvantages by offering quick, inexpensive and non-destructive procedures for quality control.*

Keywords— Bioplastics, Biopolymers, Packaging, Biosensors, Allergens, Pathogens.

I. INTRODUCTION

Fresh food products get easily degraded due to physical injuries resulting from handling, transportation, storage, or intrinsic factors caused by chemical reactions, enzyme action, and microbial spoilage. The use of packaging is therefore a strategic choice for protecting and conserving food (Rodrigues et al., 2021). Packaging has four basic functions, viz., Containment, convenience, protection and communication. Food packaging is a vital element of the food industry, as it supports all operations associated with the processing, handling, transport, and distribution of the contained food (Marangoni Junior et al., 2022). In today's food industry, packaging is a foundation that performs several important tasks to ensure product quality and consumer safety. It acts as a shield and protects against external elements such as bacteria, insects, light, heat, oxygen and odours, thus preserving the food during its shelf life. In addition to this basic function, it also serves as a means of communication with consumers. It conveys important information through labels, branding and design, meeting the convenience and time-saving needs of today's consumers (Bhatlawande et al., 2023).

Generally, packaging is classified based on the material type used for packaging, which can be divided into metal, glass, polymer, paper cardboard, wood, textile, multi-layered, ceramic and other types (Ivankovic et al., 2017). Over half a century, plastic packaging has prevailed owing to its versatility and cost-effectiveness, eclipsing traditional materials such as glass, metal, paper, and cardboard. As a result of their non-biodegradable nature and pollution generated throughout their life cycle, petroleum-based plastics have catalysed a cascade of environmental concerns. In response to these pressing issues, the industry is undergoing a rapid transition towards eco-friendly packaging, with biodegradable and bioplastic materials, derived from biomass and characterized by their biodegradability, gaining remarkable traction (Bhatlawande et al., 2023). Biodegradable and renewable materials represent a great alternative for protecting the environment and transforming underutilized products or industrial waste materials into valuable products. In this sense, bioplastics have begun to gain prominence (Salgado et al., 2021).

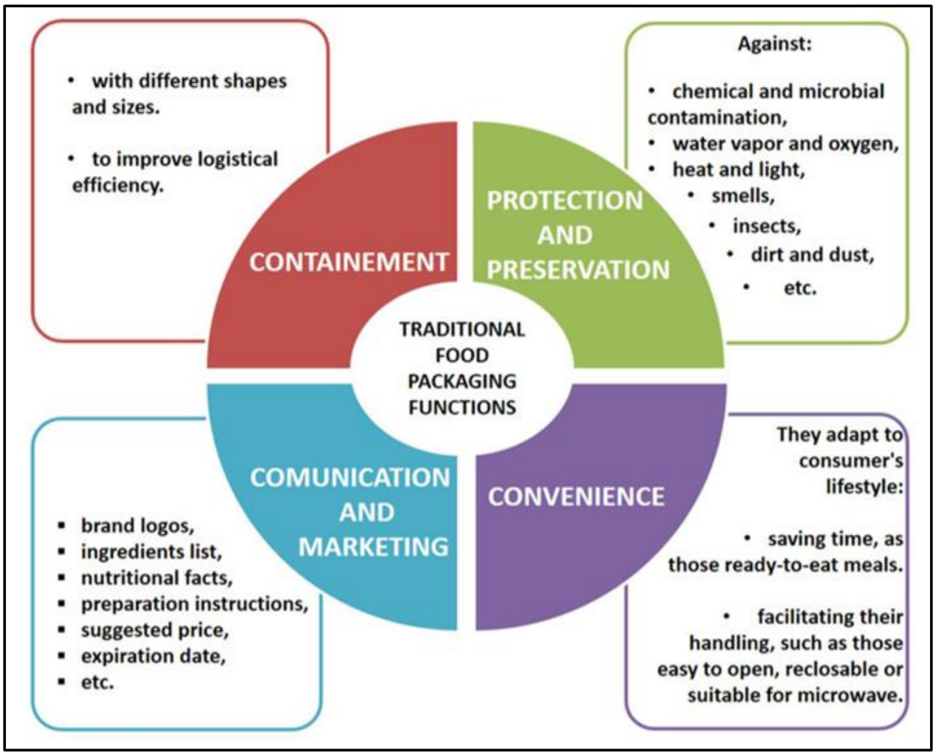


FIGURE 1: Traditional food packaging functions (Salgado et al., 2021)

II. BIOTECHNOLOGY

Biotechnology is a multidisciplinary field that integrates natural and engineering sciences to achieve the application of organisms and parts thereof for products and services. The term biotechnology refers to the production of products from raw materials with the aid of living organisms. The core principle of biotechnology involves harnessing biological systems and organisms, such as bacteria), and plants, to perform specific tasks or produce valuable substances (Biotechnology, Wikipedia).

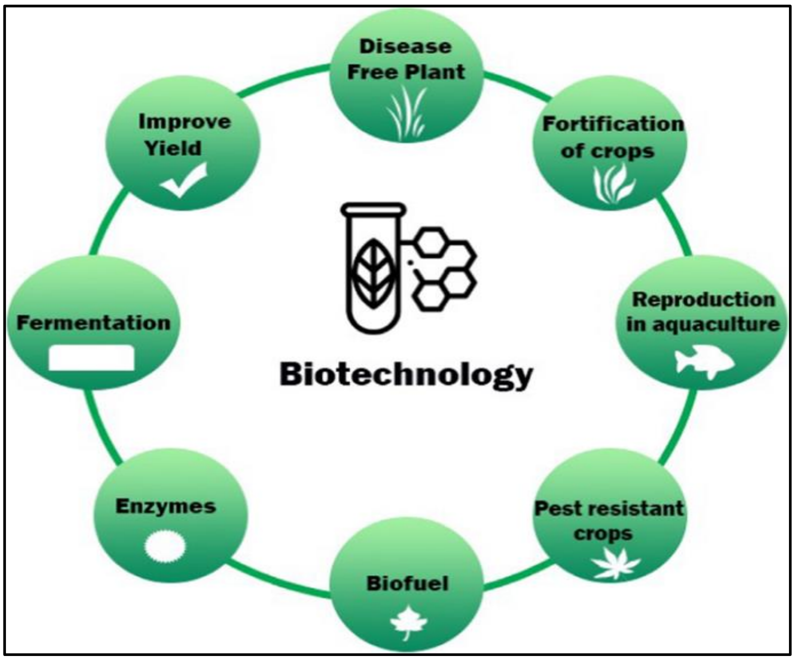


FIGURE 2: Biotechnology in Food and Agriculture (Ranjha et al., 2022)

2.1 Biotechnology in food processing:

Biotechnology is a branch of science concerned with the utilization of various living organisms in the creation of useful products. It can be defined as any technological application that uses biological systems, living organisms, or derivatives to produce or modify products or processes for specific use. Biotechnology integrates animals, humans, and microorganisms that have contributed to every aspect of our lives. It has opened numerous opportunities to various sectors such as food technology, agriculture, animal sciences, cell biology, plant sciences, environmental sciences, and medicine. For example, food technology is not only an important but a promising research area that applies biotechnology tools to improve the oldest food processing techniques such as fermentation, enzyme production, as well as conservation of plants (Yu, 2017).

