

Sustainable Food Technology

Accepted Manuscript

This article can be cited before page numbers have been issued, to do this please use: H. Ranjan, M. Joshi and S. Roy, *Sustainable Food Technol.*, 2025, DOI: 10.1039/D5FB00637F.



This is an Accepted Manuscript, which has been through the Royal Society of Chemistry peer review process and has been accepted for publication.

Accepted Manuscripts are published online shortly after acceptance, before technical editing, formatting and proof reading. Using this free service, authors can make their results available to the community, in citable form, before we publish the edited article. We will replace this Accepted Manuscript with the edited and formatted Advance Article as soon as it is available.

You can find more information about Accepted Manuscripts in the [Information for Authors](#).

Please note that technical editing may introduce minor changes to the text and/or graphics, which may alter content. The journal's standard [Terms & Conditions](#) and the [Ethical guidelines](#) still apply. In no event shall the Royal Society of Chemistry be held responsible for any errors or omissions in this Accepted Manuscript or any consequences arising from the use of any information it contains.

Sustainability Spotlight Statement

View Article Online
DOI: 10.1039/D5FB00637F

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.



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

3 Harshita Ranjan¹, Manisha Joshi¹, Swarup Roy^{2,3*}

4 ¹ School of Bioengineering and Food Technology, Shoolini University, Bajhol, Solan 173229,
5 India

6 ² Department of Food Technology and Nutrition, School of Agriculture, Lovely Professional
7 University, Phagwara 144411, Punjab, India

8 ³ Department of Food and Nutrition, Kyung Hee University, Seoul 02447, Republic of Korea

9
10 *Corresponding author's email: swaruproy2013@gmail.com

11
12 **Abstract**

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

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

29



30 1. Introduction

31 Packaging is a crucial aspect in the food industry for the protection of food from external
32 conditions¹, such as temperature, humidity, and light, and maintaining quality, integrity, freshness,
33 and safety during its shelf life by controlling gas and vapor exchange with the atmosphere
34 preventing degradation while preserving sensory and nutritional qualities. Beyond protection,
35 packaging significantly influences consumer perception as the appearance of the product are often
36 associated with its freshness and overall quality ultimately affecting consumption patterns.
37 Traditionally, food packaging has used materials such as paper, glass. Paper is lightweight,
38 recyclable, and cost-effective while glass is inert, and provides excellent barriers to oxygen and
39 moisture, suitable for acidic or fatty products. Further, plastic being versatile with excellent barrier
40 properties ideal for wide range of foods². In recent years there has been a growing emphasis on
41 environmentally friendly and sustainable packaging alternatives. This shift has driven research and
42 innovations in biomaterials for food packaging, leading to the rise in the application of advanced
43 techniques such as coatings, antimicrobial, antioxidant packaging and modified atmosphere
44 packaging^{3,4}.

45 Active and intelligent packaging has garnered attention for its ability to extend functionality
46 beyond passive containment. Active packaging interacts with the food component to extend the
47 shelf life mitigating the microbial spoilage⁵ while intelligent packaging monitors the
48 environmental factors⁶ through visible color changes or variations in fluorescence provide
49 non-invasive information on food freshness, spoilage⁷, or changes in the package
50 microenvironment⁸. Addressing issues such as temperature fluctuations, microbial contamination,
51 and package integrity these packaging systems contribute to reduced food waste, improved
52 traceability, and decreased risk of food borne illness^{9,10,11}.

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



60 There have been recent advancements in biodegradable films and smart packaging showing the
61 potential of natural extracts and nanoparticles as functional additives. Numerous studies concluded
62 the efficiency of chlorophylls -based packaging, highlighting the pigment's amphiphilic structure,
63 pH sensitivity and antioxidant activity which has the potential advantages in both active and
64 intelligent applications. For example, sodium iron chlorophyllin incorporated into chitosan/ gelatin
65 films enhanced antimicrobial and antioxidant activity, improved UV barrier properties, and
66 effectively delayed spoilage in fresh cut chilli peppers, showed its potential as an active packaging
67 agent¹². Similarly, chlorophyllin incorporated into photoactive coatings generated reactive oxygen
68 species (ROS) enabling effective inactivation of *L. monocytogenes* demonstrating both
69 antimicrobial activity and light responsive packaging behavior¹³. Further, another study reported
70 that cornstarch chlorophyllin composite films under light exposure generated ROS resulting in
71 lower microbial and nitrogen levels compared to control samples and maintaining acceptable
72 quality of shrimp up to 4 days¹⁴. Moreover, chitosan based films incorporating chlorophylls with
73 curcumin exhibited enhanced barrier and mechanical properties, exhibited significant
74 antimicrobial activity and extended the shelf life of the cherries and pork¹⁵. The integration of
75 chlorophylls pigment has significantly expanded the functionality of food packaging¹⁶. These
76 natural components are especially found in plant extracts such as green tea and basil and are
77 explored for smart packaging, due to its unique chemical and functional properties.

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

85 **2. Chlorophylls chemistry and properties**

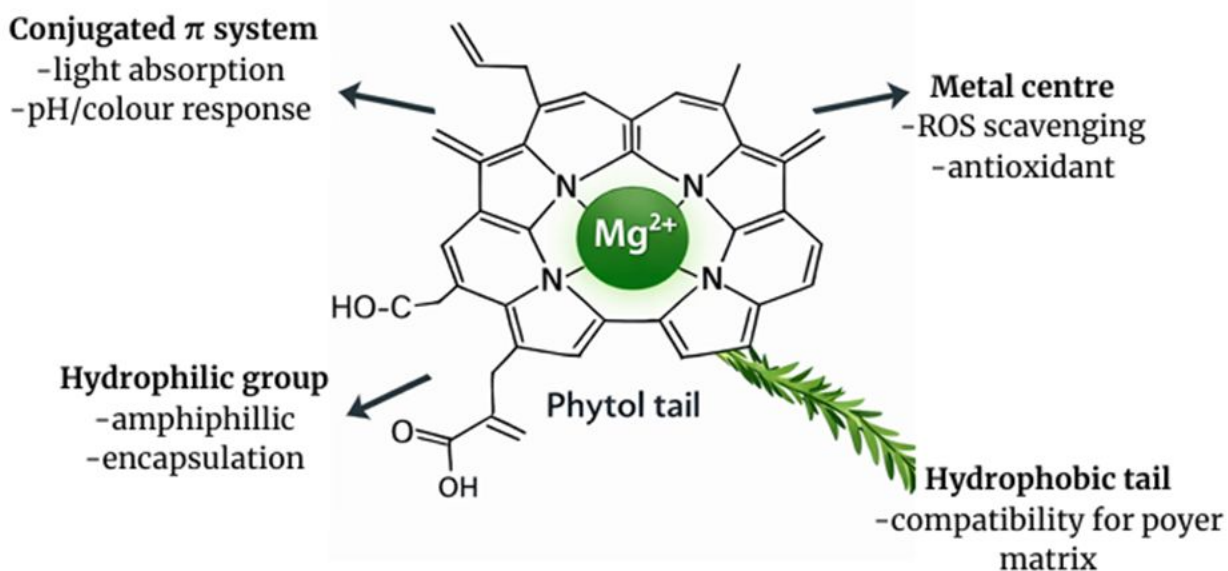
86 Chlorophylls has a unique chemical structure and properties which are fundamentally responsible
87 for its characteristic color, potent antioxidant activity, and suitability for packaging technologies



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

90 2.1 Molecular structure of chlorophylls

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



97

98 **Figure 1** Molecular structure of chlorophyll^{23,24}

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

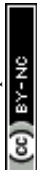


105 instance, chlorophyll c absorbs primarily in the blue-green region, chlorophyll d in the red region,
106 and chlorophyll e in the far-red region of the spectrum¹⁹. Structurally, chlorophylls molecules vary
107 chiefly in the degree of saturation in their pyrrolic rings and in functional groups attached to the
108 macrocycle. For example, chlorophyll b differs from chlorophyll a by having an aldehyde group
109 instead of a methyl group at the C7 position, which results from enzymatic oxidation of the methyl
110 group catalyzed by oxygenase. chlorophyll c contains a fully unsaturated phytyl system
111 (with a double bond between C17–C18), whereas chlorophylls a, d, and f contain partially
112 saturated phytyls. These structural differences significantly affect the absorption properties:
113 chlorophyll a, d, and f show approximately balanced absorption intensities in blue, red, and green
114 regions, while chlorophyll c absorbs weakly in the red and more strongly around 450 nm. This
115 variety in the absorption spectra are mirrored in their distinctive green hues, chlorophyll a appears
116 bluish-green, chlorophyll b bright green, chlorophyll c yellowish-green, chlorophyll d bright forest
117 green and chlorophyll f emerald green. This diversity makes these pigments promising candidates
118 as natural colorants¹⁹. Chlorophyll molecules possess two distinct regions: a hydrophilic
119 macrocycle and a hydrophobic phytyl tail. The most hydrophilic segments of the macrocycle
120 include the cyclopentanone ring and a propionic acid ester group at the C17 position. This
121 amphiphilic nature influences solvent selection for chlorophyll extraction, impacting yield and
122 purity important for technological applications²².

