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Food Technology

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REVIEW

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Cite this: DOI: 10.1039/d5fb00636h

Biodegradable polymer films incorporating aggregation-induced emission luminogens for smart food packaging

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Received 29th September 2025
Accepted 30th December 2025

DOI: 10.1039/d5fb00636h

rsc.li/susfoodtech

Packaging is essential for preserving food quality by protecting against microbial contamination and environmental factors such as oxygen, moisture, and light. Polymers are widely used for food packaging due to their versatility, low cost, and ease of processing. Over the past several decades, biodegradable polymer films have been extensively developed, either by using naturally derived polymers or by chemically modifying conventional polymers to enhance their environmental degradability. These advances have improved the sustainability of packaging and reduced the environmental impact associated with polymer use. More recently, the integration of aggregation-induced emission (AIE) luminogens into biodegradable polymer films has further enabled multiple functionalities, including real-time monitoring of food spoilage. This review highlights strategies for incorporating AIE into biodegradable polymer matrices, summarizes current progress, and discusses key challenges and future opportunities involved.

Sustainability spotlight

The convergence of biodegradable polymers and aggregation-induced emission (AIE) luminogens is redefining the future of food packaging by making materials not only environmentally friendly but also smart. Conventional packaging films, predominantly made from petroleum-based plastics, pose serious environmental challenges, due to their persistence in ecosystems. In contrast, biodegradable polymer films, derived from renewable resources or engineered for enhanced degradability, offer a sustainable alternative. These materials can break down under natural conditions, significantly reducing pollution and supporting circular economy principles. When AIE luminogens are integrated into biodegradable films, the resulting materials gain the ability to monitor food freshness through changes in luminescence signals triggered by spoilage-related chemical cues. This functionality empowers consumers and retailers to assess food quality directly, addressing two major sustainability challenges simultaneously: (i) plastic waste reduction through the use of biodegradable materials, and (ii) food waste mitigation *via* real-time spoilage detection and freshness monitoring. By combining degradability with smart functionality, AIE-incorporating packaging films exemplify how materials innovation can drive sustainability in everyday applications while making food packaging smarter and more eco-conscious.

1. Background

Packaging helps prolong the freshness of food and reduces quality loss during storage and distribution.[1–3] Nearly all food items available in the marketplace are enclosed within some form of packaging, which functions as a protective barrier against microbial invasion and harmful environmental factors, including oxygen, moisture, and light.[4,5] Among the wide variety of materials employed for packaging, polymers have gained the most extensive use.[6–9] Their popularity stems from the fact that, compared with alternatives such as glass or wood, polymer-based materials offer far greater adaptability in both structure and functionality.[10] Their characteristics can also be modified with relative ease to suit the specific requirements of diverse food packaging applications.[11–13] Polymer packaging can be fabricated into an array of shapes and sizes, and many types possess added advantages, being heat-sealable and suitable for microwave heating.[14,15] Another attractive feature is their potential transparency, which enables consumers to view the packaged product directly, thereby enhancing market appeal and supporting product design strategies.[16–18] Combined with their light weight, low production cost, and ease of surface printing,[19] polymers have become an indispensable class of food packaging materials.

In the context of developing food packaging films, synthetic polymers represent one of the most extensively utilized groups of polymer materials for film production. Some of their advantages include low cost, excellent mechanical strength, durability, and good barrier properties.[20] However, synthetic polymers may also present drawbacks, including non-biodegradability, and reliance on non-renewable petroleum resources,[21] which raise environmental concerns. Another important category of polymers used in film fabrication is

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natural polymers, which are valued for their abundance and sustainability.[22,23] Their utilization helps decrease dependence on petroleum-based resources and alleviates environmental pollution.[22] Examples of natural polymers employed in film production include proteins,[24–26] starch,[27–30] pectin,[31–34] chitosan,[35–38] alginate,[34,39,40] and cellulose.[41–44] Compared with many synthetic polymers, they are more environmentally friendly, and are more preferable options for sustainable food packaging applications.[45–47] In this article, recent advances in the development of biodegradable polymer films, particularly those integrated with aggregation-induced emission (AIE) features, for smart food packaging are discussed, with key challenges and future opportunities in this emerging field also outlined.

