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# Sustainable Food Technology

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## Sustainability Spotlight Statement

Chlorophylls are the most abundant natural pigment which can be extracted and utilized in making functional packaging. This review investigated the recent advances in chlorophylls included packaging in improving and monitoring the shelf life of packed food. The area of this study is directly aligned with sustainability development goal 3, good health and well-being. The presence of chlorophylls in packaging could be beneficial in developing smart packaging materials.

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# A review on chlorophyll-based active and intelligent packaging: chemistry, stability and applications in food freshness monitoring

Harshita Ranjan[1], Manisha Joshi[1], Swarup Roy[2,3]*
[1] School of Bioengineering and Food Technology, Shoolini University, Bajhol, Solan 173229, India
[2] Department of Food Technology and Nutrition, School of Agriculture, Lovely Professional University, Phagwara 144411, Punjab, India
[3]Department of Food and Nutrition, Kyung Hee University, Seoul 02447, Republic of Korea

*Corresponding author's email: swaruproy2013@gmail.com

## Abstract

Chlorophylls, a natural bioactive pigment that has recently gained significant attention as multifunctional component in sustainable food packaging due to its antioxidant, antimicrobial, and pH-sensitive properties. The incorporation of chlorophylls into biodegradable films, coating and encapsulated systems provides dual functionality acting as an active agent that extends shelf life by reducing oxidative damage and microbial spoilage and serving as an intelligent indicator that signals freshness through colorimetric or fluorescence changes. Despite these advantages, chlorophylls are inherently unstable and degrades rapidly under light, heat, oxygen. Additional challenges including large scale processing limitations and the high cost of advanced extraction and stabilization techniques restricts its practical implementation. This review highlights the chemical properties of chlorophylls, conventional and non-conventional extraction methods, stabilization strategies, and encapsulation approaches along with their integration into biopolymeric matrices within scalable and regulatory frameworks. Therefore, chlorophylls-based packaging represents a sustainable approach with strong potential to reduce microbial spoilage, enable real-time quality monitoring and contribute to food waste reduction.

**Keywords** Chlorophylls, sustainable, active & intelligent packaging, microencapsulation, bioactive compound, antioxidant

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## 1. Introduction

Packaging is a crucial aspect in the food industry for the protection of food from external conditions[1], such as temperature, humidity, and light, and maintaining quality, integrity, freshness, and safety during its shelf life by controlling gas and vapor exchange with the atmosphere preventing degradation while preserving sensory and nutritional qualities. Beyond protection, packaging significantly influences consumer perception as the appearance of the product are often associated with its freshness and overall quality ultimately affecting consumption patterns. Traditionally, food packaging has used materials such as paper, glass. Paper is lightweight, recyclable, and cost-effective while glass is inert, and provides excellent barriers to oxygen and moisture, suitable for acidic or fatty products. Further, plastic being versatile with excellent barrier properties ideal for wide range of foods[2]. In recent years there has been a growing emphasis on environmentally friendly and sustainable packaging alternatives. This shift has driven research and innovations in biomaterials for food packaging, leading to the rise in the application of advanced techniques such as coatings, antimicrobial, antioxidant packaging and modified atmosphere packaging[3,4].

Active and intelligent packaging has garnered attention for its ability to extend functionality beyond passive containment. Active packaging interacts with the food component to extend the shelf life mitigating the microbial spoilage[5] while intelligent packaging monitors the environmental factors[6] through visible color changes or variations in fluorescence provide non-invasive information on food freshness, spoilage[7], or changes in the package microenvironment[8]. Addressing issues such as temperature fluctuations, microbial contamination, and package integrity these packaging systems contribute to reduced food waste, improved traceability, and decreased risk of food borne illness[9,10,11].

Chlorophylls are naturally derived pigment with antioxidant properties and nutritional value. It eliminates free radicals and protecting the cells from oxidative damage. Several studies reported the promising antioxidant, anti-inflammatory and anti-cancer properties of chlorophylls and its derivatives but oxidation of chlorophylls phenolic compounds can contribute to pigment loss is one of the challenges. Despite these properties, chlorophylls are sensitive to light and oxidation, but advanced techniques such as encapsulation with different carriers, such as carboxymethylcellulose, can increase its stability and performance[17,18,19].

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There have been recent advancements in biodegradable films and smart packaging showing the potential of natural extracts and nanoparticles as functional additives. Numerous studies concluded the efficiency of chlorophylls -based packaging, highlighting the pigment's amphiphilic structure, pH sensitivity and antioxidant activity which has the potential advantages in both active and intelligent applications. For example, sodium iron chlorophyllin incorporated into chitosan/ gelatin films enhanced antimicrobial and antioxidant activity, improved UV barrier properties, and effectively delayed spoilage in fresh cut chilli peppers, showed its potential as an active packaging agent[12]. Similarly, chlorophyllin incorporated into photoactive coatings generated reactive oxygen species (ROS) enabling effective inactivation of *L. monocytogenes* demonstrating both antimicrobial activity and light responsive packaging behavior[13]. Further, another study reported that cornstarch chlorophyllin composite films under light exposure generated ROS resulting in lower microbial and nitrogen levels compared to control samples and maintaining acceptable quality of shrimp up to 4 days[14]. Moreover, chitosan based films incorporating chlorophylls with curcumin exhibited enhanced barrier and mechanical properties, exhibited significant antimicrobial activity and extended the shelf life of the cherries and pork[15]. The integration of chlorophylls pigment has significantly expanded the functionality of food packaging[16]. These natural components are especially found in plant extracts such as green tea and basil and are explored for smart packaging, due to its unique chemical and functional properties.

The aim of this review is to comprehensively analyze recent advancements in chlorophylls-based smart packaging for maintaining and monitoring food quality and freshness, focusing on key properties of chlorophylls and further its relevance in the packaging, active and intelligent packaging. It also discusses the development and characterization of chlorophylls -incorporated films and coatings, while analyzing their applications in both active and intelligent packaging. Furthermore, the review also highlights the existing knowledge gaps and areas require further development for commercial optimization and broader adoption.

## 2. Chlorophylls chemistry and properties

Chlorophylls has a unique chemical structure and properties which are fundamentally responsible for its characteristic color, potent antioxidant activity, and suitability for packaging technologies

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aimed at maintaining and monitoring food freshness. Figure 1 shows the molecular structure of chlorophylls, highlighting the porphyrin ring with the central magnesium ion and the phytol tail.

### 2.1 Molecular structure of chlorophylls

Chlorophylls are a complex organic molecule made of a porphyrin ring which is hydrophilic, a central magnesium ion, and side chain containing the phytol chain, which is strongly hydrophobic. The porphyrin ring, a macrocyclic conjugated tetrapyrrole structure which contains four nitrogen atoms in pyrrole groups; responsible for absorbing light energy, while the magnesium ion acts as an electron acceptor. Various conjugated double bonds impart an advantage to the ability of chlorophylls to absorb visible light [19,21,22].