123 Chlorophyll's distinctive structure positively influences its function in the packaging. For example,
124 the hydrophilic porphyrin macrocycle promotes the antioxidant activity allowing chlorophylls and
125 its derivatives act as singlet oxygen quenchers and free radical scavengers. This protective effect
126 against lipid oxidation attributes not only to their free radical scavenging capacity but also to their
127 ability to chelate pro-oxidant metal ions such as Fe²⁺ and Cu²⁺ which retards lipid peroxidation in
128 food ⁵. On the other hand, chlorophylls acts as a photosensitizer, absorbing visible light and
129 transferring the energy to molecular oxygen to produce singlet oxygen and other reactive oxygen
130 species²⁵.

131 2.2 Extraction methods

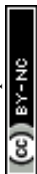
132 Chlorophylls are widely extracted for industrial applications from stinging nettle, spinach, algae,
133 silkworm excreta, alfalfa, pine needles, other pasture grasses and plant harvest by-products²⁶.



134 Several methods were used to extract chlorophylls of natural ingredients from the plants, such as
 135 aqueous extraction, enzyme-assisted extraction, alcoholic/organic solvent extraction, and
 136 supercritical/subcritical extraction²⁷. Several methods were used to extract chlorophylls from the
 137 plants, such as aqueous extraction, enzyme-assisted extraction, alcoholic/organic solvent
 138 extraction, and supercritical/subcritical extraction²⁶ summarized in table 1. Extraction can be
 139 carried out in various ways, involving different solvents and preparation methods. Variables such
 140 as pressure, temperature, contact efficiency, and time are critical. Since chlorophylls are sensitive
 141 to extreme light exposure, pH, and temperature, solvent selection must consider factors like
 142 density, viscosity, heat of evaporation, cost, environmental and health effects. The solvent should
 143 not react with or damage the extracted compound and must not be corrosive. Different methods
 144 are tailored for different microalgae species²⁸.

145 **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 \approx 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 +	<i>Laminaria japonica</i> 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



ethanol cosolvent)				Box–Behnken design	
Subcritical CO ₂ extraction	<i>Nigella sativa</i> seeds	Volatile oil: 66.6 wt.% of oleoresin	NA	70 bar, 30 °C, 2 hours	32
Supercritical CO ₂ extraction with a static modifier	<i>Scenedesmus obliquus</i> (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	<i>Scenedesmus obliquus</i> , <i>Arthrospira platensis</i> (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

146

147 Over the years, several approaches have been reported to remove chlorophylls from botanical
 148 crude extracts (CEs). Most rely on solid-phase extraction (SPE) with stationary phases such as
 149 Diaion HP-20 for initial fractionation. Charcoal has also been used to remove chlorophylls or other
 150 pigments entirely from CEs without fractionation of other constituents. However, these methods
 151 often eliminate other unspecified, potentially bioactive compounds along with chlorophylls.
 152 Detailed protocols vary by author, and preservation of the original phytochemical profiles is
 153 generally not assessed³⁵.

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



162 both phases can be recovered with solvent evaporation, making CCS effectively loss-free when
163 analytes are non-volatile. A recent study implemented CCS to selectively remove chlorophylls
164 from botanical CEs to produce chlorophylls -free "degreened" Knock-Out Extracts (chlorophylls
165 -KOE). This method enables subtraction of assay interference compounds while optimally
166 recovering other phytochemicals. The study produced chlorophylls -KOE from three
167 botanicals: *Epimedium sagittatum*, *Senna alexandrina L.*, and *Trifolium pratense L.*, evaluating
168 reproducibility and selectivity with HPLC, UHPLC-UV/MS, LC-MS, and ¹H NMR
169 spectroscopy³⁵.

170 Supercritical/subcritical CO₂ extraction selectively isolates components suitable for heat-sensitive
171 products. Traditionally, chlorophylls extraction uses liquid solvents followed by evaporation and
172 drying at high temperatures, risking degradation. Supercritical/subcritical CO₂ extraction operates
173 at low temperatures, preventing thermal degradation. CO₂ is inert, non-toxic, non-flammable,
174 inexpensive, and easily separated from extracts without heating, producing solvent-free extracts.
175 Stability tests on chlorophylls from *katuk* leaves showed decreased content at high temperatures,
176 indicating supercritical/subcritical CO₂ as the preferred extraction method to preserve
177 chlorophylls²⁷. Enzyme-assisted extraction is gaining attention for eco-friendly processing.
178 Targeted enzymes like pectinases, cellulases, and hemicellulases degrade cell walls, increasing
179 solvent pre-treatment efficiency, reducing solvent use, or increasing bioactive compound yield.
180 Used widely in juice processing and beer clarification, enzymatic pretreatment enhances
181 extractability. Enzyme-assisted extraction of Zn-chlorophylls derivatives from spinach pulp under
182 optimized conditions (8% enzyme concentration, 45°C, 30 min) increased yield by 39%⁵.

183 **2.3 Key properties of chlorophylls relevant to packaging**

184 The chemical structure of chlorophylls determines its bioactivity, influences potential health
185 benefits¹⁹. As mentioned earlier, chlorophylls are among the most prominent bioactive
186 compounds, having positive health impacts and high antioxidant activity. They are used as natural
187 food coloring agents and have wound healing and anti-mutagenic properties²⁰.

188 **2.3.1 Antioxidant activity**

189 Chlorophylls is a strong antioxidant that has the capability to scavenge free radicals and chelate
190 metal ions (e.g., Fe²⁺), hence they prevent the oxidative damage to lipids and cells. This activity
191 inhibits a major cause of food spoilage which is lipid peroxidation. It also protects against oxidative



192 DNA damage and reduces reactive oxygen species (ROS) formation, helping in preserving food
193 freshness by delaying spoilage processes. Natural chlorophylls possess antioxidant properties
194 making them promising candidates for preventing or mitigating the formation of reactive species.
195 Lanfer-Marquez et al., (2005)³⁶ demonstrated that Cu-chlorophylls in displayed higher antioxidant
196 activity compared to natural chlorophylls, highlighting the influence of the chelated metal in the
197 porphyrin ring on the strength of the antioxidant capacity¹⁹. Additionally, a study showed that the
198 kale chlorophylls which were microencapsulated in isolated whey protein, resulted in increased
199 antioxidant activity by 20% as assessed through the DPPH method³⁷.

200 **2.3.2 Photoactivity and reactive oxygen species generation**

201 Chlorophylls are very unstable compound and the stability is highly affected by pH, temperature,
202 heat, and light²¹. When exposed to irradiation, it can generate singlet oxygen (1O_2) through
203 photosensitive reactions causing discoloration²⁰. The chlorophylls content decreased faster under
204 light than in the dark because of singlet oxygen. Samples with added lipids showed lower and
205 slower degradation of chlorophylls than in samples without lipids. High pressure high temperature
206 processing results in the degradation of chlorophyll *a* and chlorophyll *b*. Both chlorophylls were
207 highly degraded at 117°C²¹. This singlet oxygen generation thereby can prolong the food shelf life
208 causing microbial inactivation; a property that can be exploited in active packaging to extend shelf
209 life.

210 **2.3.3 Color properties and sensitivity to pH, light, and oxygen**

211 As mentioned in the earlier section, chlorophylls is highly unstable compound, sensitive to light;
212 therefore, it becomes difficult to keep its molecules intact with a green color; a photosensitive light
213 harvesting pigment with special electronic properties³⁸. Furthermore, it is susceptible to heat,
214 oxygen, and chemical degradation. The pH has an effect on chlorophylls degradation as well³⁹.
215 Koca et al., (2006)⁴⁰ studied the effect of pH on the chlorophylls degradation and visual green
216 color loss in blanched green peas were studied at 70, 80, 90 and 100°C in buffered solutions of pH
217 5.5, 6.5 and 7.5. The rate constants of green color loss and chlorophylls degradation decreased
218 with increasing pH, indicating that the green color was retained at higher pH conditions. It was
219 found that chlorophyll *a* degraded faster than chlorophyll *b* at all pH values for each temperature
220 applied. The results revealed that chlorophyll *a* was more susceptible to thermal degradation than
221 chlorophyll *b* in acidic conditions⁴⁰.

222 **2.3.4 Stability challenges and encapsulation**



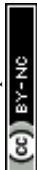
223 The chlorophylls incorporation into the food matrix is challenging because of its instability
224 towards light, oxygen and pH and poor bioavailability. Encapsulation is an excellent process to
225 enhance its bioaccessibility, digestibility, and controlled release²¹. For example, the encapsulation
226 carriers like maltodextrin (MD) and whey protein isolate (WPI) can provide multi-layered
227 protection. The MD/WPI walls acts as light barriers through scattering and UV absorption, oxygen
228 diffusion barriers limiting the access of reactive oxygen species, and pH buffers via hydrogen
229 bonding between WPI amine groups and MD hydroxyls with chlorophylls's porphyrin nitrogen.
230 Freeze-dried microcapsules of chlorophylls (MD/WPI from *Ulva intestinalis*) retained 38.12 %
231 green color after light exposure versus 1.84 % for unencapsulated chlorophylls, whereas the
232 chemical stability and retention rates increased significantly ($p < 0.05$). Spray-dried microcapsules
233 showed DPPH scavenging of 67.5% and freeze-dried 79.1%. Thus, chlorophylls can be protected
234 from bad light conditions and have a longer shelf-life during storage via microencapsulation and
235 possible hydrogen bonding with MD and WPI complexes⁴¹.