2. Fundamentals of aggregation-induced emission and its relevance to food packaging

Conventional smart packaging systems often employ small-molecule dyes, enzyme substrates,[48] or electroactive compounds to provide a detectable signal in response to specific stimuli. While these agents can be incorporated into multifunctional packaging architectures, their intrinsic role is generally limited to indication or sensing. In contrast, many AIE luminogens explored for food packaging could exhibit additional bioactivities, such as antibacterial or antioxidant properties, depending on molecular structure and formulation. This intrinsic multifunctionality at the molecular level suggests the potential to integrate sensing and active packaging functions within a single film. AIE is a phenomenon whereby certain molecules (ranging from metal nanoclusters[49,50] to naturally occurring flavonoids such as epigallocatechin gallate[51] and kaempferol[52]) exhibit a pronounced enhancement of luminescence upon aggregation.[53–55] Over the years, AIE luminogens have been explored in diverse applications.[56–60] For instance, the luminogen synthesized by condensing equimolar amounts of 2-hydroxy-1-naphthaldehyde and 3-hydroxy-2-naphthohydrazide has been examined for detection of sparfloxacin and azithromycin;[56] whereas the one consisting of a tetraphenylethylene-ethylene-benzimidazole π-conjugated backbone has been adopted for monitoring the concentration and structural transition of human serum albumin.[61] Since the beginning of this century, efforts to explore the application potential of AIE have increasingly extended into the field of food science. One example was the pH-sensitive probe developed by incorporating a pH-responsive *N*-alkylated indole moiety onto an AIE-active tetraphenylethylene (TPE) core.[62] The probe's fluorescence intensity showed a clear linear correlation with pH over the range of 5.8–8.8.[62] Upon further pH increase, the probe displayed a turn-off response, accompanied by the fading of the solution's light magenta color.[62] Such behaviour suggested its possible use in food safety applications, where monitoring pH changes or spoilage metabolites can help assess food quality and shelf-life.

Given that milk and other dairy products experience a decline in pH upon microbial contamination,[63,64] and that seafood and meat products can generate volatile amines during spoilage, leading to an increase in pH,[65–67] AIE-active probes capable of detecting pH fluctuations are of practical value. In general, AIE luminogens can be categorized into two types: natural luminogens and synthetic luminogens. The former include berberine,[68] kaempferol,[52] jatrorrhizine,[69] mangiferin[70] and palmatine;[71] while the latter encompass metal nanoclusters,[72] siloles,[73] TPE derivatives[74] and triphenylamine derivatives.[75] Both natural and synthetic AIE luminogens have distinct advantages and limitations for applications, which are summarized in Table 1. To date, several mechanisms have been proposed to account for AIE in different organic systems, including the suppression of nonradiative decay pathways,[76] restriction of intramolecular motion,[77] excited-state intramolecular proton transfer,[78] inhibition of E-Z isomerization processes,[49] and restricted access to conical intersections.[79] In contrast to conventional luminogens, which frequently experience aggregation-caused quenching (ACQ) in the solid state,[80–82] AIE luminogens display enhanced fluorescence upon aggregation and demonstrate good photostability.[83] This renders AIE luminogens favourable for real-world use, as it ensures reliable and long-lasting performance under prolonged exposure to light.

Practically, the use of AIE materials enables the incorporation of the sensing functionality into food packaging films (Table 2).[84–98] In addition, some AIE luminogens (*e.g.*, berberine, and quercetin) contain aromatic moieties and/or phenolic hydroxyl groups. This renders them capable of absorbing ultraviolet (UV) light at defined wavelengths to improve the UV-shielding performance of food packaging systems.[88,99,100] Numerous AIE materials obtained from nature also exhibit various bioactivities, ranging from antioxidant capacity to antibacterial properties. For example, the AIE-active packaging film incorporating self-assembled berberine-cinnamic acid nanoparticles exhibits notable mechanical strength and demonstrates strong antibacterial activity against *Escherichia coli* and *Staphylococcus aureus*,[88] with the AIE effect contributing

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Table 1 Pros and cons of different types of AIE luminogens used in food packaging

Type	Pros	Cons
Natural AIE luminogen	• Typically non-toxic and environmentally friendly, making them suitable for biomedical and food-related applications • Derived from biomass or widely available natural products, supporting sustainable sourcing • Some possess additional bioactivities (*e.g.*, antioxidant and antimicrobial activities) beyond luminescence • Align with green chemistry principles and circular economy goals • Certain natural compounds may benefit from existing safety data, facilitating regulatory approval	• Natural extracts often contain complex mixtures, making it difficult to isolate uniform AIE-active species • Photophysical properties (*e.g.*, emission wavelength and quantum yield) are harder to fine-tune compared to synthetic analogues • Susceptible to degradation under pH changes, enzymatic activity, or oxidative stress • Source variability and processing conditions can affect reproducibility and performance
Synthetic AIE luminogen	• Molecular structures can be precisely engineered to control emission color, intensity, and lifetime • Often exhibit higher quantum yields, longer lifetimes, and stable emission under diverse conditions • Easily functionalized for targeted applications such as sensing, imaging, and optoelectronics • Chemical synthesis yields uniform products with predictable properties • Tunable emission profiles enable simultaneous detection of multiple targets	• Some synthetic AIE luminogens may be cytotoxic and non-degradable • Synthesis may involve hazardous reagents, organic solvents, or energy-intensive processes • Complex synthetic routes can increase production costs, especially for large-scale applications

to enhanced antimicrobial performance through reactive oxygen species (ROS) generation. This extends existing research on intelligent food packaging by incorporating active food protection concepts. In general, packaging films incorporating AIE materials provide sensitive optical signals for real-time monitoring of food quality. Along with their high photostability, packaging films incorporating AIE luminogens are expected to exhibit high durability and consistent performance throughout the product's shelf life.