In the food processing sector, biotechnology plays a crucial role, especially in cereal processing, fruit and vegetable processing, beverages, oils and fats, dairy processing, poultry and confectionary processing. Nowadays, biotechnology is used in every aspect of life (Ghoshal, 2018). It can convert non-edible and perishable food items to palatable and longer shelf-life food, which is safe and improved quality in terms of nutrition and physicochemical and sensory properties. Through the use of modern biotechnology in the food industry, the reduction of food losses has not only been made possible but the efficiency of food quality has also been improved (Awulachew, 2021).

2.2 Potential Areas for Biotechnological Applications in Food Processing:

The food processing industry has several potential areas where traditional and modern biotechnological tools can be applied during processing to enhance the nutritional quality, safety and health-promoting attributes of processed foods, particularly dairy-based fermented foods. Some of the potential areas of considerable commercial interest in the food processing industry that can be targeted for biotechnological interventions are listed below:

1. Food fermentations
2. Starter cultures technology and genetic manipulation
3. Recombinant Enzymes
4. Bio-preservation of foods
5. Functional / Health foods and Nutraceuticals
6. Probiotics, prebiotics and symbiotic foods
7. Genetically modified foods (GM Foods)
8. Milk-derived bioactive peptides and other functional ingredients
9. Low calorie foods
10. Food packaging
11. Diagnostic tests for food safety and quality assurance
12. Biosensors (Evans and Furlong, 2003)

Traditionally, food packaging protects foods from physical, chemical, and biological factors, maintains quality, and facilitates distribution and marketing (Jacob et al., 2020). In recent years, plastic packaging has proven to be one of the most versatile polymer materials due to its unique mechanical properties, high functionalities, and relatively low costs. A global packaging market of USD 1002.48 billion was estimated in 2021, and it is expected to reach USD 1275.06 billion in 2027 (Anonymous[2], 2022). Global plastic waste generated from 2000 to 2019 has more than doubled to 353 million tons, with packaging contributing approximately 40% (Anonymous[3], 2022). Recently, various countries have taken bold steps to manage plastic packaging waste. Biotechnology has emerged as a viable solution (Fig. 3) for engineering biodegradable, active, and functional polymers/bioplastics for use in food packaging system design, development of edible films/coatings, and packaging technologies (Alim et al., 2022; Caleb and Belay, 2023).

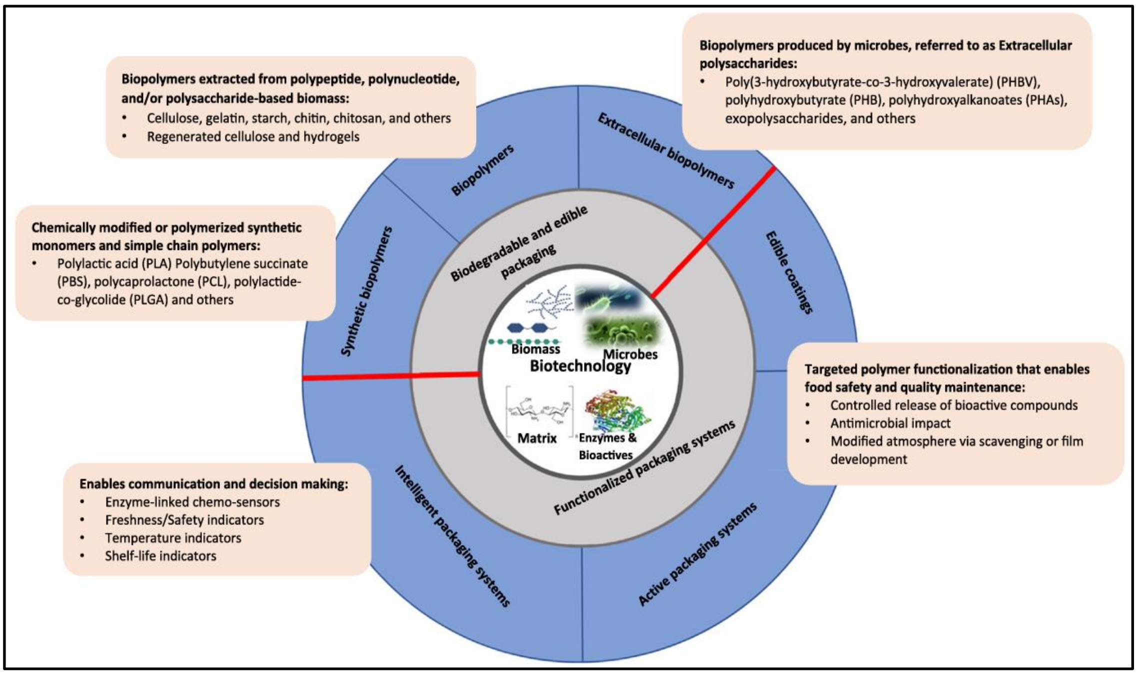


FIGURE 3: Role of biotechnology in food packaging systems (Caleb and Belay, 2023)

2.3 Biopolymer:

Biopolymers are polymers that are developed from living organisms. The term " biopolymer" implies a biodegradable polymer. A biopolymer has existed on earth for billions of years and is much older than synthetic polymers such as plastic. They are compounds prepared by using various living organisms, including plants. Biopolymers are composed of repeated units of the same or similar structure (monomers) linked together. Rubber, starch, cellulose, proteins and DNA, RNA, chitin, and peptides are some examples of natural biopolymers. Biopolymers are a diverse and remarkably versatile class of materials that are either produced by biological systems or synthesized from biological sources. Biopolymers are used in the food and pharmaceutical industries (Upadhye et al., 2022).