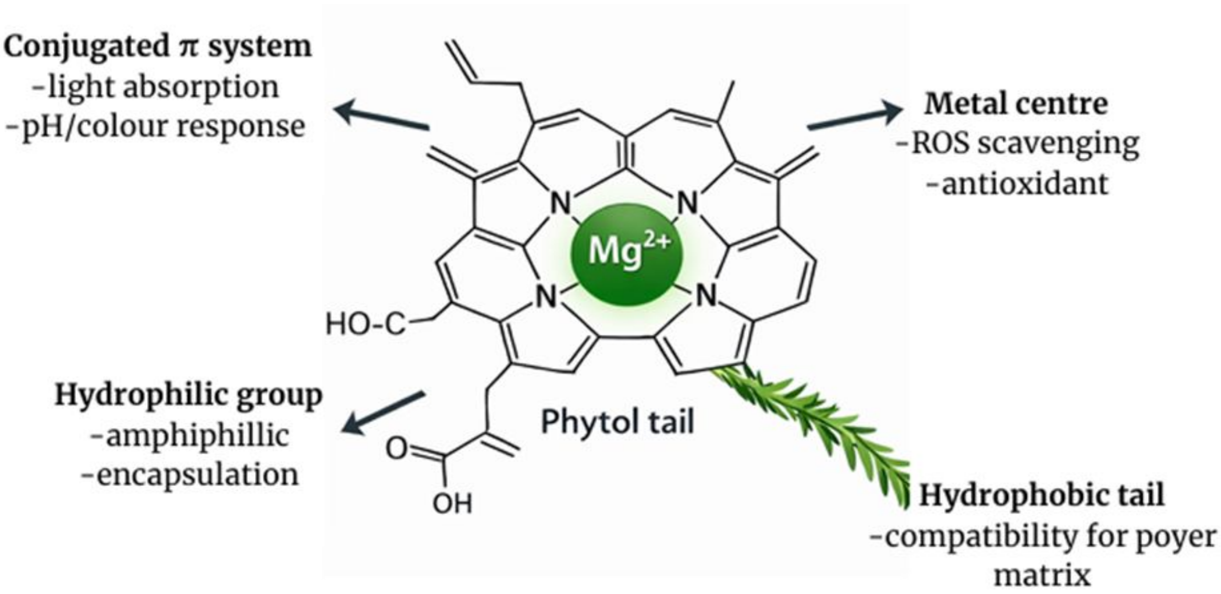

***Figure 1*** *Molecular structure of chlorophyll*[23,24]

There are several forms of chlorophylls, including chlorophyll a, b, c, d, and e, with chlorophyll a being the most common in plants. Chlorophylls efficiently absorb light in the red and blue regions of the spectrum, exhibiting peak absorption around 430 and 662 nanometers, respectively. chlorophyll b, which mainly functions to protect chlorophyll a from excessive light, absorbs light optimally near 453 nanometers. Other chlorophylls forms such as chlorophyll c, d, and e are found in diverse organisms like algae and differ in their absorption spectra and biological roles. For

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instance, chlorophyll c absorbs primarily in the blue-green region, chlorophyll d in the red region, and chlorophyll e in the far-red region of the spectrum[19]. Structurally, chlorophylls molecules vary chiefly in the degree of saturation in their pyrrolic rings and in functional groups attached to the macrocycle. For example, chlorophyll b differs from chlorophyll a by having an aldehyde group instead of a methyl group at the C7 position, which results from enzymatic oxidation of the methyl group catalyzed by oxygenase. chlorophyll c contains a fully unsaturated phytoporphyrin system (with a double bond between C17–C18), whereas chlorophyll s a, d, and f contain partially saturated phytochlorins. These structural differences significantly affect the absorption properties: chlorophyll a, d, and f show approximately balanced absorption intensities in blue, red, and green regions, while chlorophyll c absorbs weakly in the red and more strongly around 450 nm. This variety in the absorption spectra are mirrored in their distinctive green hues, chlorophyll a appears bluish-green, chlorophyll b bright green, chlorophyll c yellowish-green, chlorophyll d bright forest green and chlorophyll f emerald green. This diversity makes these pigments promising candidates as natural colorants[19]. Chlorophyll molecules possess two distinct regions: a hydrophilic macrocycle and a hydrophobic phytol tail. The most hydrophilic segments of the macrocycle include the cyclopentanone ring and a propionic acid ester group at the C17 position. This amphiphilic nature influences solvent selection for chlorophyll extraction, impacting yield and purity important for technological applications[22].

Chlorophyll's distinctive structure positively influences its function in the packaging. For example, the hydrophilic porphyrin macrocycle promotes the antioxidant activity allowing chlorophylls and its derivatives act as singlet oxygen quenchers and free radical scavengers. This protective effect against lipid oxidation attributes not only to their free radical scavenging capacity but also to their ability to chelate pro-oxidant metal ions such as $Fe^{2+}$ and $Cu^{2+}$ which retards lipid peroxidation in food [5]. On the other hand, chlorophylls acts as a photosensitizer, absorbing visible light and transferring the energy to molecular oxygen to produce singlet oxygen and other reactive oxygen species[25].

## 2.2 Extraction methods

Chlorophylls are widely extracted for industrial applications from stinging nettle, spinach, algae, silkworm excreta, alfalfa, pine needles, other pasture grasses and plant harvest by-products[26].

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Several methods were used to extract chlorophylls of natural ingredients from the plants, such as aqueous extraction, enzyme-assisted extraction, alcoholic/organic solvent extraction, and supercritical/subcritical extraction[27]. Several methods were used to extract chlorophylls from the plants, such as aqueous extraction, enzyme-assisted extraction, alcoholic/organic solvent extraction, and supercritical/subcritical extraction[26] summarized in table 1. Extraction can be carried out in various ways, involving different solvents and preparation methods. Variables such as pressure, temperature, contact efficiency, and time are critical. Since chlorophylls are sensitive to extreme light exposure, pH, and temperature, solvent selection must consider factors like density, viscosity, heat of evaporation, cost, environmental and health effects. The solvent should not react with or damage the extracted compound and must not be corrosive. Different methods are tailored for different microalgae species[28].

***Table 1*** *Extraction of chlorophylls from different source and extraction method*

| **Extraction method** | **Raw material/food** | **Yield** | **Purity** | **Conditions** | **References** |
|---|---|---|---|---|---|
| Solid- liquid extraction | Spinach (solid phase) | NA | Chlorophyll a/b ratio 4.8 in ethyl acetate phase | 25 °C, 30 min, 600 rpm agitation; mild energy (centrifugation + vacuum drying); solvent recovery-condenser | [29] |
| Extraction by methanol (1:50) atmospheric | Cucumber | Chlorophyll a: 480.14 mg/100 g Chlorophyll b: 342 mg/100 g | Chlorophyll a/b ratio ≈ 1.4 (480/342 ); CV: 52% chlorophyll a, 48% chlorophyll b | 1:5 ratio (1 g:50 mL methanol); centrifugation 3000 rpm, 10 min; room temp. | [30] |
| Enzyme-assisted extraction (Pectinex Ultra SP-L) | Spinach pulp | 50.747 mg TCC/100 g spinach pulp (optimized); 39% higher Zn-chlorophylls derivative yield vs non-enzymatic | NA | 8% enzyme (Pectinex Ultra SP-L), 45 °C, 30 min; followed by ethanol extraction (2.5:1 ratio, 60 °C, 45 min) | [5] |
| Subcritical fluid extraction (R134a + | *Laminaria japonica* Aresch (seaweed) | Chlorophyll a: 2.326 g/kg (optimized) | NA | Optimized: 324.13 K (51.13 °C), 17 MPa, 4.73% ethanol cosolvent; RSM | [31] |