3. Strategies for fabricating AIE-active food packaging films

In most reported studies, AIE luminogens are incorporated into biodegradable polymer films by blending them with the film-forming solution before the film is produced. This approach is compatible with the process of solution casting. One example of AIE luminogen-incorporating films generated by this method was reported by He and coworkers,[101] who mixed a quercetin solution in a tetrahydrofuran (THF)–water mixture with an aqueous poly(vinyl alcohol) (PVA) solution to produce a smart food packaging film. The film exhibited excellent mechanical properties as well as favourable water and CO_2 permeability.[101] Its optical characteristics were evaluated using ultraviolet-visible (UV-vis) and fluorescence spectroscopy. The prepared film was transparent and demonstrated pronounced AIE enhancement upon contact with foods containing Al^{3+} residues or with seafood producing biogenic amines during spoilage.[101]

Another example of directly mixing AIE luminogens with the film-forming solution during fabrication was provided by Ma and coworkers,[88] who loaded self-assembled berberine-cinnamic acid nanoparticles (BC NPs) into a biodegradable polymer film. During film preparation, solutions of cinnamic acid and berberine chloride hydrate were first adjusted to neutral pH and then combined. The resulting mixture was gradually added to heated water under vigorous stirring and maintained under continuous stirring for several hours to obtain a stable BC NP solution. The nanoparticles were then incorporated into a film-forming solution containing gelatin, κ-carrageenan, and glycerol. After defoaming, the film-forming solution was cast in clean Petri dishes and dried in desiccators to produce a solution-cast film. More recently, the AIE luminogen 3-(3-(benzo[*d*]thiazol-2-yl)-2-hydroxyphenyl)-2-(4′-(diphenylamino)-[1,1′-biphenyl]-4-yl)acrylonitrile (BTPA) was also incorporated into an electrospun film for the detection of CN^- ions in food samples such as sprouting potatoes and cassava roots.[102] Because luminogen incorporation and film formation can be achieved in a single step, the overall production process is simplified. Direct mixing can facilitate uniform dispersion and straightforward fabrication, making the method applicable to a wide range of polymer matrices. However, depending on polymer-luminogen compatibility and processing conditions, this one-step approach may also lead to aggregation or uneven luminogen distribution, and the final optical properties can be influenced by polymer–luminogen interactions or residual solvents.

Table 2 Functional properties of AIE luminogens relevant to food packaging applications

Property	Description	Underlying principle	Example	Ref.
Antioxidant activity	Help prevent oxidative degradation in food products	Certain AIE-active molecules possess phenolic or conjugated structures that scavenge free radicals	PVA films loaded with natural AIE luminogens (*viz.*, gallic acid and quercetin) showed substantial antioxidant activity	84
			Polylactide-based films containing berberine and quercetin displayed radical scavenging activity and could preserve the freshness of blueberries	85
			The poly(lactic acid)/gelatin bilayer film incorporated with epigallocatechin gallate exhibited 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging activity, which increased with higher epigallocatechin gallate content	86
			The cassia gum/quercetin composite film was more effective at delaying pork lard oxidation than the commercially available high-density polyethylene film	87
Antimicrobial activity	Used to inhibit or kill microorganisms, contributing to food safety	AIE luminogens can be functionalized with cationic or hydrophobic groups that disrupt microbial membranes. Some AIE luminogens also generate reactive oxygen species (ROS) under light, enhancing antimicrobial effects	Packaging films containing AIE-active berberine-based nanoparticles exhibited strong antibacterial activity against both *E. coli* and *S. aureus*	88
			The agar-based photodynamic sterilization film doped with an AIE luminogen possessing a D–π–A structure was found to have good inhibitory effects on *E. coli*, *S. aureus*, *C. albicans*, *A. baumannii*, *P. aeruginosa,* and *P. leiognathi*	89
			The gelatin-based film incorporating AIE-active self-assembled berberine–3,4,5-methoxycinnamic acid nanoparticles utilized sunlight to generate ROS, leading to the inactivation of *Staphylococcus aureus* and an extension of the shelf life of pork loin	90
			The κ-carrageenan/carboxylated cellulose nanofibril film incorporating an AIE-active berberine–citric acid salt showed photodynamic antibacterial activity, effectively killing bacteria from cooked chicken under white light	91
Ultraviolet screening capacity	Protect photosensitive food components or ingredients	AIE luminogens with extended π-conjugation or	Packaging films prepared by incorporating AIE-active self-	92