236 Emerging stabilization technologies such as core-shell nanoparticle encapsulation using zein,
237 casein, or whey protein isolate as wall materials offers enhanced protection for chlorophylls in
238 food packaging applications. Encapsulation efficiencies of chlorophylls retention after 10 days
239 were 83.6–96.3% and 39–97.8% at pH 3.0 under light/acidic stress; compared to 40% for free
240 chlorophylls. These technologies therefore offer superior photostability and controlled delivery for
241 active packaging applications⁴².

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

243 The active and intelligent smart packaging based on chlorophylls is a promising method which
244 leverages the natural bioactivity and colorimetric responsiveness of chlorophylls extracts from
245 various sources including plants or algae. Active compounds as intelligent indicators enhance the
246 stability and function of packaging or coating matrices. These pigments can change color because
247 of environmental stimuli, such as temperature, pH, oxygen, light or microbial activity, providing
248 visual cues to consumers about the freshness, spoilage, ripeness, or contamination of food⁴³. The
249 packaging is typically developed by incorporating chlorophylls or microencapsulated chlorophylls
250 into biodegradable polymer matrices like alginate, chitosan, gelatin, or pectin. Common
251 fabrication methods include solution casting, extrusion⁴⁴ designed to preserve the functional and
252 colorimetric properties of chlorophylls during processing.

253 **3.1 Film/coating fabrication using chlorophylls**



254 As mentioned earlier in the introduction part, chlorophylls have currently emerged to be a
 255 promising bioactive compound for the development of active and intelligent packaging films and
 256 coatings because of its unique chemical, antioxidant, and colorimetric properties. For example,
 257 edible coatings are revolutionizing food preservation by offering a sustainable and effective
 258 solution to key industry challenges. They are produced from natural biopolymers such as proteins
 259 (e.g., gelatin, zein), polysaccharides (e.g., starch, chitosan, alginate), and lipids, these coatings
 260 form a thin, edible layer on food surfaces. These biodegradable and edible matrices reduce
 261 moisture loss, protects against oxidative damage, and limits microbial growth, thereby extending
 262 shelf life while preserving food quality. Enhanced with natural additives like essential oils and
 263 antioxidants, these coatings offer antimicrobial benefits and contribute to health⁴⁵. Figure 2 shows
 264 the overall process for chlorophylls extraction, incorporation into the matrix, and subsequent
 265 analysis leading to the development of chlorophylls-integrated film and food packaging
 266 application. Lv et al. (2023)¹⁶ mentioned a study film containing chlorophylls and chitosan having
 267 the potential for generating color within the colorimetric temperature range of 50–75 °C. The
 268 system will undergo an irreversibly color change from green to yellow when exposed to this
 269 temperature range.

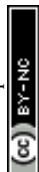


270
 271 *Figure 2 Schematic representation of chlorophylls-based active film formation*^{46 47}

270

271

272 3.1.1 Casting method



273 A lab or pilot scale method, also known as solvent casting, is a rather simple and one of the most
274 common techniques of edible film formation⁴⁸. It involves manufacturing films from biopolymers,
275 and includes the following steps: (i) solubilizing the biopolymer in a suitable edible and non-toxic
276 solvent, such as ethyl alcohol or water. The solubilization step ensures an even dispersion of the
277 biopolymer in the solvent. This solubilization step is crucial as the film formation depends on the
278 polymer's solubility rather than melting; (ii) casting of the solution in a predefined mould, where
279 it forms a gel structure (cohesive film adhering to the mould) as the solvent evaporates with time;
280 (iii) drying the cast solution layer, which is necessary to form a cohesive film, but with the moisture
281 content maintained at 5% to 8% to prevent wrinkling and tearing of the film during peeling.
282 Moreover, optimization of the drying temperatures and methods for a particular film is done to
283 produce high-quality edible films⁴⁹. A study investigated the formation of fractal structures in
284 chlorophylls films prepared by casting technique using two different chlorophylls concentrations
285 solution. Results were based on DLA model analyzed on optical microscopy showed that
286 chlorophylls cast films formed distinct fractal aggregates at both 0.50 g/L and 0.12 g/L
287 concentrations. Further image analysis showed a consistent fractal dimension for about 1.55 for
288 all samples which suggests fast aggregation. There was no effect of change in concentration on the
289 fractal dimension, suggesting that aggregation dynamics were stable across the tested range⁵⁰.

290 3.1.2 Extrusion

291 The extrusion method is one of the underexplored techniques for manufacturing edible films, but
292 is now attracting more attention, particularly for starch/protein combinations. Extrusion forms
293 films through a thermomechanical process⁴⁹. There are various steps involved in extrusion process;
294 preparation of formulations using different composition of raw materials and their mixing,
295 blending the mixture in an extruder in order to pelletize all film-forming ingredients, cutting
296 extrudates into pellets through the pelletizer, drying pellets in a hot-air oven, followed by extruding
297 the pellets into sheets through the second extruder, and finally blowing the mixed resins into a film
298 by a blown film extruder. Extrusion process often provides the films with acceptable mechanical
299 properties and good thermal stability⁵¹.

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



304 higher content (5.0%) of intact *Chlorella pyrenoidosa* biomass exhibited superior tensile strength
305 (4.37 ± 0.24 MPa) and elongation ($88.43 \pm 6.8\%$) compared to films with disrupted biomass
306 suggesting better dispersion and interactions between the phases which enhances homogeneity
307 because of amphiphilic compatibilization further confirmed by SEM. Furthermore, these films
308 displayed lower water vapor permeability (5.19×10^{-11} g m⁻¹ s⁻¹ Pa⁻¹), enhancing their barrier
309 properties. Films produced by blown extrusion from starch, PBAT, and *Chlorella pyrenoidosa*
310 microalgae biomass have the technological potential to be used as packaging for food products.
311 Starch and PBAT blends are widely studied⁵². Overall, the films produced by blown extrusion
312 blending starch or biodegradable polymers incorporating microalgae biomass containing
313 chlorophylls have shown good mechanical and antioxidant properties.

314 3.1.3 Encapsulation

315 Encapsulation technology has been extensively used to enhance the stability, specificity, and
316 bioavailability of essential food ingredients⁵³. Microencapsulation is a nanotechnology method
317 which can be used to prevent damage to bioactive compounds by protecting the encapsulated
318 compounds during edible film processing. The enrichment of alginate-based edible film with
319 chlorophylls microcapsules enabled to blend into the alginate-based edible film where they
320 migrated and slowly released compounds which were able to prevent or retard some microbial
321 growth on the fish bubble snack product tested. The enrichment increased the film thickness,
322 improved the surface texture of the film, increased the resistance of the coated food (fish bubble
323 snacks) to the growth of the mold *Rhizopus sp.*, and increased resistance to the proliferation of *E.*
324 *coli* but not of *S. aureus*. At room temperature the antifungal effect was twice as strong as for the
325 same product without enrichment of the edible film coating. The antifungal properties of the
326 enriched edible film extended the shelf life of the product tested⁵⁴.

327 Another study showed the encapsulation of chlorophylls with MD and WPI as carriers applying
328 both spray drying and freeze-drying methods was done in order to increase the stability of
329 chlorophylls extracted from *Ulva intestinalis* algae. The optimum combination of wall and core
330 materials to achieve the highest response including encapsulation efficiency (EE) and chlorophylls
331 content (CC) was obtained by response surface methodology and central composite design. The
332 optimal chlorophylls microcapsule obtained was chosen for subsequent tests containing solubility,
333 moisture content, and antioxidant properties. The results showed that the highest EE and CC were
334 $90.27 \pm 0.21\%$, 55.36 ± 0.36 µg/mL, and $90.46 \pm 0.62\%$, 85.85 ± 0.43 µg/mL, respectively in SD

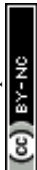


335 and FD. The microcapsules produced by the freeze dryer (FD) had higher antioxidant activity (79.1
336 ± 0.24) than the microcapsules produced by the spray dryer (SD) (67.5 ± 0.16). The highest
337 solubility (95.32%) and the lowest moisture content (3.7 ± 0.05) were related to the SD. Freeze
338 drying method (FDM) had the highest EE (91.2%), CC ($89.67 \mu\text{g/mL}$), and antioxidant properties
339 (79.1%)⁵⁵.

340 **3.1.4 Compression molding**

341 Either thermo-compression or ultrasonic compression binds the film-forming materials into a
342 desirable shape and thickness. An ultrasonic welder is used for welding the film materials; post
343 compression, the welded materials are cut and processed to elaborate sustainable edible packaging
344 systems. This technique has not yet gained popularity for manufacturing edible films but is a fast
345 and economical method and needs to be adapted to suit the edible film packaging industry⁴⁸.