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| | | | | | |
|---|---|---|---|---|---|
| ethanol cosolvent) | | | | Box–Behnken design | |
| Subcritical $CO_2$ extraction | *Nigella sativa* seeds | Volatile oil: 66.6 wt.% of oleoresin | NA | 70 bar, 30 °C, 2 hours | 32 |
| Supercritical CO2 extraction with a static modifier | *Scenedesmus obliquus* (microalga) | Chlorophyll a: 0.848 mg/g biomass; chlorophyll b: 0.356 mg/g biomass; chlorophyll c: 0.018 mg/g biomass | NA | 200–250 bar; 40–60 °C; $CO_2$ flow rate varied; 7.7% v/v ethanol cosolvent | 33 |
| Ultrasound-assisted green solvent extraction | *Scenedesmus obliquus, Arthrospira platensis* (microalgae) | Optimized ultrasound + ethanol/ionic liquid solutions; carotenoid/chlorophyll extracts potent peroxyl scavengers (5.94–26.08× α-tocopherol) | NA | Ultrasound extraction; ethanol + ethanolic ionic liquid solutions; optimized extraction time, repetitions | 34 |

Over the years, several approaches have been reported to remove chlorophylls from botanical crude extracts (CEs). Most rely on solid-phase extraction (SPE) with stationary phases such as Diaion HP-20 for initial fractionation. Charcoal has also been used to remove chlorophylls or other pigments entirely from CEs without fractionation of other constituents. However, these methods often eliminate other unspecified, potentially bioactive compounds along with chlorophylls. Detailed protocols vary by author, and preservation of the original phytochemical profiles is generally not assessed[35].

Liquid-liquid or countercurrent separation (CCS) methods are effective for isolating large quantities of target compounds from complex matrices. CCS offers ease of use, affordable cost, reduced solvent consumption, and efficient equipment performance, making it valuable in natural product research. CCS has been applied to isolate plant pigments like anthocyanins and carotenoids from chlorophylls -enriched extracts obtained from grass, spinach, and other plant materials. However, CCS suitability for chlorophylls removal remains under evaluation. In CCS, both the stationary and mobile phases are liquids forming a biphasic solvent mixture. This mixture solubilizes extracts entirely while balancing partitioning of target compounds. Phytochemicals in

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both phases can be recovered with solvent evaporation, making CCS effectively loss-free when analytes are non-volatile. A recent study implemented CCS to selectively remove chlorophylls from botanical CEs to produce chlorophylls -free "degreened" Knock-Out Extracts (chlorophylls -KOEs). This method enables subtraction of assay interference compounds while optimally recovering other phytochemicals. The study produced chlorophylls -KOEs from three botanicals: *Epimedium sagittatum, Senna alexandrina L., and Trifolium pratense L.,* evaluating reproducibility and selectivity with HPLC, UHPLC-UV/MS, LC-MS, and $^1$H NMR spectroscopy[35].

Supercritical/subcritical $CO_2$ extraction selectively isolates components suitable for heat-sensitive products. Traditionally, chlorophylls extraction uses liquid solvents followed by evaporation and drying at high temperatures, risking degradation. Supercritical/subcritical $CO_2$ extraction operates at low temperatures, preventing thermal degradation. $CO_2$ is inert, non-toxic, non-flammable, inexpensive, and easily separated from extracts without heating, producing solvent-free extracts. Stability tests on chlorophylls from *katuk* leaves showed decreased content at high temperatures, indicating supercritical/subcritical $CO_2$ as the preferred extraction method to preserve chlorophylls[27]. Enzyme-assisted extraction is gaining attention for eco-friendly processing. Targeted enzymes like pectinases, cellulases, and hemicellulases degrade cell walls, increasing solvent pre-treatment efficiency, reducing solvent use, or increasing bioactive compound yield. Used widely in juice processing and beer clarification, enzymatic pretreatment enhances extractability. Enzyme-assisted extraction of Zn–chlorophylls derivatives from spinach pulp under optimized conditions (8% enzyme concentration, 45°C, 30 min) increased yield by 39%[5].

### 2.3 Key properties of chlorophylls relevant to packaging

The chemical structure of chlorophylls determines its bioactivity, influences potential health benefits[19]. As mentioned earlier, chlorophylls are among the most prominent bioactive compounds, having positive health impacts and high antioxidant activity. They are used as natural food coloring agents and have wound healing and anti-mutagenic properties[20].

#### 2.3.1 Antioxidant activity

Chlorophylls is a strong antioxidant that has the capability to scavenge free radicals and chelate metal ions (e.g., $Fe^{2+}$), hence they prevent the oxidative damage to lipids and cells. This activity inhibits a major cause of food spoilage which is lipid peroxidation. It also protects against oxidative

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DNA damage and reduces reactive oxygen species (ROS) formation, helping in preserving food freshness by delaying spoilage processes. Natural chlorophylls possess antioxidant properties making them promising candidates for preventing or mitigating the formation of reactive species. Lanfer-Marquez et al., (2005)[36] demonstrated that Cu-chlorophylls in displayed higher antioxidant activity compared to natural chlorophylls, highlighting the influence of the chelated metal in the porphyrin ring on the strength of the antioxidant capacity[19]. Additionally, a study showed that the kale chlorophylls which were microencapsulated in isolated whey protein, resulted in increased antioxidant activity by 20% as assessed through the DPPH method[37].

### 2.3.2 Photoactivity and reactive oxygen species generation

Chlorophylls are very unstable compound and the stability is highly affected by pH, temperature, heat, and light[21]. When exposed to irradiation, it can generate singlet oxygen ($^1O_2$) through photosensitive reactions causing discoloration[20]. The chlorophylls content decreased faster under light than in the dark because of singlet oxygen. Samples with added lipids showed lower and slower degradation of chlorophylls than in samples without lipids. High pressure high temperature processing results in the degradation of chlorophyll *a* and chlorophyll *b*. Both chlorophylls were highly degraded at 117°C[21]. This singlet oxygen generation thereby can prolong the food shelf life causing microbial inactivation; a property that can be exploited in active packaging to extend shelf life.

### 2.3.3 Color properties and sensitivity to pH, light, and oxygen

As mentioned in the earlier section, chlorophylls is highly unstable compound, sensitive to light; therefore, it becomes difficult to keep its molecules intact with a green color; a photosensitive light harvesting pigment with special electronic properties[38]. Furthermore, it is susceptible to heat, oxygen, and chemical degradation. The pH has an effect on chlorophylls degradation as well[39]. Koca et al., (2006)[40] studied the effect of pH on the chlorophylls degradation and visual green color loss in blanched green peas were studied at 70, 80, 90 and 100$^0$C in buffered solutions of pH 5.5, 6.5 and 7.5. The rate constants of green color loss and chlorophylls degradation decreased with increasing pH, indicating that the green color was retained at higher pH conditions. It was found that chlorophyll a degraded faster than chlorophyll b at all pH values for each temperature applied. The results revealed that chlorophyll a was more susceptible to thermal degradation than chlorophyll b in acidic conditions[40].

### 2.3.4 Stability challenges and encapsulation

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The chlorophylls incorporation into the food matrix is challenging because of its instability towards light, oxygen and pH and poor bioavailability. Encapsulation is an excellent process to enhance its bioaccessibility, digestibility, and controlled release[21]. For example, the encapsulation carriers like maltodextrin (MD) and whey protein isolate (WPI) can provide multi-layered protection. The MD/WPI walls acts as light barriers through scattering and UV absorption, oxygen diffusion barriers limiting the access of reactive oxygen species, and pH buffers via hydrogen bonding between WPI amine groups and MD hydroxyls with chlorophylls's porphyrin nitrogen. Freeze-dried microcapsules of chlorophylls (MD/WPI from Ulva intestinalis) retained 38.12 % green color after light exposure versus 1.84 % for unencapsulated chlorophylls, whereas the chemical stability and retention rates increased significantly ($p < 0.05$). Spray-dried microcapsules showed DPPH scavenging of 67.5% and freeze-dried 79.1%. Thus, chlorophylls can be protected from bad light conditions and have a longer shelf-life during storage via microencapsulation and possible hydrogen bonding with MD and WPI complexes[41].