Table 2 (*Contd.*)

Property	Description	Underlying principle	Example	Ref.
	from UV-induced damage by blocking UV light	aromatic rings can absorb UV light efficiently. This enables them to show UV-blocking performance while maintaining visible fluorescence for dual functionality	assembled berberine-cinnamic acid nanoparticles into gelatin, κ-carrageenan, and glycerol matrices exhibited enhanced UV-shielding capacity relative to films lacking the nanoparticles	
			Chitosan–riboflavin composite films showed strong UV barrier properties while maintaining a transparent yellow appearance	93
			Introducing berberine enhanced the UV-shielding capability of starch/PVA composite films	94
			The epigallocatechin gallate/hydroxypropyl methylcellulose film was reported to act as an effective UV filter, blocking both UV-B and UV-A radiation	95
Sensing capacity	Serve as visual or fluorescent sensors to detect spoilage	AIE luminogens exhibit fluorescence "turn-on" behaviour upon aggregation triggered by specific analytes	An AIE-active fluorescent probe exhibited a large emission wavelength shift in response to H_2S, enabling it to be used for ratiometric monitoring H_2S when detecting the beef and shrimp freshness	96
			The AIE-active, ammonia-responsive sensor film, prepared on bacterial cellulose, enabled real-time visual monitoring of chicken freshness by detecting amine vapours, with a distinct color change from red to blue-green visible to consumers	97
			2-(benzo[*d*]thiazol-2-yl)-4-hydroxy-7-methylphthalazin-1(2H)-one exhibited changes in AIE in response to biogenic amines and was applied for real-time, visual monitoring of pork and shrimp freshness	98

An alternative to solution casting is melt extrusion. The feasibility of using this approach to generate AIE-active films was demonstrated in the production of poly(butylene adipate-co-terephthalate) (PBAT) films incorporating a quercetin-grafted epoxy chain extender.[103] During processing, PBAT and the modified chain extender were premixed at various ratios and compounded using a twin–screw extruder. The resulting composites were then pelletized and dried, after which the films were formed using a single-screw film blower. Compared with solution casting, which has a relatively slow processing rate and raises potential concerns related to residual solvents that may limit industrial use, melt extrusion provides a continuous and solvent-free method for film production. However, the higher processing temperatures in melt extrusion can cause thermal quenching or degradation of heat-sensitive AIE luminogens, whereas solution casting allows film formation under mild conditions that help minimise thermal degradation. Overall, the choice between solution casting and melt extrusion reflects a balance between molecular level control and industrial scalability.

Besides being incorporated directly into the packaging films, AIE luminogens can also be embedded into a separate tag which is then attached to a food package for sensing purposes. A good example is the use of the AIE luminogen, 6,7-dimethyl-2-buthy-2,3-dimethphenyl-1,2-dihydroquinoxaline (H^+DQ2), in food packaging to monitor spoilage in shrimps.[104] During package fabrication, polydimethylsiloxane (PDMS)-coated filter paper served as a hydrophobic base layer for depositing the AIE indicator. Shrimp were placed in a bowl-shaped container made of biodegradable polylactic acid (PLA) and subsequently sealed with a PBAT film. A label with adhesive was attached to the inside of the PBAT film, with the H^+DQ2 indicator positioned at the centre for monitoring seafood spoilage. This approach avoids compromising the mechanical strength, barrier properties, and transparency of the packaging film. In addition, as the tag can be designed to be modular, replaceable, or disposable, this allows flexibility in the use of the tag in different packaging systems. Despite the advantages mentioned above, as the sensing area is restricted to the tag itself, this may limit overall sensitivity if analyte diffusion from the food to the tag is slow.

4. Applications in smart food packaging

Over the past decade, packaging films incorporating AIE luminogens have transitioned from theoretical concepts to experimentally validated systems, demonstrating applicability across a diverse range of food products, from fruits to seafood. As delineated in proceeding sections, the restriction of intramolecular motion in aggregated or confined states enables strong solid-state fluorescence when AIE luminogens are embedded in films. The emission of AIE luminogens is often sensitive to environmental factors (such as pH, biogenic amines, or gases associated with food spoilage) which influence molecular interactions, making them suitable as indicators in smart food packaging. In some cases, such as naturally derived berberine–baicalin nanocomposite films,[105] the aggregated luminogens also act as photosensitizers under light irradiation, producing ROS that confer photodynamic antibacterial activity. Thus, while AIE itself does not inherently confer antibacterial properties, the aggregated state can enable additional functionalities, giving the resulting films potential for multifunctional applications (*viz.*, combining sensing and antimicrobial properties) and providing real-time, reliable indicators of food quality.