The Biopolymers Market size is projected to reach US$27.5 billion by 2030, after growing at a CAGR of 11.5% over the forecast period 2024-2030. The various benefits associated with biopolymers such as polyesters, polylactic acid, polyhydroxy butyrate, polybutylene succinate and more include biocompatibility, biodegradability, renewability and more. These benefits make biopolymers a sustainable replacement for petroleum-derived materials. The bolstering food and beverage industry, including poultry products, dried food and more is the primary factor driving the biopolymers market growth [Biopolymers Market – Forecast (2024 - 2030)].

2.5.1 Biopolymer in the food industry:

Biopolymers are increasingly being explored and utilized in the food industry due to their biodegradability, renewable sources, and potential to replace synthetic polymers. They offer a range of applications including packaging, edible coating and ingredients to enhance the nutritional and functional properties of food. The use of biopolymers as packaging materials is becoming an emerging trend worldwide due to their major benefits over plastics, such as biodegradability, eco-friendly nature, nontoxicity, and biocompatibility. In recent years, numerous biopolymers such as starch, chitosan, carrageenan, polylactic acid, etc. have been investigated for their potential application in food packaging. The trend of using biopolymers in the packaging industry has increased immensely; therefore, many legislations have been approved by various organizations (Horst et al., 2020; Perera et al., 2022).

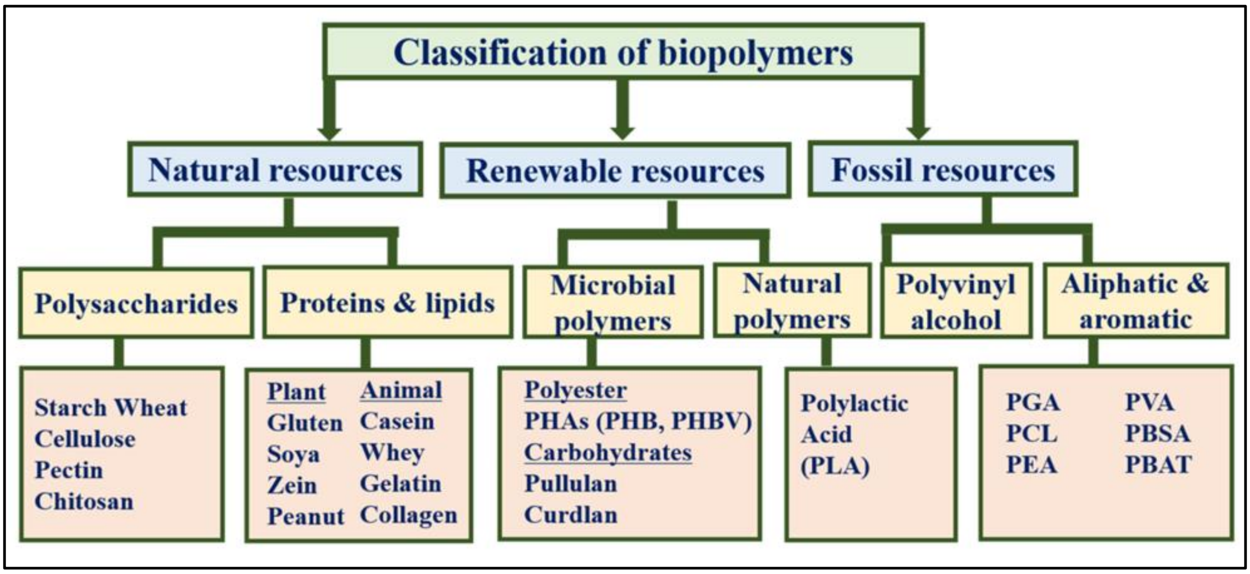


FIGURE 4: Classification of biopolymers for food packaging applications (Basavegowda and Baek, 2021)

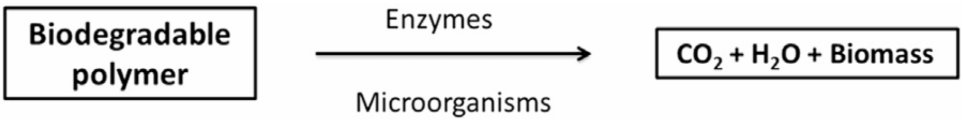
TABLE 1
VARIOUS BIOPOLYMERS AND THEIR APPLICATIONS IN THE FOOD INDUSTRY

Biopolymer	Source	Applications in Food Industry	References
Starch	Corn, potatoes, wheat	Edible films, biodegradable packaging, thickeners, stabilizers	Tako et al., 2020
Chitosan	Shellfish exoskeletons	Antimicrobial films, food coatings, preservative agents	Ravi Kumar, 2000
Alginate	Brown seaweed	Gelling agent, encapsulation of flavors and probiotics, edible films	Draget et al., 2005
Pectin	Citrus peels, apple pomace	Gelling agent, stabilizer, thickener, edible films, encapsulation	Voragen et al., 2009
Gelatin	Animal bones, skin, connective tissue	Gelling agent, stabilizer, film-forming agent, encapsulation	Karim and Bhat, 2009
Carrageenan	Red seaweed	Thickener, gelling agent, stabilizer, film-forming agent	Necas and Bartosikova, 2013
Polylactic Acid (PLA)	Fermented plant starch (corn, sugarcane)	Biodegradable packaging materials, disposable cutlery, food containers	Auras et al., 2004
Polyhydroxyalkanoates (PHA)	Bacterial fermentation	Biodegradable packaging, food service ware	Chen, 2010
Pullulan	Fermentation of starch by fungus	Edible films, coatings, capsules	Singh et al., 2008
Xanthan Gum	Fermentation by Xanthomonas campestris	Thickener, stabilizer, emulsifier, gelling agent	Garcia-Ochoa et al., 2000

2.5.2 Biodegradation of biopolymer:

Biopolymers or biodegradable polymers are renewable natural resources derived from biological systems, such as plants, animals, and microorganisms, and/or chemically synthesized from the starting materials of natural fats, sugars, and starch (Pawar and Purwar, 2013). Natural biopolymers are alternatives to synthetic polymers generated from non-renewable petroleum resources. Biodegradation of biopolymers is an essential process in the natural environment, where microorganisms break down biopolymers into smaller molecules, eventually converting them into carbon dioxide, water, and biomass (Folino et al., 2020).

The process of biodegradation is based on the fact that microorganisms (bacteria, fungi, and algae) identify the polymer as a source of organic building blocks and a source of energy they need for life. Simply put, biodegradable polymers represent food to microorganisms. The polymer chemically reacts under the influence of either cellular or extracellular enzymes whereby the polymer chain is split. The process can take place under the influence of a variety of enzymes and gradually leads to smaller molecules. Thus, different mechanisms can be involved in the degradation process that comprises physical, chemical, and biological processes.