346 The modern packaging, embedded with sensors, not only interacts with the food product but also
347 assesses its surrounding conditions, providing stakeholders with real-time information and
348 insights, detecting freshness, pathogens, pH levels and other environmental changes, offering more
349 insight than traditional measures such as weight or appearance. Compared to other natural food
350 colorants, the color of chlorophylls is relatively stable, making it a less sensitive and observable
351 colorimetric indicator in intelligent biodegradable packaging. This suggests that it may be less
352 applicable for providing real-time information⁵⁶. The study by Chavoshizadeh et al.,(2020)¹⁷
353 introduces a wheat gluten-based biodegradable film incorporating chlorophylls, highlighting its
354 role in enhancing the shelf life of sesame oil and indicating expiration dates. The film reduces oil
355 oxidation, evident from the halved peroxide value and changes color from green to yellow in
356 response to oil quality after a prolonged storage period. Integrating chlorophylls into edible films
357 or coatings has a significant effect enhancing their physical and functional properties. For
358 example, incorporated chlorophylls microcapsules into an alginate-based edible film showed
359 enhanced film thickness and improved surface texture which ultimately resulted in a smoother,
360 more homogeneous film without agglomeration⁵⁴ (discussed in table 2). This resulted in enhanced
361 morphology of the surface, improving the barrier properties of the film while protecting the food
362 product. Moreover, scanning electron microscopy (SEM) for microstructure showed that
363 chlorophylls -enriched films exhibited a clearly different and smoother surface compared to
364 control films without chlorophylls. Also, Fourier transform infrared spectroscopy (FTIR) analyses
365 showed interactions between chlorophylls microcapsules and the film matrix. The films based on



366 their function demonstrated the enhanced antimicrobial activity by slowly releasing chlorophylls
367 compounds that inhibited the growth of molds such as *Rhizopus sp.*; and bacteria such as
368 *Escherichia coli* on food products, thereby extending shelf life⁵⁴.

369

370 **3.2 Key properties of chlorophylls based smart packaging**

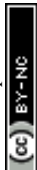
371 **3.2.1 Color**

372 Films enriched with chlorophylls microcapsules exhibits pronounced greenish intensity, and the
373 value increases with higher microcapsule content. A study by Dewi et al., (2022) showed that a*
374 color values shift to more negative numbers (e.g., from -0.41 ± 0.09 to -11.25 ± 0.24), reflecting
375 the deepening greenness imparted by chlorophylls encapsulation⁵⁴. Moreover, microencapsulation
376 or film matrix stabilization significantly enhance the green color stability under environmental
377 stress (heat, light, pH change) shown by the study in which freeze-dried microcapsules retain up
378 to 38% of chlorophylls color after light exposure, while unencapsulated chlorophylls may retain
379 as little as 1.84%⁴¹. The intensity and stability of green color can also act as a freshness or shelf-
380 life indicator for intelligent packaging due to visual changes upon degradation. Also review papers
381 focused on chlorophylls integration into smart packaging systems with color changes serving as
382 effective freshness and shelf-life indicators, emphasizing their application potential²⁵.

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

389 **3.2.2 Mechanical properties**

390 Chlorophylls often act as a natural filler or plasticizer modifying the tensile strength, elongation,
391 modulus, and impact resistance. For example, in polypropylene blends, low chlorophylls content
392 (0.1–0.25 wt%) reduce rigidity and ductility slightly, but when there is an optimal concentration
393 (0.5 wt%), it acts as a plasticizer increasing elongation and impact resistance while maintaining
394 tensile strength comparable to pure polypropylene. Higher chlorophylls concentrations (>0.5
395 wt%) typically reduce mechanical strength due to filler agglomeration disrupting polymer chain
396 cohesion⁴³. Also, Dewi et al., (2022)⁵⁴ showed in their study the chlorophylls microencapsulation



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

399 **3.2.3 Barrier properties**

400 Chlorophylls incorporation leads to thicker films with improved moisture and solubility barriers,
401 promoting longer shelf life and quality retention in packaged foods. Study discussed in table 2 in
402 which cornstarch-Chlorophylls in composite films added with coconut oil, oregano essential oil,
403 and beeswax showed significant reduction in moisture content (~12.58%), water solubility
404 (~15.41%), swelling ability (~29.30%), and water vapor permeability ($\sim 1.78 \times 10^{-10} \text{ gm}^{-1}\text{s}^{-1}\text{Pa}^{-1}$)
405 were observed. These changes enhance the ability of packaging films to maintain food quality by
406 limiting moisture-induced spoilage and degradation⁵⁹.

407 **3.2.4 Antioxidant and antimicrobial properties**

408 The antioxidant and antimicrobial performance of packaging films depends on many factors, such
409 as the molecular interaction between natural pigments and polymer substrates, the quantity of
410 added natural pigments, structural modifications, and environmental conditions¹⁶. Moreover, the
411 encapsulation of chlorophylls has shown to preserve the antioxidant/antibacterial properties of the
412 film during a long time. It is noteworthy that chlorophylls changes color in nitrate media, which
413 gives the film the ability to be used in the future as a smart film in identifying nitrate compounds
414 used in food¹⁸. For example, biodegradable films based on wheat gluten modified with
415 chlorophylls /polypyrrole showed that the addition of both increased the antioxidant activity of the
416 films as mentioned in the table 2¹⁷. Chlorophylls have a notable antibacterial property when it is
417 incorporated into various food packaging films. For example, López-Carballo et al. (2008)⁶⁰
418 developed gelatin films incorporating water-soluble chlorophylls in salts which showed substantial
419 reduction of *Staphylococcus aureus* and *Listeria monocytogenes* growth, showing that s
420 derivatives act as effective photosensitizers with antimicrobial effects under light exposure.

421

422 **4. Application of chlorophylls -based packaging film/coating**

423 Chlorophylls, a naturally occurring green pigment essential for the photosynthetic process in
424 plants, has garnered attention in sustainable packaging research due to its biocompatibility, eco-
425 friendly characteristics, and functional versatility²⁰. It exists in several forms, primarily classified
426 into six types i.e., chlorophyll a, b, c, d, e, and f. Among these, chlorophyll a and b are predominant
427 in higher terrestrial plants, with chlorophyll a serving as the principal photosynthetic pigment



428 found across plants, algae, cyanobacteria, and other phototrophic organisms, while chlorophyll b
429 functions as an accessory pigment predominantly located in green algae and higher plants⁶¹. The
430 presence of extensive conjugated double bonds in these molecules contributes to their significant
431 antioxidant capacity³⁷.

432 **4.1 Active packaging**

433 Chlorophylls are widely distributed across various plant-based sources, particularly in green
434 vegetables and fruits. Its distinctive physicochemical and biological properties including strong
435 light absorption, pH sensitivity, antioxidant activity, and chromatic responsiveness render it a
436 valuable component in the formulation of both active and intelligent biodegradable packaging
437 systems⁶². Furthermore, its molecular structure, characterized by a porphyrin ring coordinated with
438 a central magnesium ion (notably in chlorophyll a and b), is inherently organic and
439 biodegradable⁶³. Natural pigments or dyes for sustainable food packaging application. This
440 structural composition allows for environmental degradation through natural enzymatic and
441 microbial pathways, enhancing its appeal for environmentally sustainable applications. Figure 3
442 illustrates a multilayer smart packaging system which consist of a barrier and an active layer. The
443 active layer has dual functions: as an active releasing system that delivers antimicrobial agents and
444 antioxidants to the food, and as an active scavenging system regulating and responding to key
445 environmental factors such as oxygen, carbon dioxide, moisture, ethylene, and odor. This
446 combination can help to maintain food quality while extending shelf life by actively interacting
447 with the packaged food environment.



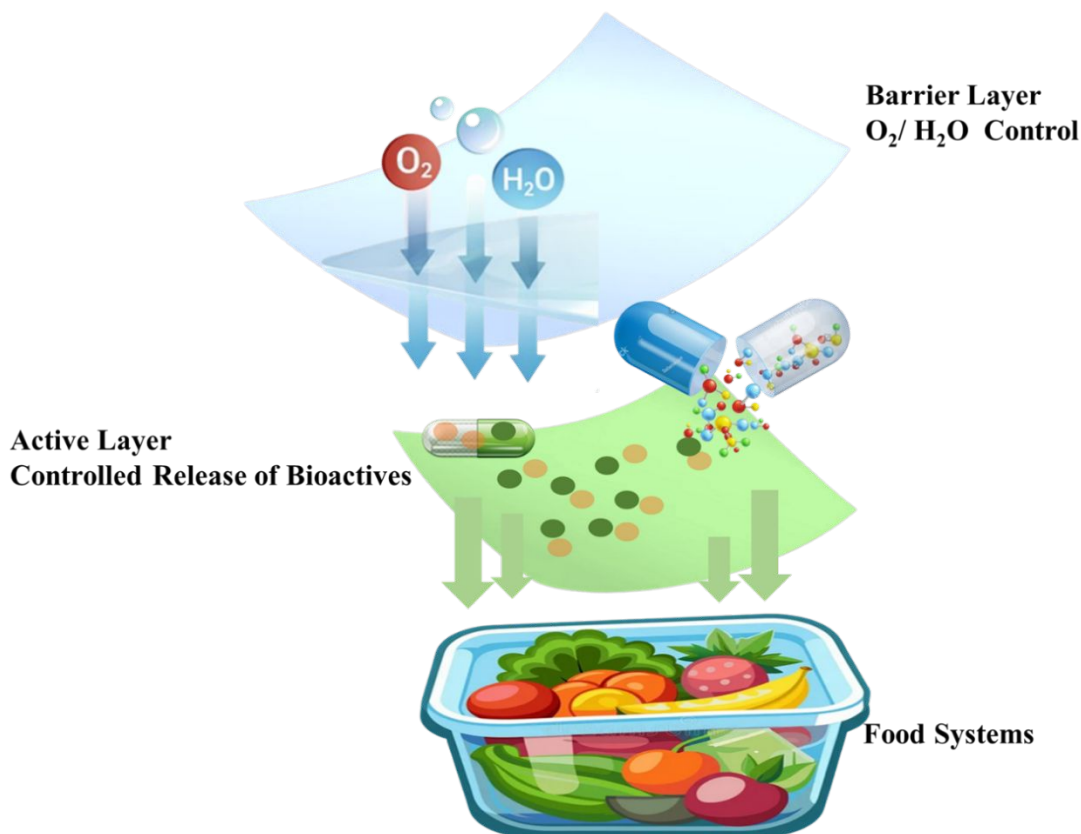


Figure 3 Multilayer smart packaging system consisting a barrier and an active layer