4.1 Packaging of animal-derived perishable foods

Seafood is one of the animal-derived foods that are highly susceptible to microbial growth and biochemical degradation.[106] Packaging strategies that enable real-time monitoring of freshness are, therefore, of significant interest.[107] Such approaches can help reduce food waste, enhance consumer confidence, and ensure safety across the supply chain. In an earlier study, shrimps were packaged in a PLA tray sealed with a PBAT film containing an H^+DQ2-based tag to monitor spoilage (Fig. 1).[104] By using ammonia vapor as a model analyte, the indicator was found to be activated by ammonia vapor at a concentration as low as 1.3×10^4 mg m^{-3}, with the photoluminescence (PL) intensity of the indicator increasing with rising concentrations of ammonia vapor.[104] This suggested that it had high sensitivity toward biogenic amines. This behaviour is mediated *via* the deprotonation of the imine group in H^+DQ2 by ammonia, which suppresses the molecule's intramolecular charge transfer (ICT) process. Consequently, the indicator exhibits both a visible color change and fluorescence activation.[104] These dual responses allow the indicator to provide a visual signal under both daylight and UV light. In the shrimp package, the indicator's color change (from red to yellow) and fluorescence activation closely corresponded with the increase in total volatile basic nitrogen (TVB-N, from 10.52 mg/100 g to 31.03 mg/100 g) and colony-forming units (from 4.4 log CFU g^{-1} to 6.5 log CFU g^{-1}) of packaged shrimp samples stored at 4 °C for five days.[104] This smart packaging system enables real-time, highly sensitive detection of seafood spoilage. The possible use of AIE luminogen-incorporating film to package seafood has also been demonstrated by the case of the quercetin-loaded PVA film, which was employed as a smart packaging material to detect biogenic amines released from packaged salmon.[101] When placed inside a sealed salmon package, the film exhibited a marked increase in AIE at room temperature over an 8-hour period, corresponding to the accumulation of biogenic amines as the fish began to spoil, while a much weaker response was observed at 5 °C.[101] This behaviour demonstrates the film's potential for tracking storage conditions and offers a straightforward visual approach to evaluate the freshness and safety of perishable food products.

More recently, Yang and coworkers created a smart packaging film capable of dual colorimetric and fluorescent detection of biogenic amines by incorporating berberine together with β-cyclodextrin-encapsulated betaine into a corn amylose framework.[108] When exposed to increasing alkalinity, the film exhibited both a visible color transition and an intensified blue–green fluorescence.[108] The observed color variation stemmed from structural rearrangements in betaine, whereas the fluorescence enhancement was linked to contributions from both berberine and encapsulated betaine. At neutral pH, spectral overlap occurred between the UV absorption band of betaine and the fluorescence emission band of berberine.[108] This overlap promoted reabsorption, leading to a quenching of berberine's inherent fluorescence.[108] Under alkaline conditions, however, structural modification of betaine shifted its absorption band, thereby preventing the overlap and enabling berberine to restore its fluorescence output.[108] When applied to shrimp packaging, the film displayed a distinct color shift from red to yellow and simultaneous fluorescence amplification during storage, effectively allowing visual and optical tracking of shrimp freshness.[108] These sensing responses were consistent with conventional freshness assessment *via* TVB-N measurements.[108] Although berberine alone did not provide a direct response signal under alkaline conditions,