Environmental factors not only regulate polymer degradation but also have a crucial impact on the microbial population and the various microorganisms' activity. Parameters such as humidity, temperature, pH, salinity, presence or absence of oxygen, and the supply of various nutrients significantly influence the microbial degradation of polymers (Nair et al., 2017).

TABLE 2
BIODEGRADATION OF BIOPOLYMERS

Biopolymer	Mechanism of Biodegradation	Microorganisms	References
Polylactic Acid (PLA)	Hydrolysis followed by microbial assimilation; enzymatic breakdown into lactic acid	Bacillus brevis, Amycolatopsis sp., Thermus thermophilus	Tokiwa and Calabia (2006)
Polyhydroxyalkanoates (PHA)	Enzymatic hydrolysis by PHA depolymerase into monomers (e.g., 3-hydroxybutyrate)	Pseudomonas lemoignei, Alcaligenes faecalis	Jendrossek (2009)
Polycaprolactone (PCL)	Hydrolytic degradation followed by microbial assimilation	Fusarium solani, Penicillium sp., Aspergillus sp.	Tokiwa and Calabia (2006)
Starch-based polymers	Enzymatic degradation by amylases into oligosaccharides and glucose	Bacillus subtilis, Aspergillus niger, Rhizopus arrhizus	Bastioli (2005)
Cellulose-based polymers	Enzymatic hydrolysis by cellulases into glucose	Trichoderma reesei, Phanerochaete chrysosporium, Cellulomonas fimi	Lynd et al. (2002)
Chitosan	Enzymatic hydrolysis by chitosanases and deacetylases into glucosamine	Streptomyces griseus, Aspergillus niger	Rinaudo (2006)
Polybutylene succinate (PBS)	Hydrolytic degradation followed by microbial assimilation	Fusarium solani, Penicillium sp.	Tokiwa and Calabia (2006)
Polyethylene terephthalate (PET)	Partial degradation by hydrolases; often requires pretreatment	Ideonella sakaiensis, Thermobifida fusca	Yoshida et al., (2016)

2.4 Current food packaging material and associated issues:

Food packaging materials play a crucial role in maintaining food quality, extending shelf life and ensuring safety. Plastic, an oil-based, versatile and ubiquitous material, is widely used in food packaging due to its lightweight, cost-effective, transparent, versatile and easy-to-process properties. These synthetic polymers have excellent mechanical, thermal and barrier properties, while ultra-thin layers extend the shelf life of packaged products and reduce food waste (Dong et al., 2021). Thus, plastics provide a direct economic benefit by reducing transportation costs.

Global plastic production has increased significantly, with 40% of all produced plastic being used for packaging, and almost half for food packaging. However, plastic’s high production rate, short usage time, non-biodegradable nature, and inadequate handling have raised concerns worldwide, with recycling challenges arising from multilayer plastics (Perera et al., 2022).

Plastic waste damages the terrestrial environment and pollutes the aquatic environment, and it accumulates as a result of long-term degradation. During abiotic and biotic decomposition, harmful substances are released from landfill plastic that pollute the soil and water. Chlorinated plastics release toxic chemicals and pollute ecosystems, while the degradation of plastics in water releases chemicals such as polystyrene and Bisphenol A that pollute water Methane and CO_2 emissions during plastic microbial digestion contribute to global warming. Animals are exposed to plastic waste through ingestion and entanglement, with harmful consequences. Countries deal with plastic pollution by reducing waste, reducing production, recycling and alternatives (Reichert et al., 2020).

2.5 Possible solution for current food packaging material:

Growing environmental problems related to plastic have prompted research into alternative food packaging materials. Biodegradable materials such as biopolymers, bio-nanocomposites, bioplastics and edible coatings are being developed to replace plastics. Biodegradable polymers are renewable, nontoxic, biodegradable, biocompatible, reproducible, versatile, abundantly available, and have a low carbon footprint (Perera et al., 2022). However, problems such as viscosity, hydrophobicity, crystallization activity, brittleness, water sensitivity, thermal stability, gas-barrier properties, mechanical strength, processing difficulties and cost have prevented their widespread industrial adoption (Chaudhary et al., 2020).

To overcome these issues, biodegradable polymers can be mixed with other biodegradable polymers, compatibilizers (e.g., essential oils) and plasticizers (e.g., glycerol). Bioplastics are bio-based and/or biodegradable plastics that have similar properties to traditional plastics and offer additional benefits such as renewability and biodegradability (Perera et al., 2022).

Bio-nanocomposites consisting of a bio-based polymer matrix and an organic/inorganic filler with at least one nanoscale material are suitable as active and/or smart packaging materials due to their enhanced mechanical, thermal, barrier, antimicrobial and antioxidant properties. Functions. These materials focus on extending shelf life and reducing microbial growth in foods (Jeya Jeevahan et al., 2020).

2.6 Important properties of Biopolymers in food processing:

The properties of packaging materials, such as barrier, mechanical, chemical and thermal properties, are important to extend the shelf life of food and maintain its quality. The sealing properties of the biopolymer used in food packaging are the main parameter to extend the shelf life of the packaged food (Perera et al., 2022).

The gas permeability of the packaging material depends on the parameters; transmission, throughput and permeability. However, the barrier properties of materials depend not only on these factors but also on environmental conditions such as temperature, pressure, relative humidity and the nature of the packaged food. As a result, food packaging materials can extend the shelf life of foods by improving barrier properties (Rukmanikrishnan et al., 2020).

The oxygen barrier properties of the packaging material play an important role in the shelf life of fresh foods. Oxygen permeability is quantified by oxygen permeability percentage and oxygen permeability. It measures the amount of oxygen in the packaging system. As the oxygen permeability decreases, the oxygen pressure in the packaging system decreases, which increases the shelf life of the food (Rukmanikrishnan et al., 2020).

The water vapour barrier properties are significant for food products to maintain physical or chemical deterioration concerning the moisture content. The water vapour barrier properties are quantified by the water vapour permeability of the packaging material by the ASTM E-96-95 standard method and the water vapour transmission rate (Mathew et al., 2019). The water vapour permeability depends upon the solubility and the diffusion of the water in the polymer material. The shelf-life of some food products directly depends on the ratio of water exchange between the external and internal environment; thus, water transfer should be reduced to protect the food from moisture (Mohamed et al., 2020).