448

449

450

451 The incorporation of chlorophylls into biopolymer-based packaging films has been shown to
 452 markedly influence their physical (e.g., thickness, opacity, and ultraviolet light-blocking
 453 capability), mechanical (such as tensile strength and elongation at break), and barrier properties
 454 (including resistance to water vapor and gas transmission). Insights into the edible and
 455 biodegradable ulvan-based films and coatings for food packaging⁶⁴. These alterations are strongly
 456 dependent on the nature of the polymer matrix as well as the method of film fabrication. Numerous
 457 studies have explored such formulations to enhance the functional attributes of environmentally
 458 sustainable packaging materials. For instance, Dewi et al., (2022)⁵⁴ developed an alginate-based
 459 film embedded with chlorophylls microcapsules derived from *Caulerpa racemosa*, reporting
 460 improved barrier performance, particularly in reducing moisture and gas permeability, which
 461 consequently extended the shelf life of packaged fish products. Similarly, Ukwatta et al. (2025)⁵⁹
 462 investigated chlorophyllin-doped corn-starch films combined with different lipid additives and
 463 observed that the addition of chlorophylls in enhanced the water vapor barrier properties. This

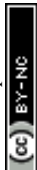


464 enhancement was attributed to increased matrix density, making the films more effective for
465 packaging applications involving light- and moisture-sensitive food items.

466 Chlorophylls -based packaging materials exhibit high environmental degradability, as their
467 constituent compounds including chlorophylls pigments and biopolymeric matrices like starch and
468 chitosan are susceptible to enzymatic breakdown by naturally occurring microbial populations,
469 particularly bacteria and fungi⁶⁵. The degradation processes typically involve the breakdown of
470 the porphyrin ring structure in chlorophylls, resulting in simpler intermediates like pheophytin and
471 chlorins, which are eventually mineralized into carbon dioxide, water, and biomass⁶⁶. These
472 degradation products are non-toxic to ecosystems and may even serve as beneficial nutrients within
473 the soil. Hence, the unique physicochemical and biological attributes of chlorophylls can be
474 effectively leveraged in the development of active and intelligent packaging systems. Such
475 packaging systems offer a sustainable and innovative approach to enhancing food preservation,
476 monitoring product quality, and reducing environmental impact within the packaging sector⁶⁷.

477 Recent developments have underscored the effectiveness of chlorophylls-derived compounds as
478 antimicrobial agents within active packaging systems, emphasizing their potential to prolong shelf
479 life and improve food safety. These packaging films are specifically designed to suppress or delay
480 the growth of spoilage and pathogenic microorganisms that compromise food quality and safety⁶⁸.

481 In a study conducted by Dewi et al., (2022)⁵⁴, an alginate-based edible film was formulated using
482 chlorophylls extracted from *Caulerpa racemosa*, a species of green seaweed. The antimicrobial
483 efficacy of the film was evaluated by wrapping fish snacks, and the results indicated a notable
484 reduction in microbial proliferation, particularly targeting spoilage organisms during storage. The
485 observed antimicrobial effect was attributed to the chlorophylls component, which exhibited both
486 antioxidant and antimicrobial functionalities, thereby positioning it as a promising natural
487 preservative for use in biodegradable packaging systems. The inclusion of antioxidants such as
488 chlorophylls in packaging materials plays a critical role in inhibiting oxidative degradation in food
489 products, especially those rich in lipids and proteins²⁵. These compounds function through various
490 mechanisms, including neutralization of singlet oxygen, scavenging of free radicals, reduction of
491 hydrogen peroxide, and chelation of pro-oxidant metal ions³⁷. Such multifunctional activities
492 contribute to the stabilization of food quality during storage and further enhance the utility of
493 chlorophylls-based systems in active packaging applications. Plant-derived botanical extracts have
494 been widely utilized as natural antioxidants in the development of active packaging materials⁶⁹. In



495 a study conducted by Micó-Vicent et al., (2020)⁷⁰, chlorophylls-containing hybrid nano pigments
496 sourced from broccoli processing residues were integrated into polyester-based bio nanocomposite
497 films. This incorporation led to a marked improvement in the antioxidant functionality of the
498 resulting packaging films. Additionally, the films exhibited improved thermal stability, color
499 uniformity, and mechanical performance, thereby indicating their suitability for active food
500 packaging applications. This study underscores the dual advantage of valorizing agricultural waste
501 while integrating naturally occurring antioxidant compounds into packaging matrices to prolong
502 food shelf life and mitigate environmental burden. Chlorophylls-based materials thus offer a
503 promising and sustainable alternative for active packaging technologies. Beyond packaging,
504 chlorophylls pigments are currently utilized across multiple sectors including cosmetics,
505 pharmaceuticals, and the food industry⁷¹. Within the food sector, chlorophylls (designated as E-
506 140) is primarily employed as natural colorants⁵⁶. However, their functionality may be further
507 extended to serve as natural pH-responsive indicators for monitoring food freshness, presenting
508 additional value in the development of intelligent packaging systems.

509 **4.2 Intelligent packaging**

510 Intelligent packaging in the food sector integrates inherent bio functional properties with real-time
511 monitoring capabilities to enhance food quality and safety management⁷². Chlorophylls, owing to
512 its chemical and optical sensitivity, serves a dual role in such systems i.e., functioning not only as
513 a packaging component but also as a responsive indicator capable of providing visual or
514 quantifiable feedback on product freshness, quality, and safety⁷³. One of the most widely employed
515 mechanisms in this context is colorimetric sensing, where chlorophylls-based compounds exhibit
516 perceptible color changes in response to environmental factors such as pH fluctuations,
517 temperature shifts, or the presence of spoilage-associated gases like ammonia or oxygen⁷⁴.

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

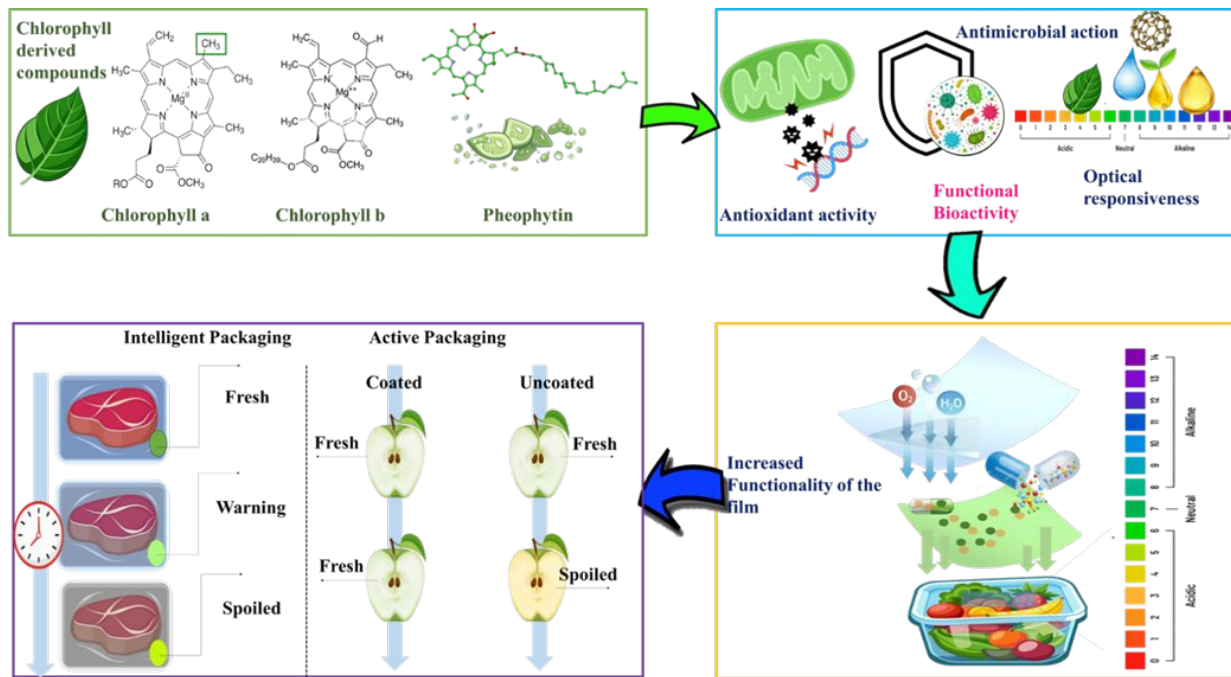


526 modifications impact absorption directly, i.e., native chlorophylls exhibits strong UV-Vis
527 absorptions near 430 nm (Soret band) and 660-665 nm (Q band)⁷⁸. Moreover, the peak broadening,
528 lower intensity, and shift in wavelengths caused by the pheophytin produced through acidic
529 environments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