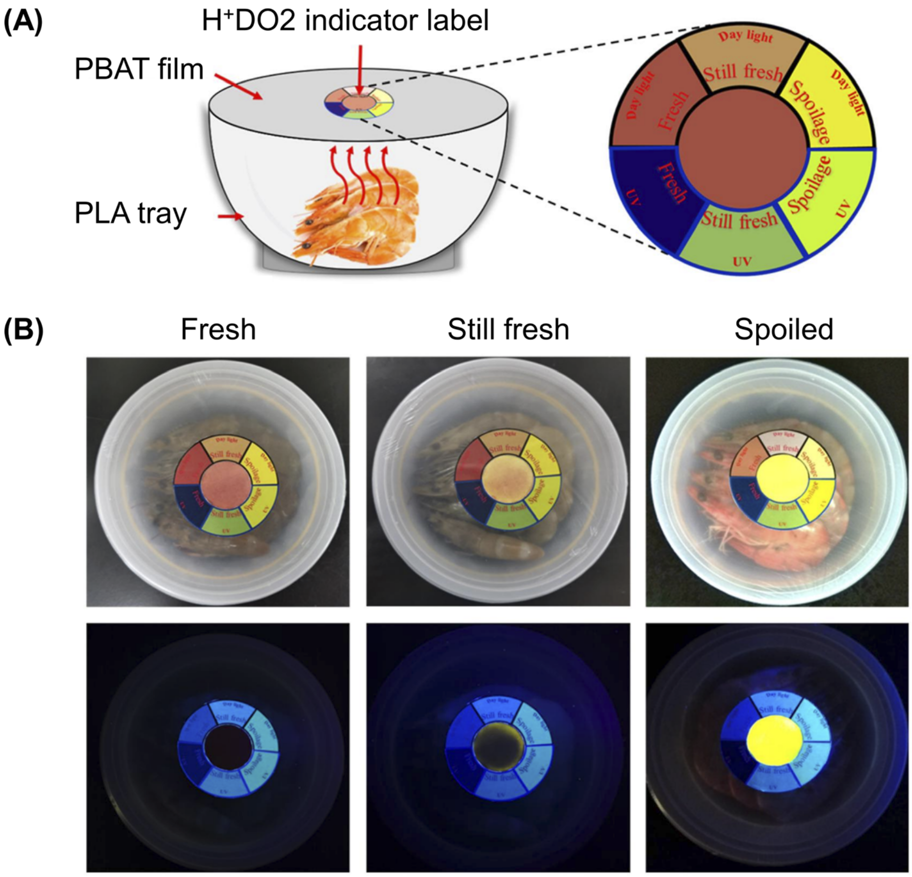

Fig. 1 (A) Schematic illustration of the biodegradable package designed for shrimp packaging. (B) Photographs of the package under daylight and UV light at 28 °C. Reproduced from ref. 104 with permission from Elsevier B.V.

its AIE properties, when integrated with the pH sensitivity of other indicators, enabled the construction of smart packaging capable of signalling food freshness through fluorescence.

In addition to the direct use of films incorporating AIE luminogens, tags loaded with AIE-active probes have also been employed in food packaging. One good example is a tag constructed from an AIE-active polymer, prepared by combining the stimuli-responsive polymethacrylic acid (PMAA) with the AIE-active molecule tetraphenylethylene (TPE), and deposited onto filter paper with rhodamine B (RhB) as an internal reference (Fig. 2).[107] The resulting tag was suitable for direct attachment to individual food packages. Its practical utility lies in enabling both retailers and consumers to assess salmon freshness using a portable UV light source or even a handheld UV flashlight.[107] Freshness was visually evaluated by comparing the fluorescence of the indicator region with the reference signal. As spoilage progressed, the fluorescence of the sensing label underwent a distinct color shift from pink (fresh) to purple (slightly spoiled) and finally to blue (spoiled).[107] This fluorescence transition arises from the ratiometric nature of the probe. Initially, the pink emission resulted from strong RhB fluorescence combined with weak TPE fluorescence.[107] As the fish deteriorated, biogenic amines released during spoilage protonated the PMAA backbone to varying extents, promoting aggregation of the TPE moieties.[107] This aggregation enhanced the blue emission of TPE, gradually dominating the fluorescence output and shifting the overall signal from pink to blue.

To validate the responsiveness of the sensing label, three representative amines commonly produced during salmon spoilage—trimethylamine, dimethylamine, and ammonia—were tested. The sensing label demonstrated rapid response kinetics, with color changes from pink to purple occurring within 2 h for trimethylamine and dimethylamine, while ammonia elicited a delayed response of approximately 3 h.[107] This variation is attributed to differences in the basicity of the amines. The selectivity of the sensing label was further examined using volatile compounds likely to be present in fish headspace, such as ethyl hexanoate, phenylethanol, and phenylacetaldehyde. Negligible interference was observed, and the fluorescence signal remained stable throughout testing.[107] Collectively, these results confirmed that the TPE/PMAA/RhB-based sensing label was a promising candidate for real-time, selective, and stable monitoring of fish freshness.

In addition to seafood, AIE has been applied in smart packaging of poultry products. This was demonstrated by an earlier study,[88] in which self-assembled BC NPs were adopted as AIE luminogens for packaging fresh chicken meat. The AIE characteristics of the nanocomposite films were evaluated using fluorescence spectroscopy, with emission spectra recorded under excitation at 405 nm. The photoluminescence intensity increased

Fig. 2 Schematic layout of the sensing label (left) and demonstration of its application in salmon samples (right). Reproduced from ref. 107 with permission from Elsevier B.V.

as the BC NP content in the films was raised.[88] BC NPs can also act as photosensitizers, with aggregation enhancing their excited-state lifetime and fluorescence quantum yield. Upon light excitation, these nanoparticles transferred energy to molecular oxygen, generating ROS. This rendered the film antibacterial in nature. For this, fresh chicken packaged with the NP-containing film was found to have a total bacterial count much lower than that wrapped in the plain film.[88] Although the AIE luminogen was not exploited for sensing applications in this study, the NP-containing film still demonstrated potential as an antibacterial packaging material capable of extending the shelf life of meat products.