The mechanical properties of the packaging system are essential to protect food under stressful conditions such as storage, handling and processing of food. The architecture of the polymer matrix is a key factor that determines the mechanical properties of a biopolymer. The mechanical properties of the packaging material determine tensile properties such as tensile strength, elongation at break and modulus of elasticity (Perera et al., 2022).

Chemical resistance is important because the food in the packaging can be acidic and mixed with the packaging material. For safety reasons, it is important to find out what the food is chemically made of before packaging. When these chemicals combine with and are absorbed into the biopolymer matrix, the mechanical properties of the material may change. (Roy et al., 2019).

The thermal properties of the packaging material are determined by thermos-gravimetric and differential scanning calorimetry. Thermal properties and thermal stability are important for the heat resistance of the packaging material. Thus, these properties allow us to store and transport the food packaging at the temperature essential for the food products (Dong et al., 2021).

TABLE 3
ADVANTAGES AND DISADVANTAGES OF BIOPOLYMERS IN FOOD PROCESSING

Advantages	Disadvantages	References
Biodegradability: Biopolymers are environmentally friendly as they decompose naturally, reducing waste and pollution.	**Cost:** The production and processing of biopolymers can be more expensive than traditional plastics.	Reddy et al., 2013
Renewable Resources: Made from renewable resources such as plants and microorganisms, contributing to sustainability.	**Mechanical Properties:** Often have inferior mechanical properties compared to conventional plastics, such as lower strength and durability.	Averous and Pollet, 2012
Reduced Carbon Footprint: Lower carbon emissions during production compared to petroleum-based plastics.	**Water Sensitivity:** Many biopolymers are sensitive to moisture, which can affect their performance in food packaging.	Emadian et al., 2017
Safety: Generally recognized as safe for food contact and consumption, posing fewer health risks.	**Shelf Life:** Biopolymers may have shorter shelf lives and are more prone to degradation during storage.	Jamshidian et al., 2010
Functional Properties: Can offer specific functionalities such as edible coatings, antimicrobial properties, and oxygen barriers.	**Processing Challenges:** Require specialized equipment and processes for production and application.	Tang et al., 2012
Regulatory Support: Increasing governmental and regulatory support for biopolymer use in food packaging.	**Recycling and Disposal:** Limited recycling infrastructure and knowledge of proper disposal methods.	Brody et al., 2008

III. BIOSENSOR

In food processing and preservation, every step involved in handling, processing or production, storage as well as distribution affects the characteristics of the food, which may be undesirable or desirable. Hence, knowing the impact of every preservation technique and handling method on the food system is crucial in the food processing area which may result in food safety (Rahman, 2007). The safety monitoring as well as nutritional parameters of food is vital. The traditional analytical methods for safety and quality monitoring are tiresome, take much time and need well-trained operators, thus there is a necessity to produce rapid, sensitive as well as reliable methods to monitor food safety and quality rapidly. Therefore, biosensors can be a suitable substitute for traditional methods. Biosensor devices are the most relevant diagnostic methods for food (Shams et al., 2020).

A biosensor is described as a combined receptor transducer system, having the capability of giving discriminative semi-quantitative or quantitative analytical descriptions using a bio-recognition unit. It could be described as an "analytical system integrating a bio-substance, a bio-derived substance well linked with or within a physiochemical transducer, that could be thermometric, electrochemical, optical, magnetic or piezoelectric" (Anonymous[1], 2000).

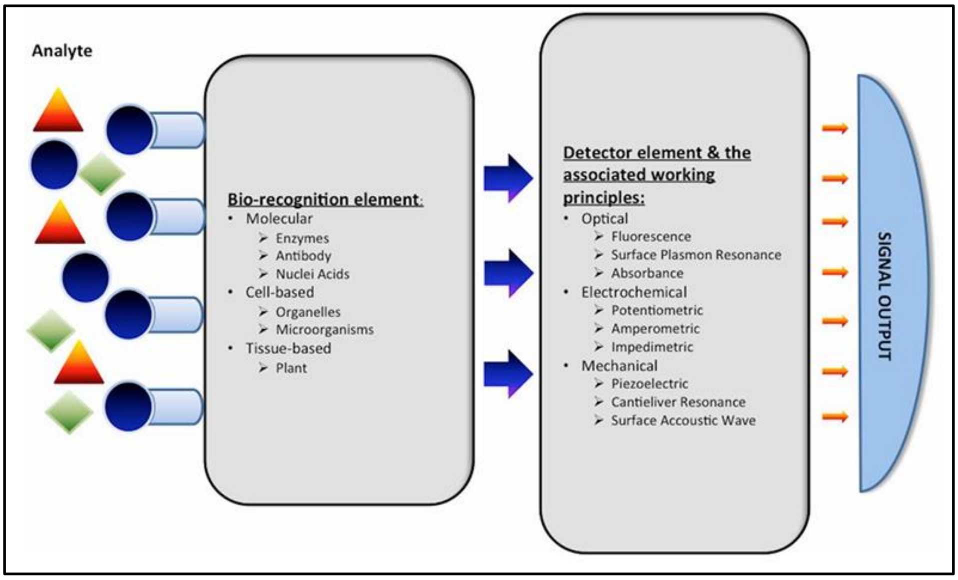


FIGURE 5: Schematic representation of a biosensor assembly (Lim and ahmed, 2024)

3.1 Generation of biosensor:

Depending upon their integration level biosensors are divided into three generations.

- **First generation:** In this generation, the biocatalyst is bound or trapped between the membranes which is then fixed to the transducer surface.
- **Second generation:** The instant covalent or adsorptive binding of the bioactive compound to the surface transducer allows the removal of the semi-permeable membrane.
- **Third generation:** The biocatalyst is bound to a piece of electric equipment that helps in transducing and amplifying the signal like the gate of a field effect transistor, which is essential for an additional miniaturization of nano-biosensors (Thakur and Ragavan, 2013).

3.2 Characteristics of biosensor:

To create a new and economically viable biosensor system, the following characteristics are crucial and must be taken into account.

- **Selectivity:** These devices must be extremely specific for the particular analyte and display less or no cross-reactivity with moieties possessing the same chemical composition.
- **Sensitivity:** These devices must have the ability to determine the variety of interest for an analyte requiring lesser further steps like pre-concentration or pre-cleaning of samples.
- **Linearity of response:** These systems should cover-up the concentration above which the specific analyte is intended to be identified.
- **Signal response reproducibility (SRR):** Whenever trial samples possessing similar amounts tend to be determined repeatedly, they must provide similar responses.
- **Recovery and quick response time:** These devices must have quick responses so that actual time monitoring of the particular analyte can be completed with efficacy. Also, the time of recovery must be little for the reusability of these devices
- **Operating life and stability:** The majority of the bio-materials are less stable under various environmental and biochemical environments. The bio-materials must be interfaced to maintain the activity for a longer time thus making these devices marketable and practically beneficial in the field (Arugula and Simonian, 2014).