Emerging stabilization technologies such as core-shell nanoparticle encapsulation using zein, casein, or whey protein isolate as wall materials offers enhanced protection for chlorophylls in food packaging applications. Encapsulation efficiencies of chlorophylls retention after 10 days were 83.6–96.3% and 39–97.8% at pH 3.0 under light/acidic stress; compared to 40% for free chlorophylls. These technologies therefore offer superior photostability and controlled delivery for active packaging applications[42].

## 3. Chlorophylls based active & intelligent packaging development and key properties

The active and intelligent smart packaging based on chlorophylls is a promising method which leverages the natural bioactivity and colorimetric responsiveness of chlorophylls extracts from various sources including plants or algae. Active compounds as intelligent indicators enhance the stability and function of packaging or coating matrices. These pigments can change color because of environmental stimuli, such as temperature, pH, oxygen, light or microbial activity, providing visual cues to consumers about the freshness, spoilage, ripeness, or contamination of food[43]. The packaging is typically developed by incorporating chlorophylls or microencapsulated chlorophylls into biodegradable polymer matrices like alginate, chitosan, gelatin, or pectin. Common fabrication methods include solution casting, extrusion[44] designed to preserve the functional and colorimetric properties of chlorophylls during processing.

### 3.1 Film/coating fabrication using chlorophylls

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As mentioned earlier in the introduction part, chlorophylls have currently emerged to be a promising bioactive compound for the development of active and intelligent packaging films and coatings because of its unique chemical, antioxidant, and colorimetric properties. For example, edible coatings are revolutionizing food preservation by offering a sustainable and effective solution to key industry challenges. They are produced from natural biopolymers such as proteins (e.g., gelatin, zein), polysaccharides (e.g., starch, chitosan, alginate), and lipids, these coatings form a thin, edible layer on food surfaces. These biodegradable and edible matrices reduce moisture loss, protects against oxidative damage, and limits microbial growth, thereby extending shelf life while preserving food quality. Enhanced with natural additives like essential oils and antioxidants, these coatings offer antimicrobial benefits and contribute to health[45]. Figure 2 shows the overall process for chlorophylls extraction, incorporation into the matrix, and subsequent analysis leading to the development of chlorophylls-integrated film and food packaging application. Lv et al. (2023)[16] mentioned a study film containing chlorophylls and chitosan having the potential for generating color within the colorimetric temperature range of 50−75 °C. The system will undergo an irreversibly color change from green to yellow when exposed to this temperature range.

*Figure 2* *Schematic representation of chlorophylls-based active film formation* [46] [47]

### 3.1.1 Casting method

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A lab or pilot scale method, also known as solvent casting, is a rather simple and one of the most common techniques of edible film formation[48]. It involves manufacturing films from biopolymers, and includes the following steps: (i) solubilizing the biopolymer in a suitable edible and non-toxic solvent, such as ethyl alcohol or water. The solubilization step ensures an even dispersion of the biopolymer in the solvent. This solubilization step is crucial as the film formation depends on the polymer's solubility rather than melting; (ii) casting of the solution in a predefined mould, where it forms a gel structure (cohesive film adhering to the mould) as the solvent evaporates with time; (iii) drying the cast solution layer, which is necessary to form a cohesive film, but with the moisture content maintained at 5% to 8% to prevent wrinkling and tearing of the film during peeling. Moreover, optimization of the drying temperatures and methods for a particular film is done to produce high-quality edible films[49]. A study investigated the formation of fractal structures in chlorophylls films prepared by casting technique using two different chlorophylls concentrations solution. Results were based on DLA model analyzed on optical microscopy showed that chlorophylls cast films formed distinct fractal aggregates at both 0.50 g/L and 0.12 g/L concentrations. Further image analysis showed a consistent fractal dimension for about 1.55 for all samples which suggests fast aggregation. There was no effect of change in concentration on the fractal dimension, suggesting that aggregation dynamics were stable across the tested range[50].

### 3.1.2 Extrusion

The extrusion method is one of the underexplored techniques for manufacturing edible films, but is now attracting more attention, particularly for starch/protein combinations. Extrusion forms films through a thermomechanical process[49]. There are various steps involved in extrusion process; preparation of formulations using different composition of raw materials and their mixing, blending the mixture in an extruder in order to pelletize all film-forming ingredients, cutting extrudates into pellets through the pelletizer, drying pellets in a hot-air oven, followed by extruding the pellets into sheets through the second extruder, and finally blowing the mixed resins into a film by a blown film extruder. Extrusion process often provides the films with acceptable mechanical properties and good thermal stability[51].

In comparison with widely used solvent casting method, extrusion of corn starch and poly (butylene adipate-*co*-terephthalate) (PBAT) blends with intact *Chlorella pyrenoidosa* biomass utilizes the amphiphilic nature of chlorophylls and algal lipids to improve compatibility for hydrophilic starch and hydrophobic PBAT phases. The results indicated that films containing a

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higher content (5.0%) of intact *Chlorella pyrenoidosa* biomass exhibited superior tensile strength (4.37 ± 0.24 MPa) and elongation (88.43 ± 6.8%) compared to films with disrupted biomass suggesting better dispersion and interactions between the phases which enhances homogeneity because of amphiphilic compatibilization further confirmed by SEM. Furthermore, these films displayed lower water vapor permeability ($5.19 \times 10^{-11}$ g m$^{-1}$ s$^{-1}$ Pa$^{-1}$), enhancing their barrier properties. Films produced by blown extrusion from starch, PBAT, and *Chlorella pyrenoidosa* microalgae biomass have the technological potential to be used as packaging for food products. Starch and PBAT blends are widely studied[52]. Overall, the films produced by blown extrusion blending starch or biodegradable polymers incorporating microalgae biomass containing chlorophylls have shown good mechanical and antioxidant properties.

### 3.1.3 Encapsulation

Encapsulation technology has been extensively used to enhance the stability, specificity, and bioavailability of essential food ingredients[53]. Microencapsulation is a nanotechnology method which can be used to prevent damage to bioactive compounds by protecting the encapsulated compounds during edible film processing. The enrichment of alginate-based edible film with chlorophylls microcapsules enabled to blend into the alginate-based edible film where they migrated and slowly released compounds which were able to prevent or retard some microbial growth on the fish bubble snack product tested. The enrichment increased the film thickness, improved the surface texture of the film, increased the resistance of the coated food (fish bubble snacks) to the growth of the mold *Rhizopus sp*., and increased resistance to the proliferation of *E. coli* but not of *S. aureus*. At room temperature the antifungal effect was twice as strong as for the same product without enrichment of the edible film coating. The antifungal properties of the enriched edible film extended the shelf life of the product tested[54].