4.2 Packaging of plant-based perishable foods

Bakery products are plant-based foods that are highly perishable due to their moisture content and susceptibility to microbial growth and staling. Effective packaging is therefore essential to extend shelf life and reduce food waste. In an earlier study, an AIE-active quercetin-loaded PVA film was adopted to package bakery products.[101] When the film was applied to freshly purchased deep-fried dough sticks and steamed buns, an AIE response was observed; however, the fluorescence enhancement was particularly pronounced with the deep-fried dough sticks.[101] This was partly because of the use of aluminium-based leavening agents during dough stick preparation. These agents helped create the porous texture and crispiness of the sticks when they decomposed during frying, causing the dough to expand. Residual Al^{3+} ions in the deep-fried dough sticks could then be detected by the film, leading to the observed AIE enhancement. In contrast, steamed buns were often leavened with yeast or baking powder that did not contain aluminium salts, resulting in much lower Al^{3+} content and, consequently, a weaker fluorescence signal. This variation in the intensity of AIE signals exhibited by the film suggested that the packaging film enabled on-site detection of Al^{3+} ions in the packaged food.

Apart from packaging bakery products, the film was also applied as a coating for various fruit products (*viz.*, bananas and apple slices), which are known to face rapid quality degradation due to microbial activity, enzymatic changes, and moisture loss (Fig. 3).[101] Upon coating, the apple slices remained visually fresh without significant browning after two hours; whereas the uncoated slices quickly developed the characteristic brown discoloration associated with enzymatic oxidation. A similar trend was observed with bananas. Coated bananas maintained their bright yellow peel and showed no signs of blackening or spoilage after five days of storage, while the uncoated ones exhibited significant darkening and decay over the same period. The ability of the coating to retard the spoilage of fruits is due to its antibacterial and antioxidant activities.[101] Such activities come from the radical-scavenging ability of quercetin,[101] and the capacity of quercetin in reducing the bacterial cell biofilms and hence altering their structures, causing inhibition of both Gram-positive and Gram-negative bacteria.[101] Although fruits contain lower levels of free amino acids compared with protein-rich foods such as seafood, biogenic amines can still be generated during fruit decay. While the AIE responses of quercetin in this context have not been extensively investigated, the quercetin-loaded PVA film has already been shown to exhibit pronounced AIE changes upon detecting biogenic amines in seafood.[101] Further research is therefore warranted to evaluate whether the film's AIE response is sufficiently sensitive to detect biogenic amines released by decaying fruits.

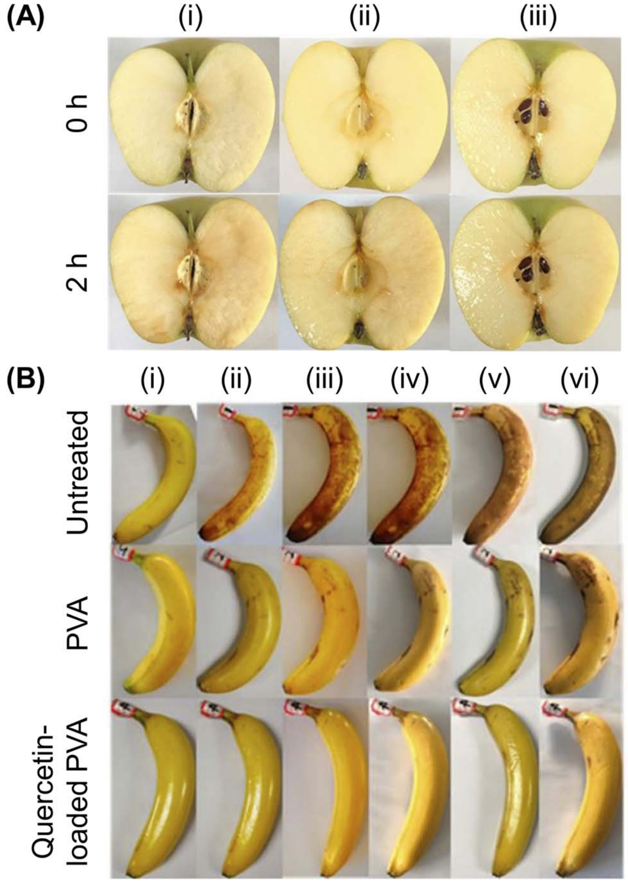

Fig. 3 (A) Images of apple slices at 0 h and 2 h under different treatments: (i) uncoated, (ii) coated with PVA, and (iii) coated with quercetin-loaded PVA. (B) Images of bananas under different treatments—uncoated, coated with PVA, and coated with quercetin-loaded PVA—at various time points: (i) day 0, (ii) day 1, (iii) day 2, (iv) day 3, (v) day 4, and (vi) day 5. Reproduced from ref. 101 with permission from American Chemical Society.