3.3 Working principle of biosensor:

The basic principle of biosensor technology is to convert a biologically induced recognition event (*viz.*, enzyme, antibody) into a detectable signal, via a transducer and processor. The output is a display depicting both the presence and the concentration of the target analyte. The bio-receptor is a biomolecule that recognizes the target analyte (Meshram et al., 2018). A bio-receptor can be a tissue, microorganism, organelle, cell, enzyme, antibody, nucleic acid and biomimic. The transducer converts the recognition event into a measurable signal21Transduction may be optical, electrochemical, is thermometric, piezoelectric, magnetic and micro-mechanical, or combinations of one or more of the above techniques (Naik et al., 2017).

Biosensor = Bio-receptor + Transducer

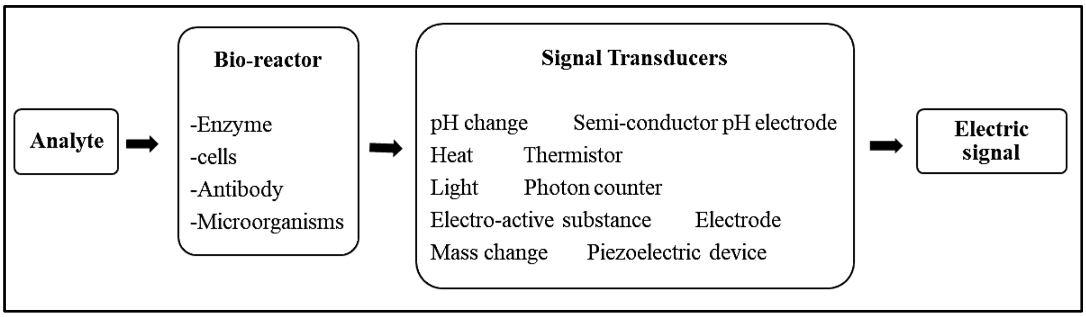


FIGURE 6: Principle of biosensors

Analytical chemistry plays an important role in food quality parameters, as almost all industries and public services depend on quality control. A food quality biosensor is a device that can respond to a food property or characteristics and transform the response(s) into a detectable, often electrical, signal. This signal may provide direct information about the quality factors being measured or may have a known relationship with the quality factor. The main immobilization methods, especially for enzymes, are physical adsorption, entrapment (using gels, polymers or inks), covalent binding or electrochemical polymerization and photo-polymerization. Physical adsorption is usually based on interactions between the biological element and the sensor, such as van der Waals forces (Shams et al., 2020).

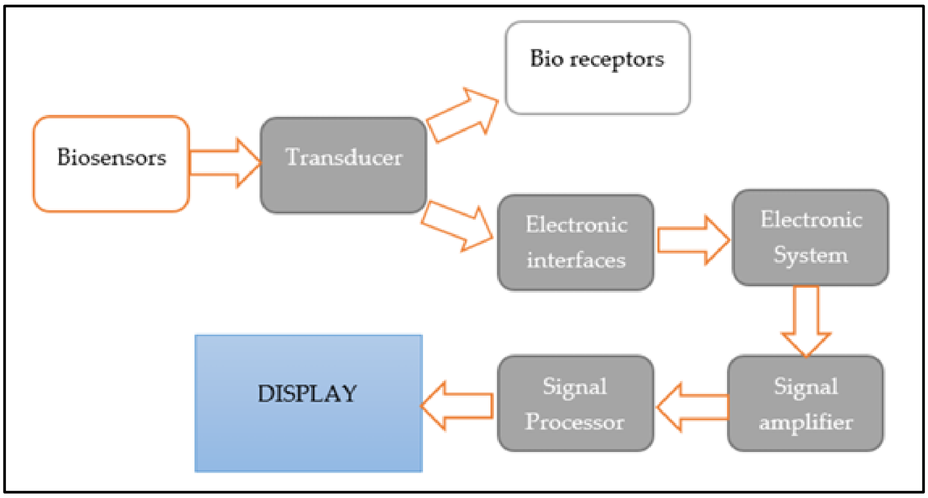


FIGURE 7: Operational mechanism of biosensors (Lee et al., 2015)

3.4 Types of biosensor

Biosensor types can be classified based on sensing elements or transducers. In the detection of foodborne pathogens, transducers play an important role.

3.4.1 Optical biosensors:

In the case of optical biosensors, the output signal measured is the emission of light, which allows direct (label-free) detection of food-borne pathogens. When cells bind to receptors or are immobilized on the surface of a sensor, these sensors can detect small changes. Optical diffraction and electrochemiluminescence are standard techniques for optical biosensors. Using the optical diffraction method, a silicon wafer is coated with proteins through covalent bonds and then exposed to ultraviolet light through a photomask. Under these conditions, antibodies exposed to ultraviolet light are inactivated. When the wafer is incubated with the antigen-antibody analyte, only the activated antibodies can bind to the antigen and signal under the laser light source. To improve sensitivity, this signal is measured directly or amplified (Yasmin et al., 2016).

Optical biosensors are classified into several subcategories such as reflection, refraction, resonance, dispersion, phosphorescence, infrared absorption, Raman scattering, fluorescence and chemiluminescence. Among them, surface plasmon resonance (SPR) and fluorescence-based optical biosensors are commonly used to detect foodborne pathogens due to their high sensitivity (Velusamy et al., 2010).

3.4.2 Electrochemical biosensors:

The basic principle of electrochemical biosensors is related to their ability to detect certain molecules. They are mainly used to detect DNA-binding drugs, glucose and hybridized DNA. In this technique, the electrons or ions to be measured are produced or suppressed by various chemical reactions. These biosensors are classified as amperometric, potentiometric or conductometric (Yasmin et al., 2016).

3.4.3 Mass-sensitive biosensors:

Mass-sensitive biosensors are used less often than optical and electrochemical biosensors. Also known as piezoelectric biosensors, they use piezoelectric crystals that are very sensitive and can detect small changes in mass. When a fixed-frequency alternating current is used, the piezoelectric crystals oscillate at a fixed frequency. This frequency depends on the mass of the crystal in addition to the fixed electrical frequency. The chemical reactions affect the frequency of oscillations, which is measured as an output signal (Velusamy et al., 2010).