Another study showed the encapsulation of chlorophylls with MD and WPI as carriers applying both spray drying and freeze-drying methods was done in order to increase the stability of chlorophylls extracted from Ulva intestinalis algae. The optimum combination of wall and core materials to achieve the highest response including encapsulation efficiency (EE) and chlorophylls content (CC) was obtained by response surface methodology and central composite design. The optimal chlorophylls microcapsule obtained was chosen for subsequent tests containing solubility, moisture content, and antioxidant properties. The results showed that the highest EE and CC were 90.27 ± 0.21 %, 55.36 ± 0.36 µg/mL, and 90.46 ± 0.62 %, 85.85 ± 0.43 µg/mL, respectively in SD

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and FD. The microcapsules produced by the freeze dryer (FD) had higher antioxidant activity (79.1 ± 0.24) than the microcapsules produced by the spray dryer (SD) (67.5 ± 0.16). The highest solubility (95.32 %) and the lowest moisture content (3.7 ± 0.05) were related to the SD. Freeze drying method (FDM) had the highest EE (91.2 %), CC (89.67 μg/mL), and antioxidant properties (79.1 %)[55].

### 3.1.4 Compression molding

Either thermo-compression or ultrasonic compression binds the film-forming materials into a desirable shape and thickness. An ultrasonic welder is used for welding the film materials; post compression, the welded materials are cut and processed to elaborate sustainable edible packaging systems. This technique has not yet gained popularity for manufacturing edible films but is a fast and economical method and needs to be adapted to suit the edible film packaging industry[48].

The modern packaging, embedded with sensors, not only interacts with the food product but also assesses its surrounding conditions, providing stakeholders with real-time information and insights, detecting freshness, pathogens, pH levels and other environmental changes, offering more insight than traditional measures such as weight or appearance. Compared to other natural food colorants, the color of chlorophylls is relatively stable, making it a less sensitive and observable colorimetric indicator in intelligent biodegradable packaging. This suggests that it may be less applicable for providing real-time information[56]. The study by Chavoshizadeh et al.,(2020)[17] introduces a wheat gluten-based biodegradable film incorporating chlorophylls , highlighting its role in enhancing the shelf life of sesame oil and indicating expiration dates. The film reduces oil oxidation, evident from the halved peroxide value and changes color from green to yellow in response to oil quality after a prolonged storage period. Integrating chlorophylls into edible films or coatings has a significant effect enhancing their physical and functional properties. For example, incorporated chlorophylls microcapsules into an alginate-based edible film showed enhanced film thickness and improved surface texture which ultimately resulted in a smoother, more homogeneous film without agglomeration[54] (discussed in table 2). This resulted in enhanced morphology of the surface, improving the barrier properties of the film while protecting the food product. Moreover, scanning electron microscopy (SEM) for microstructure showed that chlorophylls -enriched films exhibited a clearly different and smoother surface compared to control films without chlorophylls. Also, Fourier transform infrared spectroscopy (FTIR) analyses showed interactions between chlorophylls microcapsules and the film matrix. The films based on

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their function demonstrated the enhanced antimicrobial activity by slowly releasing chlorophylls compounds that inhibited the growth of molds such as *Rhizopus sp.*; and bacteria such as *Escherichia coli* on food products, thereby extending shelf life[54].

### 3.2 Key properties of chlorophylls based smart packaging

#### 3.2.1 Color

Films enriched with chlorophylls microcapsules exhibits pronounced greenish intensity, and the value increases with higher microcapsule content. A study by Dewi et al., (2022) showed that a* color values shift to more negative numbers (e.g., from −0.41 ± 0.09 to −11.25 ± 0.24), reflecting the deepening greenness imparted by chlorophylls encapsulation[54]. Moreover, microencapsulation or film matrix stabilization significantly enhance the green color stability under environmental stress (heat, light, pH change) shown by the study in which freeze-dried microcapsules retain up to 38% of chlorophylls color after light exposure, while unencapsulated chlorophylls may retain as little as 1.84%[41]. The intensity and stability of green color can also act as a freshness or shelf-life indicator for intelligent packaging due to visual changes upon degradation. Also review papers focused on chlorophylls integration into smart packaging systems with color changes serving as effective freshness and shelf-life indicators, emphasizing their application potential[25].

Chlorophylls pH-driven color change occurs because of the loss of $Mg^{2+}$ from the porphyrin ring, the bright green color of the chlorophylls turns to olive brown [57]. Resulting in absorption bands shift from ~430/662 nm (green) to ~410/650 nm (yellow/brown) species [58]. Koca et al. (2006)[40] observed that chlorophyll a degraded faster than chlorophyll b across pH 5.5–7.5 at higher temperatures, and due to reduced pheophytinization, the green color loss rate constants decreased at higher pH.

#### 3.2.2 Mechanical properties

Chlorophylls often act as a natural filler or plasticizer modifying the tensile strength, elongation, modulus, and impact resistance. For example, in polypropylene blends, low chlorophylls content (0.1–0.25 wt%) reduce rigidity and ductility slightly, but when there is an optimal concentration (0.5 wt%), it acts as a plasticizer increasing elongation and impact resistance while maintaining tensile strength comparable to pure polyprophylene. Higher chlorophylls concentrations (>0.5 wt%) typically reduce mechanical strength due to filler agglomeration disrupting polymer chain cohesion[43]. Also, Dewi et al., (2022)[54]showed in their study the chlorophylls microencapsulation

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improved tensile strength by interacting with film matrices and enhancing polymer network bonding while increasing film thickness.

### 3.2.3 Barrier properties

Chlorophylls incorporation leads to thicker films with improved moisture and solubility barriers, promoting longer shelf life and quality retention in packaged foods. Study discussed in table 2 in which cornstarch-Chlorophylls in composite films added with coconut oil, oregano essential oil, and beeswax showed significant reduction in moisture content (~12.58%), water solubility (~15.41%), swelling ability (~29.30%), and water vapor permeability ($\sim 1.78 \times 10^{-10}$ $gm^{-1}s^{-1}Pa^{-1}$) were observed. These changes enhance the ability of packaging films to maintain food quality by limiting moisture-induced spoilage and degradation[59].

### 3.2.4 Antioxidant and antimicrobial properties

The antioxidant and antimicrobial performance of packaging films depends on many factors, such as the molecular interaction between natural pigments and polymer substrates, the quantity of added natural pigments, structural modifications, and environmental conditions[16]. Moreover, the encapsulation of chlorophylls has shown to preserve the antioxidant/antibacterial properties of the film during a long time. It is noteworthy that chlorophylls changes color in nitrate media, which gives the film the ability to be used in the future as a smart film in identifying nitrate compounds used in food[18]. For example, biodegradable films based on wheat gluten modified with chlorophylls /polypyrrole showed that the addition of both increased the antioxidant activity of the films as mentioned in the table 2[17]. Chlorophylls have a notable antibacterial property when it is incorporated into various food packaging films. For example, López-Carballo et al. (2008)[60] developed gelatin films incorporating water-soluble chlorophylls in salts which showed substantial reduction of *Staphylococcus aureus* and *Listeria monocytogenes* growth, showing that s derivatives act as effective photosensitizers with antimicrobial effects under light exposure.

## 4. Application of chlorophylls -based packaging film/coating

Chlorophylls, a naturally occurring green pigment essential for the photosynthetic process in plants, has garnered attention in sustainable packaging research due to its biocompatibility, eco-friendly characteristics, and functional versatility[20]. It exists in several forms, primarily classified into six types i.e., chlorophyll a, b, c, d, e, and f. Among these, chlorophyll a and b are predominant in higher terrestrial plants, with chlorophyll a serving as the principal photosynthetic pigment

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found across plants, algae, cyanobacteria, and other phototrophic organisms, while chlorophyll b functions as an accessory pigment predominantly located in green algae and higher plants[61]. The presence of extensive conjugated double bonds in these molecules contributes to their significant antioxidant capacity[37].