531 These alterations enable visual detection of food spoilage without the need to open the package,
532 offering a user-friendly freshness assessment tool for both manufacturers and consumers. For
533 example, Yu et al. (2024)⁷⁹ developed a chlorophylls-infused colorimetric film that demonstrated
534 distinct color transitions under varying pH conditions. These pH-responsive films were effectively
535 applied to monitor spoilage in actual food systems. Chlorophylls functioned as the primary
536 halochromic pigment, undergoing progressive discoloration in response to acidic or alkaline
537 environments typically resulting from microbial activity, thereby serving as a reliable indicator of
538 food degradation⁸⁰. Similarly, in a study by Mohammadian et al. (2020)⁸¹, chlorophylls was
539 incorporated as a natural pigment in packaging films designed to function as temperature-sensitive
540 indicators. While the primary focus was pH and gas sensitivity, the study observed visible color
541 variations at elevated temperatures, correlating with the microbial spoilage activity. In another
542 study, Kılıç (2024)⁸² fabricated a thermoplastic starch-based film enriched with chlorophylls -rich
543 *Aronia* extract, which demonstrated a gas-responsive colorimetric behavior. Exposure to
544 ammonia, a volatile compound typically generated during the initial stages of spoilage in protein-
545 rich food products such as fish, induces a noticeable color change in the film, shifting its hue from
546 green to brown⁸³. Fig. 4 illustrates the utilization process of extracted chlorophylls from plants to
547 develop bioactive compounds which are further incorporated into intelligent and active packaging
548 systems. In intelligent packaging these chlorophylls-based indicators visually signal food
549 freshness by changing color, whereas in active packaging, chlorophylls coatings help maintain
550 food freshness by slowing spoilage compared to uncoated packaging, thereby extending shelf life
551 through bioactive protection. Collectively, these studies confirm the efficacy of chlorophylls as
552 functional indicator in intelligent packaging systems aimed at real time spoilage detection⁸⁴.



553



554

555

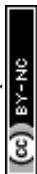
556 **Figure 4** Schematic illustration of chlorophylls extraction from plants and its incorporation into
 557 intelligent and active food packaging systems.

558 Chlorophylls also possess intrinsic fluorescence properties that can be exploited in the design of
 559 fluorescent sensing systems for intelligent packaging. Its fluorescence is highly responsive to
 560 environmental variations, making it a viable noninvasive indicator for detecting food spoilage and
 561 microbial contamination⁸⁵. Upon exposure to light, chlorophylls emits red fluorescence in the
 562 spectral range of approximately 680 to 740 nm⁸⁶. During food degradation, metabolic by products
 563 such as organic acids, ammonia, However, during food degradation, metabolic by-products such
 564 as organic acids, ammonia, and reactive oxygen species alter local pH and oxidative conditions,
 565 leading to structural modifications in chlorophylls that reduce fluorescence intensity or shift
 566 emission wavelength. Such fluorescence variations provide measurable signals corresponding to
 567 the degree of food spoilage⁸⁷. For instance, Xue et al. (2025)⁸⁸ designed a dual channel pH
 568 responsiveness fluorescent bio ink system that integrated chlorophylls natural fluorescence to
 569 generate visual cues corresponding to pH fluctuations during spoilage. Similarly, Herppich
 570 (2021)⁸⁹ evaluated chlorophylls fluorescence imaging (CFI) as a non-destructive tool for assessing
 571 the physiological status and quality of fresh produce demonstrating its potential for real time
 572 contactless evaluation in intelligent packaging.



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

586
587
588
589



590 **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 <i>E. coli</i> and <i>S. aureus</i>); 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, 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



592 **5. Conclusion, challenges, and future perspective**

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

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

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



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

628

629 **Conflict of interest**

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

631 **Data availability statement**

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

634 **Funding**

635 No funding received.

636 **Acknowledgment**

637 None

638 **Authors contribution**

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

642

643 **References**

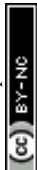
- 644 1. Turan, D. Food packaging technology considerations for designers : Attending to food ,
645 consumer , manufacturer , and environmental issues. 1–32 (2024) doi:10.1111/1541-
646 4337.70058.
- 647 2. González-lópez, M. E. & Calva-estrada, S. D. J. Current trends in biopolymers for food
648 packaging : a review. 1–20 (2023) doi:10.3389/fsufs.2023.1225371.
- 649 3. Mahmud, Z. Al, Mobarak, H. & Hossain, N. Heliyon Emerging trends in biomaterials for
650 sustainable food packaging : A comprehensive review. *Heliyon* **10**, e24122 (2024).
- 651 4. Biji, K. B., Ravishankar, C. N. & Mohan, C. O. Smart packaging systems for food
652 applications : a review. **52**, 6125–6135 (2015).
- 653 5. Özkan, G. & Bilek, S. E. Enzyme-assisted extraction of stabilized chlorophylls from



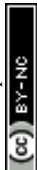
- 654 spinach. **176**, 152–157 (2015).
- 655 6. Park, B., Wi, S., Chung, H. & Lee, H. Chlorophylls Fluorescence Imaging for
656 Environmental Stress Diagnosis in Crops. (2024).
- 657 7. Liu, H., Zhou, Y., Ji, Z., Wang, Z. & Yang, X. Development of a fluorescence imaging
658 system for real-time assessment and monitoring of the quality deterioration in Lapins
659 cherries during refrigerated storage. *Food Chem.* **504**, 147890 (2026).
- 660 8. Maleeka Singh, Ke Wang, Chang Chen, M. G. C. Luminescence-based techniques to
661 monitor pre-, post-harvest and processing changes in fresh produce and derivatives:
662 Principles, applications and trends. *Trends Food Sci. Technol.* **162(2):105**, (2025).
- 663 9. Doderò, A., Escher, A., Bertucci, S., Castellano, M. & Lova, P. applied sciences Intelligent
664 Packaging for Real-Time Monitoring of Food-Quality : Current and Future Developments.
665 (2021).
- 666 10. Mkhari, T. & Adeyemi, J. O. Recent Advances in the Fabrication of Intelligent Packaging
667 for Food Preservation : A Review. 1–49 (2025).
- 668 11. Palanisamy, Y., Kadirvel, V. & Ganesan, N. D. Sustainable Food Technology Recent
669 technological advances in food packaging : sensors , automation , and application. 161–180
670 (2025) doi:10.1039/d4fb00296b.
- 671 12. Yan, Bing, Jingyu Huang, Xiaoyu Yin, Xinyue Guan, Yingxue Tang, Jiamin Wen, Bolin
672 Zhang, Junfeng Fan, and Xiuting Li. "Sodium iron chlorophyllsin-reinforced
673 chitosan/gelatin films for fresh-cut vegetable packaging." *Food Packaging and Shelf
674 Life* 52 101608 (2025).
- 675 13. López-Carballo, Gracia, Pilar Hernández-Muñoz, and Rafael Gavara. "Photoactivated self-
676 sanitizing chlorophyllsin-containing coatings to prevent microbial contamination in
677 packaged food." *Coatings* 8, no. 9, 328 (2018).
- 678 14. Ukwatta RH, Zheng Y, Ma Y, Xue F, Xiong X, Li C. The characterisation of cornstarch-
679 based chlorophyllsin composite film for preservation of shrimp under photodynamic
680 irradiation. *International Journal of Food Science and Technology.* 59(6):3950-66 (2024).
- 681 15. Ni Y, Li Y, Wang M, Li H, Zhang W, Tan L, Zhao J, Xu B. Chitosan-based packaging films
682 with antibacterial-sterilization integrated continuous activity for extending the shelf life of
683 perishable foods. *International Journal of Biological Macromolecules.* 1;275:133351.
684 (2024).