3.5 Application of Biosensors in the food industry:

Food quality control is essential in the food industry; nowadays, efficient quality assurance is becoming increasingly important. Food producers gradually demand for effective quality control procedures to satisfy and regulate the requirements of consumers to enhance production feasibility, automation, quality sorting and decrease time and cost of production. Also, there is the requirement for rapid and efficient techniques to identify the allergens and pathogens present in the food product which can be fulfilled by the biosensors (Shams et al., 2020). Conventional methods for the detection of microbial contaminants are sensitive and inexpensive, but they require several days to yield results. In contrast, biosensors can rapidly relay results based on a progressive organic reaction. The biosensors play a vital role in the rapid and sensitive detection of foodborne (Yang et al., 2008).

Biosensors in the food industry are used for mainly two purposes. First is enzyme biosensor, which is mainly used in the liquor and beverages industry for detecting or measurement of carbohydrates from alcohol, amino acids, amines, amides, phenol etc. The second type of biosensor used in the food industry is for the detection of microorganisms. They are detected by two methods: Direct detection and indirect detection (Murugaboopathi et al., 2013).

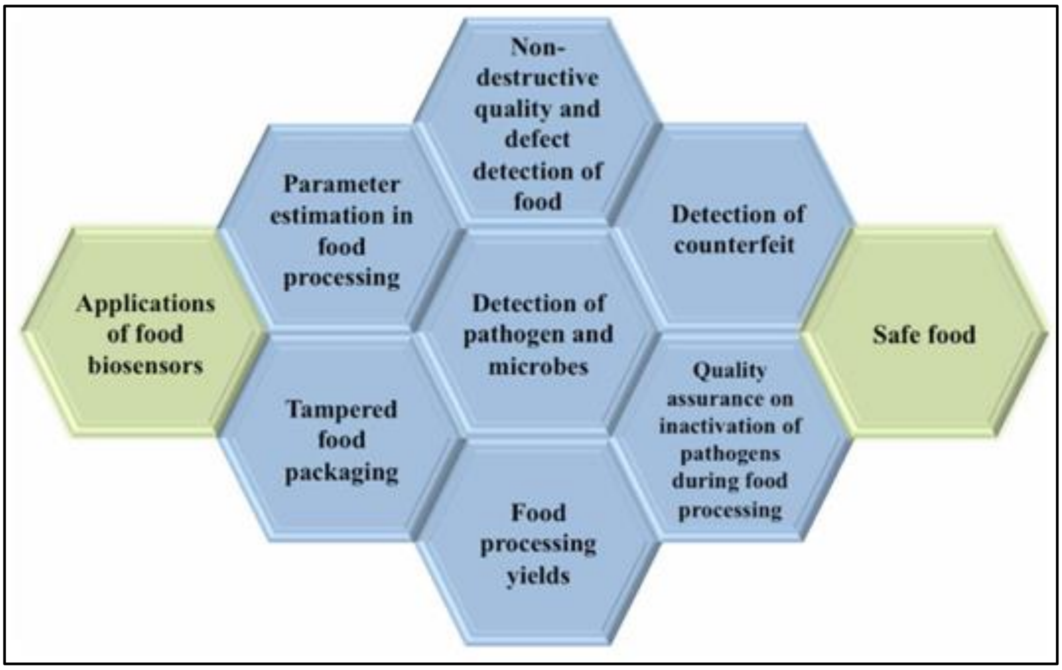


FIGURE 8: Various applications of food biosensors used in food industries

3.6 Important applications of biosensors in the food sector includes:

3.6.1 Safety of foods:

a. Xenobiotics such as additives, fertilizers, pesticides drugs, and other contaminations like: PCB's, dioxins, PAH's, bio-toxins and various heavy metals.

b. Bacterial toxins such as marine toxins, and mycotoxins.

c. Pathogens such as viruses, protozoa, and bacteria.

3.6.2 Food quality:

a. Food composition like amino acids, sugars, organic acids, alcohols, cholesterol

b. Shelf life: such as polyphenols and fatty acids (rancidity), biogenic amines (for freshness index), sugars and organic acids (maturation).

c. Ensures food safety in various fresh poultry, meat or fish.

d. Measures the concentration of organophosphate pesticides in dairy-based products such as milk.

Technological methods such as amino acids (fermentation), and sugars (pasteurization and fermentation). (Shams et al., 2020)

3.7 Future trends in Biopolymer/Biodegradable packaging:

Over the years, synthetic packaging materials have been the primary source of food packaging. However, the use of synthetic polymers presents challenges and limitations, mainly due to environmental pollution issues caused by plastics. In recent years, the trend to use biopolymers in food packaging has grown significantly. Their biodegradability, ecological friendliness, renewability, non-toxicity and lightness make them suitable for food packaging. However, the use of biopolymers in their pure form is limited due to their low mechanical, barrier and thermal properties. Furthermore, they are less cost-effective compared to synthetic polymers. The negative characteristics of biopolymers can be overcome by adding reinforcement agents such as nano-fillers and active agents. These reinforcing agents enhance the properties of the packaging materials, making them suitable for active and intelligent packaging materials by extending their shelf-life and improving the quality of packaged food products.

TABLE 4
FUTURE TRENDS IN BIOPOLYMER OR BIODEGRADABLE PACKAGING

Future trend	Description	References
Enhanced Performance	Development of biopolymers with improved mechanical and barrier properties to compete with conventional plastics.	Mohanty et al. (2018)
Cost Reduction	Innovations in production processes and economies of scale to reduce the cost of biopolymers.	Aeschelmann et al. (2016)
Smart Packaging (Active and Intelligent Packaging)	Integration of smart technologies such as sensors and indicators to monitor the freshness and quality of packaged products. Integration of active packaging (e.g., oxygen scavengers, antimicrobial agents) and intelligent packaging (e.g., sensors for real-time condition monitoring) to extend product shelf life and ensure quality	Ahmed et al. (2018)
Compostability and Biodegradability	The composting and biodegradation rates are enhanced to ensure complete breakdown in natural environments.	Tokiwa et al. (2009)
Functional Additives	Use of natural additives to improve properties such as antimicrobial activity, UV resistance, and shelf-life extension.	Arrieta et al. (2014)
Consumer Awareness	Growing consumer demand for sustainable packaging solutions driving the market for biopolymers.	Global Data (2020)

IV. SMART PACKAGING

Anything that offers “something extra” besides food containment and protection is considered smart food packaging. These “extras” can include anything from displays for monitoring pH, temperature, moisture, and freshness to a tracking device or extended shelf life. Smart packaging also analyses storage conditions, food quality, and the inside/outside environment of the package using a variety of sensors, indicators, and smart levels (Bhatlawande et al., 2023). Smart packaging such as active and intelligent packaging technologies, is considered as an innovative packaging technique for the development of a wide variety of products with competitive costs and achieved a great position in the preservation of different food systems. It is a fast-growing technology with a market demand projected to reach $28 billion by 2024, which will outgrowth superior market acceptance for a variety of product types (Bindu et al., 2023).