### 4.1 Active packaging

Chlorophylls are widely distributed across various plant-based sources, particularly in green vegetables and fruits. Its distinctive physicochemical and biological properties including strong light absorption, pH sensitivity, antioxidant activity, and chromatic responsiveness render it a valuable component in the formulation of both active and intelligent biodegradable packaging systems[62]. Furthermore, its molecular structure, characterized by a porphyrin ring coordinated with a central magnesium ion (notably in chlorophyll a and b), is inherently organic and biodegradable[63]. Natural pigments or dyes for sustainable food packaging application. This structural composition allows for environmental degradation through natural enzymatic and microbial pathways, enhancing its appeal for environmentally sustainable applications. Figure 3 illustrates a multilayer smart packaging system which consist of a barrier and an active layer. The active layer has dual functions: as an active releasing system that delivers antimicrobial agents and antioxidants to the food, and as an active scavenging system regulating and responding to key environmental factors such as oxygen, carbon dioxide, moisture, ethylene, and odor. This combination can help to maintain food quality while extending shelf life by actively interacting with the packaged food environment.

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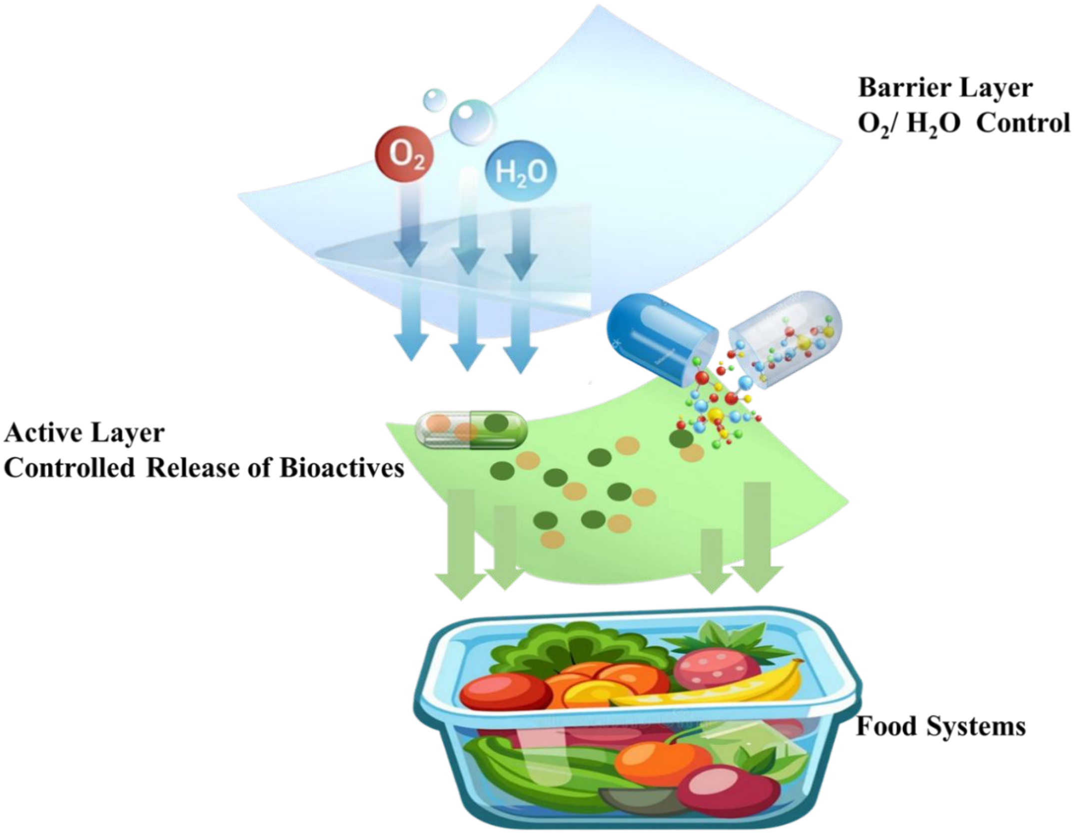

***Figure 3** Multilayer smart packaging system consisting a barrier and an active layer*

The incorporation of chlorophylls into biopolymer-based packaging films has been shown to markedly influence their physical (e.g., thickness, opacity, and ultraviolet light-blocking capability), mechanical (such as tensile strength and elongation at break), and barrier properties (including resistance to water vapor and gas transmission). Insights into the edible and biodegradable ulvan-based films and coatings for food packaging[64]. These alterations are strongly dependent on the nature of the polymer matrix as well as the method of film fabrication. Numerous studies have explored such formulations to enhance the functional attributes of environmentally sustainable packaging materials. For instance, Dewi et al., (2022)[54]developed an alginate-based film embedded with chlorophylls microcapsules derived from *Caulerpa racemosa*, reporting improved barrier performance, particularly in reducing moisture and gas permeability, which consequently extended the shelf life of packaged fish products. Similarly, Ukwatta et al. (2025)[59] investigated chlorophyllin-doped corn-starch films combined with different lipid additives and observed that the addition of chlorophylls in enhanced the water vapor barrier properties. This

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enhancement was attributed to increased matrix density, making the films more effective for packaging applications involving light- and moisture-sensitive food items.

Chlorophylls -based packaging materials exhibit high environmental degradability, as their constituent compounds including chlorophylls pigments and biopolymeric matrices like starch and chitosan are susceptible to enzymatic breakdown by naturally occurring microbial populations, particularly bacteria and fungi[65]. The degradation processes typically involve the breakdown of the porphyrin ring structure in chlorophylls, resulting in simpler intermediates like pheophytin and chlorins, which are eventually mineralized into carbon dioxide, water, and biomass[66]. These degradation products are non-toxic to ecosystems and may even serve as beneficial nutrients within the soil. Hence, the unique physicochemical and biological attributes of chlorophylls can be effectively leveraged in the development of active and intelligent packaging systems. Such packaging systems offer a sustainable and innovative approach to enhancing food preservation, monitoring product quality, and reducing environmental impact within the packaging sector[67].

Recent developments have underscored the effectiveness of chlorophylls-derived compounds as antimicrobial agents within active packaging systems, emphasizing their potential to prolong shelf life and improve food safety. These packaging films are specifically designed to suppress or delay the growth of spoilage and pathogenic microorganisms that compromise food quality and safety[68]. In a study conducted by Dewi et al., (2022)[54], an alginate-based edible film was formulated using chlorophylls extracted from *Caulerpa racemosa*, a species of green seaweed. The antimicrobial efficacy of the film was evaluated by wrapping fish snacks, and the results indicated a notable reduction in microbial proliferation, particularly targeting spoilage organisms during storage. The observed antimicrobial effect was attributed to the chlorophylls component, which exhibited both antioxidant and antimicrobial functionalities, thereby positioning it as a promising natural preservative for use in biodegradable packaging systems. The inclusion of antioxidants such as chlorophylls in packaging materials plays a critical role in inhibiting oxidative degradation in food products, especially those rich in lipids and proteins[25]. These compounds function through various mechanisms, including neutralization of singlet oxygen, scavenging of free radicals, reduction of hydrogen peroxide, and chelation of pro-oxidant metal ions[37]. Such multifunctional activities contribute to the stabilization of food quality during storage and further enhance the utility of chlorophylls-based systems in active packaging applications. Plant-derived botanical extracts have been widely utilized as natural antioxidants in the development of active packaging materials[69]. In

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a study conducted by Micó-Vicent et al., (2020)[70], chlorophylls-containing hybrid nano pigments sourced from broccoli processing residues were integrated into polyester-based bio nanocomposite films. This incorporation led to a marked improvement in the antioxidant functionality of the resulting packaging films. Additionally, the films exhibited improved thermal stability, color uniformity, and mechanical performance, thereby indicating their suitability for active food packaging applications. This study underscores the dual advantage of valorizing agricultural waste while integrating naturally occurring antioxidant compounds into packaging matrices to prolong food shelf life and mitigate environmental burden. Chlorophylls-based materials thus offer a promising and sustainable alternative for active packaging technologies. Beyond packaging, chlorophylls pigments are currently utilized across multiple sectors including cosmetics, pharmaceuticals, and the food industry[71]. Within the food sector, chlorophylls (designated as E-140) is primarily employed as natural colorants[56]. However, their functionality may be further extended to serve as natural pH-responsive indicators for monitoring food freshness, presenting additional value in the development of intelligent packaging systems.