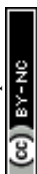
- 685 16. Lv, Y., Ai, Y., Fang, F. & Liao, H. Development of active packaging films utilized natural
686 colorants derived from plants and their diverse applications in protein-rich. (2023).
- 687 17. Chavoshizadeh, S., Pirsa, S. & Mohtarami, F. Conducting / smart color film based on wheat
688 gluten / chlorophylls / polypyrrole nanocomposite. *Food Packag. Shelf Life* **24**, 100501
689 (2020).
- 690 18. Sharifi, K. A. & Pirsa, S. Biodegradable film of black mulberry pulp pectin / chlorophylls
691 of black mulberry leaf encapsulated with carboxymethylcellulose / silica nanoparticles :
692 Investigation of physicochemical and antimicrobial properties. *Mater. Chem. Phys.* **267**,
693 124580 (2021).
- 694 19. Martins, T., Barros, A. N. & Rosa, E. Enhancing Health Benefits through Chlorophylls and
695 Chlorophylls-Rich Agro-Food : A Comprehensive Review. (2023).
- 696 20. Ebrahimi, P., Shokramraji, Z., Tavakkoli, S. & Mihaylova, D. Chlorophylls as Natural
697 Bioactive Compounds Existing in Food By-Products : A Critical Review. 1–12 (2023).
- 698 21. Ghosh, S., Sarkar, T., Das, A. & Chakraborty, R. Natural colorants from plant pigments and
699 their encapsulation : An emerging window for the food industry. **153**, (2022).
- 700 22. Pareek, S., Sagar, N. A., Sharma, S., Kumar, V. & Agarwal, T. Chlorophylls : Chemistry
701 and Biological Functions Chlorophylls : Chemistry and Biological Functions. (2017).
- 702 23. Tanaka, R. & Tanaka, A. Biochimica et Biophysica Acta Chlorophylls cycle regulates the
703 construction and destruction of the light-harvesting complexes . *BBA - Bioenerg.* **1807**, 968–
704 976 (2011).
- 705 24. Mandal, R. & Dutta, G. From photosynthesis to biosensing : Chlorophylls proves to be a
706 versatile molecule. *Sensors Int.* **1**, 100058 (2020).
- 707 25. Ndwandwe, B. K., Malinga, S. P., Kayitesi, E. & Dlamini, B. C. Review Recent
708 developments in the application of natural pigments as pH-sensitive food freshness
709 indicators in biopolymer-based smart packaging : challenges and opportunities. 2148–2161
710 (2024) doi:10.1111/ijfs.16990.
- 711 26. Amarasinghe, P. Extraction and degradation of chlorophylls a and b from *Alternanthera*
712 *sessilis* Extraction and degradation of chlorophylls a and b from *Alternanthera sessilis*. 10–
713 21 (2016) doi:10.4038/jnsfsr.v44i1.7977.
- 714 27. Kwartiningsih, E., Ramadhani, A. N., Ami, N. G., Clarissa, V. & Damara, J. Chlorophylls
715 Extraction Methods Review and Chlorophylls Stability of Katuk Leaves (*Sauropus*



- 716 androgynous) Chlorophylls Extraction Methods Review and Chlorophylls Stability of
717 Katuk Leaves (*Sauropus androgynous*). *J. Phys. Conf. Ser.* (2021) doi:10.1088/1742-
718 6596/1858/1/012015.
- 719 28. Olnár, É. V. A. M., Ó, D. Ó. R. A. R. I. E. T. H. & Ocsi, R. Ó. B. Solid-liquid extraction of
720 chlorophylls from microalgae from photoautotrophic open-air cultivation. **41**, 119–122
721 (2013).
- 722 29. Ferreira, A. M., Leite, A. C., Coutinho, J. A. P. & Freire, M. G. Chlorophylls Extraction
723 from Spinach Leaves Using Aqueous Solutions of Surface-Active Ionic Liquids. *Sustain.*
724 *Chem.* **2**, 764–777 (2021).
- 725 30. Costache, M. A., Campeanu, G. & Neata, G. Studies concerning the extraction of
726 chlorophylls and total carotenoids from vegetables. *Rom. Biotechnol. Lett.* **17**, 7702–7708
727 (2012).
- 728 31. Lu, J., Feng, X., Han, Y. & Xue, C. Optimization of subcritical fluid extraction of
729 carotenoids and chlorophylls a from *Laminaria japonica* Aresch by response surface
730 methodology. *J. Sci. Food Agric.* **94**, 139–145 (2014).
- 731 32. Edris, A. E., Wawrzyniak, P. & Kalemba, D. Subcritical CO₂ extraction of a volatile oil-
732 rich fraction from the seeds of *Nigella sativa* for potential pharmaceutical and nutraceutical
733 applications. *J. Essent. Oil Res.* **30**, 84–91 (2018).
- 734 33. Guedes, A. C. *et al.* Supercritical fluid extraction of carotenoids and chlorophylls a, b and
735 c, from a wild strain of *Scenedesmus obliquus* for use in food processing. *J. Food Eng.* **116**,
736 478–482 (2013).
- 737 34. Fernandes, A. S., Caetano, P. A., Jacob-Lopes, E., Zepka, L. Q. & de Rosso, V. V.
738 Alternative green solvents associated with ultrasound-assisted extraction: A green
739 chemistry approach for the extraction of carotenoids and chlorophylls from microalgae.
740 *Food Chem.* **455**, 139939 (2024).
- 741 35. Kim, S. B., Bisson, J., Friesen, J. B. & Pauli, G. F. HHS Public Access. **83**, 1846–1858
742 (2021).
- 743 36. Lanfer-marquez, U. M., Barros, R. M. C. & Sinnecker, P. Antioxidant activity of
744 chlorophylls and their derivatives. **38**, 885–891 (2005).
- 745 37. Pérez-gálvez, A., Viera, I. & Roca, M. Carotenoids and chlorophylls as antioxidants.
746 *Antioxidants* **9**, 1–39 (2020).



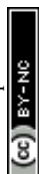
- 747 38. Hsu, C., Chao, P., Hu, S. & Yang, C. The Antioxidant and Free Radical Scavenging
748 Activities of Chlorophylls and Pheophytins. **2013**, 1–8 (2013).
- 749 39. Nurafifah, I., Hardianto, M. A., Erfianti, T., Amelia, R. & Suyono, E. A. The effect of acidic
750 pH on chlorophylls , carotenoids , and carotenoid derivatives of *Euglena sp* . as antioxidants.
751 **16**, 2391–2401 (2023).
- 752 40. Koca, N., Karadeniz, F. & Burdurlu, H. S. Food Chemistry Effect of pH on chlorophylls
753 degradation and colour loss in blanched green peas. **100**, 609–615 (2006).
- 754 41. Amadi, S., Milani, J. M., Shahidi, S. & Golkar, A. Food Chemistry : X Comparative analysis
755 of freeze drying and spray drying methods for encapsulation of chlorophylls with
756 maltodextrin and whey protein isolate. *Food Chem. X* **21**, 101156 (2024).
- 757 42. Emiezi Agarry, I. *et al.* Utilization of different carrier agents for chlorophylls encapsulation:
758 Characterization and kinetic stability study. *Food Res. Int.* **160**, 111650 (2022).
- 759 43. Sheibani, S., Jafarzadeh, S. & Qazanfarzadeh, Z. International Journal of Biological
760 Macromolecules Sustainable strategies for using natural extracts in smart food packaging.
761 *Int. J. Biol. Macromol.* **267**, 131537 (2024).
- 762 44. Huang, K. & Wang, Y. Advances in bio-based smart food packaging for enhanced food
763 safety. *Trends Food Sci. Technol.* **159**, 104960 (2025).
- 764 45. Karnwal, A., Kumar, G., Singh, R. & Selvaraj, M. Food Chemistry : X Natural biopolymers
765 in edible coatings : Applications in food preservation. **25**, (2025).
- 766 46. Soiklom, S., Siri-anusornsak, W., Petchpoung, K. & Soiklom, S. Development of Bioactive
767 Edible Film and Coating Obtained from *Spirogyra sp* . Extract Applied for Enhancing Shelf
768 Life of Fresh Products. (2025).
- 769 47. Roshanak, S., Rahimmalek, M. & Goli, S. A. H. Evaluation of seven different drying
770 treatments in respect to total flavonoid, phenolic, vitamin C content, chlorophylls,
771 antioxidant activity and color of green tea (*Camellia sinensis* or *C. assamica*) leaves. *J. Food*
772 *Sci. Technol.* **53**, 721–729 (2016).
- 773 48. Bangar, S. P., Chaudhary, V., Thakur, N., Kajla, P. & Kumar, M. Natural Antimicrobials
774 as Additives for Edible Food Packaging Applications : A Review. (2021).
- 775 49. Gupta, D., Lall, A., Kumar, S., Patil, T. D. & Gaikwad, K. K. Sustainable Food Technology.
776 1428–1455 (2024) doi:10.1039/d4fb00110a.
- 777 50. G C Pedro, F D S Gorza, N. C. de S. and J. R. S. Fractal structures in casting films from