4.1 Active packaging:

Active packaging is an innovative concept that can be defined as a type of packaging that changes the condition of the packaging and maintains these conditions throughout the storage period to extend shelf-life or to improve safety or sensory properties while maintaining the quality of packaged food. Active packaging performs some desired role other than providing an inert barrier between the product and external conditions and combines advances in food technology, biotechnology, packaging and material science, to comply with consumer demands for ‘fresh-like’ products. This involves the incorporation of certain additives into the packaging film or within packaging containers to maintain and extend product shelf life. Active packaging technique is either scavenging or emitting systems added to emit (e.g., N_2, CO_2, ethanol, antimicrobials, antioxidants) and/or to remove (e.g., O_2, CO_2, odour, ethylene) gases during packaging, storage and distribution (Bindu et al., 2023).

4.2 Intelligent packaging:

Intelligent packaging detects certain characteristics of food it contains or the environmental conditions in which it is placed and notifies the people of the state of these properties. The attributes of intelligent packaging could be employed to check the efficiency and reliability of active packaging systems. Intelligent packaging has been described as packaging technology that can monitor the state of packaged foods to issue details about the quality of the packaged food during transport and storage. A variety of indicators such as temperature, time temperature, pack integrity, microbial growth, product authenticity and freshness are of interest to the fish packaging industry (Bindu et al., 2023).

TABLE 5
EXAMPLES OF ACTIVE AND INTELLIGENT PACKAGING SYSTEMS

Packaging system	Description	References
1) Active packaging		
Oxygen Scavengers	Absorb oxygen inside the packaging to prolong shelf life and prevent spoilage.	Brody et al., 2008
Moisture Absorbers	Absorb excess moisture to prevent mold growth and maintain product quality.	Yam et al., 2005
Ethylene Scavengers	Absorb ethylene gas to slow down ripening and extend the shelf life of fruits and vegetables.	Vermeiren et al., 1999
Antimicrobial Packaging	Incorporates antimicrobial agents to inhibit the growth of bacteria, fungi, and other microorganisms.	Quintavalla and Vicini, 2002
2) Intelligent packaging		
Temperature Indicators	Provide real-time information on the temperature history of the packaged product.	Kerry et al.,2006
Time-Temperature Indicators	Change colour based on the cumulative time-temperature exposure, indicating product freshness.	Mills, 2005
RFID Tags	Use radio frequency identification to track and monitor product information throughout the supply chain.	Espitia et al., 2012
Gas Indicators	Indicate the presence of gases like CO2 or O2, reflecting product status.	Mills, 2005

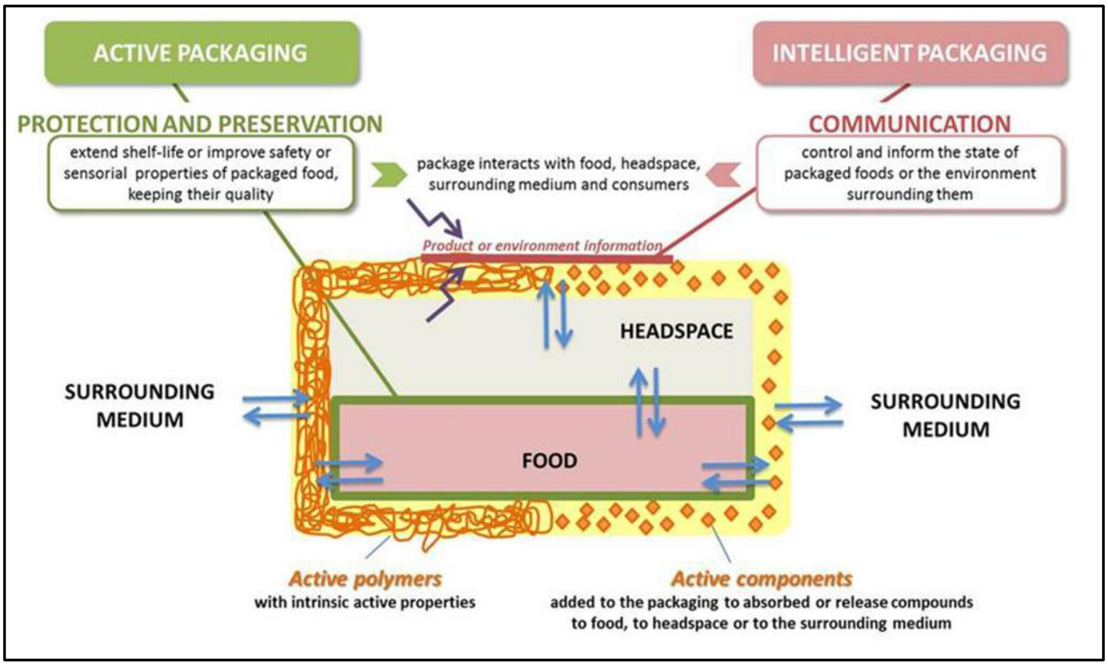


FIGURE 9: Schematic representation of active and intelligent packaging (Salgado et al., 2021)

V. CONCLUSION

In today's food industry, packaging is a foundation that performs several important tasks to maintain food quality, extend shelf life, and ensure consumer safety. New food packaging technologies seek to meet consumers' and industrial demands. The changes related to food production, sale practices, consumer lifestyles, environmental awareness, and the advances in new fields of knowledge such as biotechnology, act as driving forces to develop smart packages that can extend food shelf-life. The safety monitoring as well as nutritional parameters of food is vital. The traditional analytical methods for safety and quality monitoring are time-consuming and need well-trained operators, thus there is a necessity to produce rapid, sensitive as well as reliable methods to monitor food safety and quality rapidly. Also, food producers gradually demand effective quality control procedures to satisfy and regulate consumer requirements to enhance production feasibility, automation, quality sorting and decrease the time and cost of production. Biosensors can overcome all these disadvantages by offering quick, inexpensive and non-destructive procedures for quality control and pave the way for quick identification of food allergens, pathogens, and pesticide residues.

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