### 4.2 Intelligent packaging

Intelligent packaging in the food sector integrates inherent bio functional properties with real-time monitoring capabilities to enhance food quality and safety management[72]. Chlorophylls, owing to its chemical and optical sensitivity, serves a dual role in such systems i.e., functioning not only as a packaging component but also as a responsive indicator capable of providing visual or quantifiable feedback on product freshness, quality, and safety[73]. One of the most widely employed mechanisms in this context is colorimetric sensing, where chlorophylls-based compounds exhibit perceptible color changes in response to environmental factors such as pH fluctuations, temperature shifts, or the presence of spoilage-associated gases like ammonia or oxygen[74].

The pH-induced chemical transformation in the chlorophyll's macrocycle determines the colorimetric properties of the chlorophylls -based intelligent indicators. Chlorophylls consists of a porphyrin (tetrapyrrole) ring complexed with a central $Mg^{2+}$ ion, giving this pigment its green coloration and visible region absorption [75]. Moreover, under acidic environment, the protonation of the porphyrin nitrogen atoms results in the removal of $Mg^{2+}$ and formation into pheophytin resulted in the visual color change from green to olive or yellow-brown [76]. While, in alkaline conditions, deprotonation occurs and changes in the porphyrin structure result in the color shift and the electron delocalization, further modifies the optical behavior [77]. These structural

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modifications impact absorption directly, i.e., native chlorophylls exhibits strong UV-Vis absorptions near 430 nm (Soret band) and 660-665 nm (Q band)[78]. Moreover, the peak broadening, lower intensity, and shift in wavelengths caused by the pheophytin produced through acidic environments strengthen the physicochemical basis concerning the use of chlorophylls as a halochromic indicator in smart packaging devices.

These alterations enable visual detection of food spoilage without the need to open the package, offering a user-friendly freshness assessment tool for both manufacturers and consumers. For example, Yu et al. (2024)[79] developed a chlorophylls-infused colorimetric film that demonstrated distinct color transitions under varying pH conditions. These pH-responsive films were effectively applied to monitor spoilage in actual food systems. Chlorophylls functioned as the primary halochromic pigment, undergoing progressive discoloration in response to acidic or alkaline environments typically resulting from microbial activity, thereby serving as a reliable indicator of food degradation[80]. Similarly, in a study by Mohammadian et al. (2020)[81], chlorophylls was incorporated as a natural pigment in packaging films designed to function as temperature-sensitive indicators. While the primary focus was pH and gas sensitivity, the study observed visible color variations at elevated temperatures, correlating with the microbial spoilage activity. In another study, Kılıç (2024)[82] fabricated a thermoplastic starch-based film enriched with chlorophylls -rich *Aronia* extract, which demonstrated a gas-responsive colorimetric behavior. Exposure to ammonia, a volatile compound typically generated during the initial stages of spoilage in protein-rich food products such as fish, induces a noticeable color change in the film, shifting its hue from green to brown[83]. Fig. 4 illustrates the utilization process of extracted chlorophylls from plats to develop bioactive compounds which are further incorporated into intelligent and active packaging systems. In intelligent packaging these chlorophylls-based indicators visually signal food freshness by changing color, whereas in active packaging, chlorophylls coatings help maintain food freshness by slowing spoilage compared to uncoated packaging, thereby extending shelf life through bioactive protection. Collectively, these studies confirm the efficacy of chlorophylls as functional indicator in intelligent packaging systems aimed at real time spoilage detection[84].

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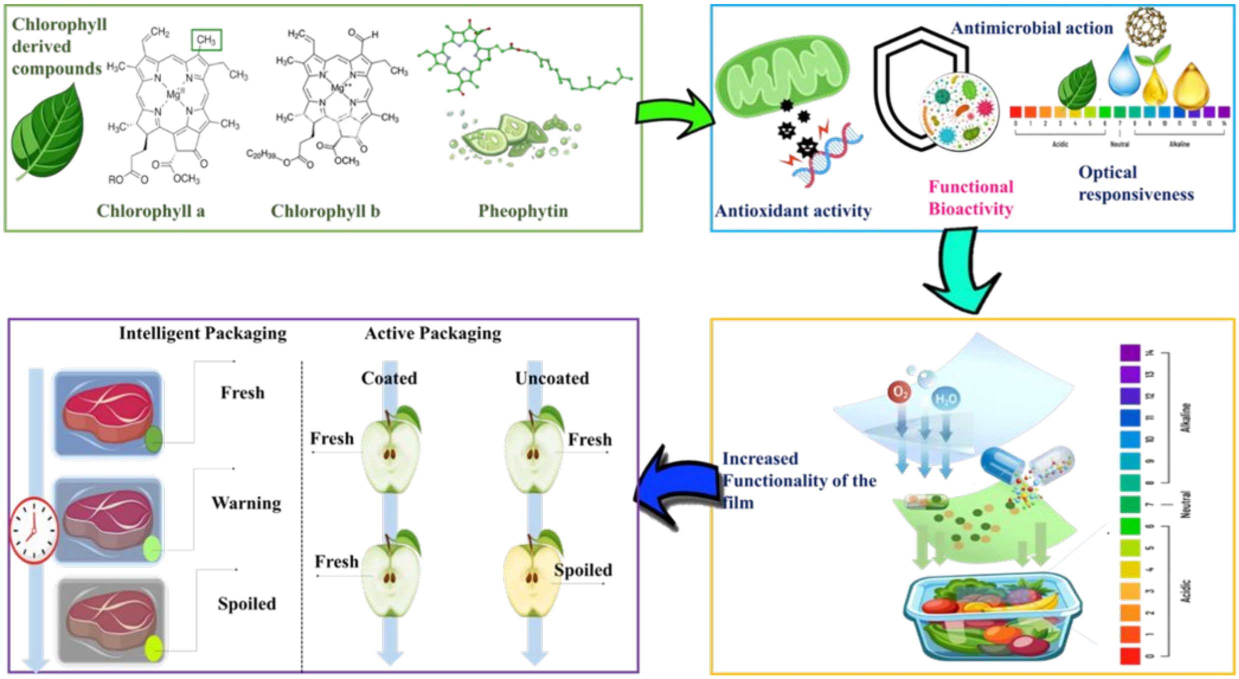

*__Figure 4__ Schematic illustration of chlorophylls extraction from plants and its incorporation into intelligent and active food packaging systems.*

Chlorophylls also possess intrinsic fluorescence properties that can be exploited in the design of fluorescent sensing systems for intelligent packaging. Its fluorescence is highly responsive to environmental variations, making it a viable noninvasive indicator for detecting food spoilage and microbial contamination[85]. Upon exposure to light, chlorophylls emits red fluorescence in the spectral range of approximately 680 to 740 nm[86]. During food degradation, metabolic by products such as organic acids, ammonia, However, during food degradation, metabolic by-products such as organic acids, ammonia, and reactive oxygen species alter local pH and oxidative conditions, leading to structural modifications in chlorophylls that reduce fluorescence intensity or shift emission wavelength. Such fluorescence variations provide measurable signals corresponding to the degree of food spoilage[87]. For instance, Xue et al. (2025)[88] designed a dual channel pH responsiveness fluorescent bio ink system that integrated chlorophylls natural fluorescence to generate visual cues corresponding to pH fluctuations during spoilage. Similarly, Herppich (2021)[89] evaluated chlorophylls fluorescence imaging (CFI) as a non-destructive tool for assessing the physiological status and quality of fresh produce demonstrating its potential for real time contactless evaluation in intelligent packaging.