- 778 chlorophylls. (2014) doi:10.1088/1742-6596/480/1/012011.
- 779 51. Kumar, S., Mukherjee, A. & Dutta, J. Chitosan based nanocomposite films and coatings:
780 Emerging antimicrobial food packaging alternatives. *Trends Food Sci. Technol.* **97**, 196–
781 209 (2020).
- 782 52. Gallo-García, L. A. *et al.* Feasibility of production starch/poly(butylene adipate-co-
783 terephthalate) biodegradable materials with microalgal biomass by blown film extrusion. *J.*
784 *Food Process Eng.* **45**, (2022).
- 785 53. Xu, Y. *et al.* The application of encapsulation technology in the food Industry:
786 Classifications, recent Advances, and perspectives. *Food Chem. X* **21**, 101240 (2024).
- 787 54. Dewi, E. N., Citra, A., Tassakka, M. A. R., Yuwono, M. & Agus, E. Effect of chlorophylls
788 in alginate-based edible film in inhibiting spoilage of fish snacks. **5**, 57–68 (2022).
- 789 55. Ahmadi, S., Milani, J. M. & Shahidi, S. Heliyon Fabrication and optimization of ultra-long
790 stable microencapsulated chlorophylls using combinations of wall material via response
791 surface methodology. *Heliyon* **10**, e40161 (2024).
- 792 56. Chiu, I. Biopolymer-based intelligent packaging integrated with natural colourimetric
793 sensors for food safety and sustainability. 1–13 (2024) doi:10.1002/ansa.202300065.
- 794 57. Ambra, R., Pastore, G. & Natella, F. The Fate of Chlorophylls in Alkali-Treated Green
795 Table Olives : A Review. (2023).
- 796 58. Sanja M. Milenković, J. B. Z., Anđelković, T. D. & Marković, D. Z. The identification of
797 chlorophylls and its derivatives in the pigment mixtures : HPLC- chromatography, visible
798 and mass spectroscopy studies. *Adv. Technol.* **1**, 34–35 (2012).
- 799 59. Ukwatta, R. H. *et al.* Effect of lipid addition on the physiochemical, structural, and
800 photoactive antibacterial properties of cornstarch-chlorophyllsin composite film. *Food Res.*
801 *Int.* **202**, 115699 (2025).
- 802 60. López-carballo, G., Hernández-muñoz, P., Gavara, R. & Ocio, M. J. International Journal
803 of Food Microbiology Photoactivated chlorophyllsin-based gelatin films and coatings to
804 prevent microbial contamination of food products. **126**, 65–70 (2008).
- 805 61. Isabel Viera, A. P.-G. and María R. Green Natural Colorants. (2019)
806 doi:10.3390/molecules24010154.
- 807 62. Kumar, Y., Bist, Y., Thakur, D., Nagar, M. & Saxena, D. C. International Journal of
808 Biological Macromolecules A review on the role of pH-sensitive natural pigments in



- 809 biopolymers based intelligent food packaging films. *Int. J. Biol. Macromol.* **276**, 133869
810 (2024).
- 811 63. Bisht, S. & Gaikwad, K. K. Natural Pigments or Dyes for Sustainable Food Packaging
812 Application. *Food Bioprocess Technol.* (2025) doi:10.1007/s11947-025-03756-2.
- 813 64. Wang, H., Cao, Z., Yao, L. & Feng, T. Insights into the Edible and Biodegradable Ulvan-
814 Based Films. (2023).
- 815 65. Magalhães, D. *et al.* Natural Pigments Recovery from Food By-Products: Health Benefits
816 towards the Food Industry. *Foods* **13**, (2024).
- 817 66. Tanaka, A. & Ito, H. Chlorophylls Degradation and Its Physiological Function. *Plant Cell*
818 *Physiol.* **66**, 139–152 (2025).
- 819 67. Ghoshal, G. Recent Trends in Active, Smart, and Intelligent Packaging for Food Products.
820 *Food Packag. Preserv.* 343–374 (2018) doi:10.1016/b978-0-12-811516-9.00010-5.
- 821 68. Jingxian Jiang , Weiran Zhang , Xijian Yi , Qin Lei , Yuru Liao, Y. T. and W. Y. Recent
822 progress in properties and application of antibacterial food packaging materials based on
823 polyvinyl alcohol. *e-Polymers* **Vol. 24 (I)**, (2024).
- 824 69. Islam, R.U., Khan, M.A. and Islam, S. U. Plant Derivatives as Promising Materials for
825 Processing and Packaging of Meat-Based Products – Focus on Antioxidant and
826 Antimicrobial Effects. *J. Food Process. Preserv.* **41**, (2017).
- 827 70. Micó-Vicent, B. *et al.* Effect of chlorophylls hybrid nanopigments from broccoli waste on
828 thermomechanical and colour behaviour of polyester-based bionanocomposites. *Polymers*
829 *(Basel)*. **12**, 1–19 (2020).
- 830 71. Latos-Brozio, M. & Masek, A. The application of natural food colorants as indicator
831 substances in intelligent biodegradable packaging materials. *Food Chem. Toxicol.* **135**,
832 110975 (2020).
- 833 72. Sobhan, A., Hossain, A., Wei, L., Muthukumarappan, K. & Ahmed, M. IoT-Enabled
834 Biosensors in Food Packaging: A Breakthrough in Food Safety for Monitoring Risks in
835 Real Time. *Foods* **14**, 1–18 (2025).
- 836 73. Luo X, Zaitoon A, L. L. review on colorimetric indicators for monitoring product freshness
837 in intelligent food packaging: Indicator dyes, preparation methods, and applications.
838 *Compr. Rev. food Sci. food Saf.* **21**, (2022).
- 839 74. B. Liu, J. Z. and G. W. Recent advances in the design of colorimetric sensors for



- 840 environmental monitoring. *Environ. Sci.* **7**, 2195–2213 (2020).
- 841 75. Karishma Devi Boraha, J. B. Magnesium porphyrins with relevance to chlorophylls. *Dalt.*
842 *Trans.* **46**, (2017).
- 843 76. Długosz, O. & Banach, M. Synthesis of metalloporphyrin complexes based on
844 chlorophyllsin. *J. Mol. Struct.* **1260**, 132841 (2022).
- 845 77. Li, X. *et al.* Rapid determination of chlorophylls and pheophytin in green tea using fourier
846 transform infrared spectroscopy. *Molecules* **23**, (2018).
- 847 78. Seifert, B., Pflanz, M. & Zude, M. Spectral shift as advanced index for fruit chlorophylls
848 breakdown. *Food Bioprocess Technol.* **7**, 2050–2059 (2014).
- 849 79. Yu, D., Cheng, S., Li, Y., Su, W. & Tan, M. Recent advances on natural colorants-based
850 intelligent colorimetric food freshness indicators: fabrication, multifunctional applications
851 and optimization strategies. *Crit. Rev. Food Sci. Nutr.* **64**, 12448–12472 (2024).
- 852 80. Eghbaljoo, H. *et al.* Development of smart packaging halochromic films embedded with
853 anthocyanin pigments; recent advances. *Crit. Rev. Food Sci. Nutr.* **65**, 770–786 (2025).
- 854 81. Mohammadian, E., Alizadeh-Sani, M. & Jafari, S. M. Smart monitoring of gas/temperature
855 changes within food packaging based on natural colorants. *Compr. Rev. food Sci. food Saf.*
856 **19**, 2885–2931 (2020).
- 857 82. Kılıç, N. N. Thermoplastic starch films doped with cellulose nanocrystals and aronia extract
858 for food spoilage detection. 4–6 (2024).
- 859 83. Marappan, G. *et al.* Natural Pigment-Based pH/Gas-Sensitive Intelligent Packaging Film
860 for Freshness Monitoring of Meat and Seafood: Influencing Factors, Technological
861 Advances, and Future Perspectives. *Food Rev. Int.* (2025)
862 doi:10.1080/87559129.2025.2473026.
- 863 84. Ingale, O. S. *et al.* A Review on Intelligent Packaging Systems Using Betalain-rich
864 Biobased Composite Films in Monitoring Freshness of Fish, Shrimp, and Meat. *Food*
865 *Bioprocess Technol.* **18**, 8154–8183 (2025).
- 866 85. Chen, C. *et al.* Effects of carotenoids on the absorption and fluorescence spectral properties
867 and fluorescence quenching of Chlorophylls a. *Spectrochim. Acta - Part A Mol. Biomol.*
868 *Spectrosc.* **204**, 440–445 (2018).
- 869 86. Janeeshma, E. *et al.* Modulations in Chlorophylls a Fluorescence Based on Intensity and
870 Spectral Variations of Light. *Int. J. Mol. Sci.* **23**, (2022).



- 871 87. Narayan, A., Misra, M. & Singh, R. Chlorophylls Fluorescence in Plant Biology. *Biophysics*
872 *(Oxf)*. (2012) doi:10.5772/35111.
- 873 88. Xue, W. *et al.* Smart fluorescent bio-inks for DIW 3D printing: real-time food freshness
874 sensors with dual-channel pH sensitivity. *Adv. Compos. Hybrid Mater.* **8**, (2025).
- 875 89. Herppich, W. B. Chlorophylls fluorescence imaging for process optimisation in horticulture
876 and fresh food production. *Photosynthetica* **59**, 422–437 (2021).
- 877 90. Kang, Y. R., Lee, Y. K., Kim, Y. J. & Chang, Y. H. Characterization and storage stability
878 of chlorophylls microencapsulated in different combination of gum Arabic and
879 maltodextrin. *Food Chem.* **272**, 337–346 (2019).
- 880 91. Zhang, Z. H. *et al.* Preparation and characterization of whey protein isolate-chlorophylls
881 microcapsules by spray drying: Effect of WPI ratios on the physicochemical and antioxidant
882 properties. *J. Food Eng.* **267**, 510640 (2020).
- 883 92. Rizzi, V. *et al.* Molecular interactions, characterization and photoactivity of Chlorophylls
884 a/chitosan/2-HP- β -cyclodextrin composite films as functional and active surfaces for ROS
885 production. *Food Hydrocoll.* **58**, 98–112 (2016).
- 886 93. Soltaninejad, H. *et al.* Antimicrobial Peptides from Amphibian Innate Immune System as
887 Potent Antidiabetic Agents: A Literature Review and Bioinformatics Analysis. *J. Diabetes*
888 *Res.* **2021**, (2021).
- 889



Data availability statementView Article Online
DOI: 10.1039/D5FB00637F

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