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When incorporated into biopolymer-based films and coatings, chlorophylls intrinsic properties including pH sensitivity, antioxidant capacity, and color responsiveness can modulate physical parameters such as tensile strength, flexibility, and barrier performance, all critical for packaging functionality and product protection. Table 2 summarizes the diverse chlorophylls-incorporated biomaterials used in active and intelligent food packaging systems, highlighting applications across various food products, functional properties such as antioxidant, antimicrobial, photoactivity, and freshness indicator alongside their physical attributes (e.g., barrier performance, mechanical strength, biodegradability). Empirical studies reported outcomes, including prolonged shelf life, minimized food spoilage, and visual cues for product freshness. Nevertheless, broader commercial application requires addressing challenges related to physicochemical stability and cost-effective extraction methods. Future advances in microencapsulation techniques, polymer matrix optimization, and integration with sensing technologies are expected to enhance the functional performance facilitating sustainable, intelligent packaging solutions.

***Table 2*** *Summary of chlorophylls-based biomaterials in food packaging applications: functional properties and physical characteristics*

| Biomaterial | Food product | Functional Properties | Packaging | Physical properties | Limitations | References |
|---|---|---|---|---|---|---|
| Cornstarch + chlorophylls in + lipids (coconut oil, oregano essential oil, beeswax) | Shrimp | Photoactive antibacterial; ROS generation; shelf-life extension | Active | Increased Tensile strength; Improved water vapour permeability; rough surface | Starch's susceptibility to moisture; lipid composition affects performance | 59 |
| Pectin + chlorophylls (leaf extract) + CMC/silica nanoparticles | - | Antioxidant; Antimicrobial (against *E. coli* and *S. aureus*); Thermally stable | Active | Increased tensile strength, increased flexibility, thickness, improved | Decreased film flexibility; enhanced opacity by the addition of nanoparticles | 18 |
| Chlorophylls microcapsules (gum arabic/maltodextrin) | - | Antioxidant activity; UV protection | Active | Improved thermal stability,<br>high encapsulation efficiency (77.19%) | spray-drying-induced chlorophylls degradation; high surface oil with gum arabic blends | 90 |
| Wheat gluten + chlorophylls extract-based film | Sesame oil | UV blocking; Color change (indicator) | Active/ Intelligent | Increased thickness; increased water vapor permeability (WVP) | weak mechanical properties; uneven nanocomposite dispersion affecting functional uniformity; higher water vapor permeability and moisture sensitivity | 17 |
| Polyester-based film (INZEA) + chlorophylls hybrid nanopigments | - | Strong antioxidant potential; pigment stabilization; UV resistance | Active | Improved Young's modulus, and increased thermal stability | Limited biodegradability; reduced transparency | 70 |

| **Biomaterial** | **Food product** | **Functional Properties** | **Packaging** | **Physical properties** | **Limitations** | **Reference** |
|---|---|---|---|---|---|---|
| Chlorophylls orella-k-carrageenan composite films | - | Rapid biodegradation; UV barrier | Active | High opacity | High opacity affects in consumer visibility | 83 |
| WPI + chlorophylls microcapsules | - | High antioxidant potential; pH-responsive indicator | Active | Low moisture content, enhanced water solubility | - | 91 |
| Chitosan + chlorophylls a + 2-HP-β-Cyclodextrin | - | High antioxidant potential; Generates reactive oxygen species (ROS) under light; antimicrobial activity | Active | Amorphous structure, modified surface roughness, good light absorbance | Absence of controlled release of bioactive compounds analysis; light dependent ROS | 92 |
| PVA + ZnO + AgI + Chlorophylls (from spinach) | - | Photocatalytic pollutants degradation; strong activity | Active | - | - | 93 |

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## 5. Conclusion, challenges, and future perspective

Chlorophylls based active and intelligent packaging has emerged as a sustainable, multi-functional food packaging technology. The chlorophylls molecular structure imparts high antioxidant activity, photo-responsiveness, pH sensitivity, and spontaneous biodegradability. These naturally occurring properties enables chlorophylls to perform the dual function in packaging which is an active ingredient which slows down food spoilage through antioxidant and antimicrobial activities; and secondly an active indicator that provides immediate visual cues about food freshness through colorimetric and fluorescent signals. Chlorophylls or microencapsulated chlorophylls addition in biodegradable polymer matrices enhances physical and functional characteristics of films. Some of the examples include improved thickness, improved barrier properties towards moisture and gases, and changed mechanical behavior, typically resulting in smoother and more homogeneous film microstructures. Active packaging films incorporated with chlorophylls have been shown to be effective scavengers of free radicals and inhibitors of spoilage bacteria which results in extended shelf life for various foods including seafood and meat. Concurrently, chlorophylls pH, temperature, and gas sensitivity (such as ammonia) provide a measurable and often observable color transition from green to yellow, brown, or other colors characteristic of spoilage, thus arming consumers, and supply chains with non-invasive freshness sensors.

Chlorophylls is inherently unstable during conventional processing and storage conditions as it is sensitive and degrades rapidly when exposed to light, heat, oxygen, and fluctuation in pH, which damages its functional shelf life and color stability. Enhancing its stability through application of advanced encapsulation methods such as micro- and nano-encapsulation by biopolymer carriers is critical but currently making manufacturing more complex and costly. Moreover, cost-effective large-scale extraction and purification procedures that preserve functionality of chlorophylls must be optimized; and compatibility with various polymer matrices can affect film homogeneity, mechanical resistance, and barrier properties, which requires proper formulation and control of processing.

Future advancements should focus more on encapsulation to preserve chlorophylls bioactivity and enable controlled release of antimicrobial and antioxidant molecules, thereby optimizing shelf-life extension potential. Refining fabrication processes (extrusion, solution casting) may increase film robustness and scalability without compromising functionality. Combinations with digital sensing technology like fluorescence-based biosensors and IoT-based smart labels can potentially advance

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real-time monitoring of food quality. As such, future research efforts should focus on developing active, and intelligent packaging from chlorophylls to offer sustainable alternative that is driving food preservation and transparency of freshness together. This will ultimately result in safer, fresher, and more sustainable global food supply chains with reduced food waste and environmental impact.

## Conflict of interest

Authors declare there is no conflict of interest in this work.

## Data availability statement

No primary research results, software or code have been included and no new data were generated or analyzed as part of this review.

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## Authors contribution

Harshita Ranjan: Writing – Original draft, Software, Methodology, Investigation, Data curation, formal analysis. Manisha Joshi: Writing – Original draft, Investigation, Software. Swarup Roy: Conceptualization, Writing – review & editing, Visualization, Validation, Supervision.

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## Data availability statement

No primary research results, software or code have been included and no new data were generated or analyzed as part of this review.