5. Performance optimization and practical considerations

The color and taste characteristics of AIE luminogens warrant careful consideration. Certain luminogens, including riboflavin[93] and quercetin,[109] can impart coloration to food packaging films when incorporated, potentially diminishing both the visual appeal and transparency of the packaging. In addition, some AIE luminogens, such as quercetin, possess a naturally bitter flavour.[110,111] If these compounds migrate into the food product, they may alter its sensory properties and negatively influence consumer acceptance. Importantly, not all AIE luminogens are suitable for human consumption. Migration from packaging into food could result in unintended oral exposure, which may pose health risks such as bioaccumulation and adverse metabolic effects.[112] From a regulatory perspective, AIE luminogens incorporated into food packaging films would fall under existing frameworks governing food-contact substances. In the European Union, Regulation (EC) No 1935/2004 requires that substances used in food-contact plastics do not migrate into food at levels that could endanger human health,[113] necessitating migration testing and toxicological evaluation for non-listed compounds. Similarly, in the United States, AIE luminogens would be regulated as indirect food additives under the FDA Food Contact Notification system.[114] While several AIE luminogens reported to be used in food packaging films are derived from naturally occurring polyphenols (*e.g.*, berberine[115] and quercetin[101,116]), for which safety data in food or nutraceutical contexts are available, toxicological data for many synthetic AIE luminogens reported in the literature remain absent. In general, the safety of AIE luminogens in food-contact applications depends critically on their chemical structure and the extent of their migration into food matrices. The major advantages and limitations of incorporating AIE luminogens into food packaging films are summarized in Table 3. Regardless of the origin of the AIE luminogens involved, comprehensive migration studies, long-term toxicological evaluations, and sensory impact analyses are required before AIE-based food packaging films can be translated from laboratory studies to practical applications.

In addition to the points discussed above, incorporating AIE luminogens into biodegradable polymer films can markedly affect film properties. For instance, the added luminogen may alter the mechanical, barrier, and thermal characteristics of the film.[117,118] Depending on its dispersion and compatibility within the polymer matrix, it can either enhance or reduce tensile strength and flexibility, modify gas and moisture permeability, and influence surface properties such as roughness and hydrophobicity. In addition to these physical effects, the concentration of the luminogen also plays a critical role in determining the film's optical performance. Excessive loading can lead to aggregation beyond the optimal level, which may reduce fluorescence efficiency, compromise transparency, or negatively impact mechanical integrity. Conversely, insufficient incorporation may yield suboptimal AIE emission, limiting the functional utility of the film. Therefore, careful optimization of the amount of the luminogen introduced into the polymer matrix is essential to achieve a balance between desirable film properties and strong AIE performance. Finally, most studies on AIE-based smart food packaging to date remain proof of concept. Direct comparison across reported systems is limited, with quantitative performance metrics (such as sensitivity thresholds and response times) for the generated films being particularly scarce. Future research should aim to quantify these parameters under standardized conditions to enable rigorous evaluation and practical application.

While the focus of this article is on AIE, there is another related yet mechanistically distinct phenomenon that also involves emission enhancement upon aggregation and is worth noting. It is called clusteroluminescence, which occurs in polymers containing electron-rich or heteroatomic moieties such as carboxylate, amide, and amine groups.[119] These groups can interact through space, leading to emission in the visible light region.[120–122] One property of clusteroluminogenic polymers, akin to AIE luminogens, is their lack of luminescence at low concentrations in solution. Emission appears only upon molecular clustering.[123,124] In addition, the wavelength of the

Table 3 Major advantages and limitations of incorporating AIE luminogens into food packaging

Domain	Advantage	Limitation
Manufacturing feasibility and scalability	AIE luminogens demonstrate strong photostability, minimizing fading over time and enabling reliable monitoring throughout the shelf life of packaged products	AIE luminogens are not yet widely available at low cost, and their integration into packaging at industrial scale may be more expensive than conventional dyes and sensors
Photophysical behaviour in solid-state environments	AIE luminogens exhibit enhanced brightness upon aggregation, unlike conventional dyes that suffer from ACQ. This makes them well-suited for the polymer-rich environments of packaging films	Incorporating AIE luminogens into films requires precise formulation to maintain their functionality and avoid adverse effects on mechanical or optical properties
Functional tunability and responsiveness	AIE luminogens can be chemically tailored to respond to stimuli (*e.g.*, pH changes and volatile organic compounds), allowing targeted detection of food deterioration	Some AIE luminogens may lack biodegradability or recyclability, posing sustainability concerns for large-scale use in disposable packaging
Suitability for food safety monitoring	AIE luminogens activate fluorescence only upon aggregation, reducing background signals and enabling clearer detection of spoilage indicators such as ammonia and hydrogen sulphide	Materials intended for food contact are subject to stringent safety regulations. Novel AIE-based systems may require extensive testing and regulatory approval, potentially delaying adoption
Real-time detection and consumer interaction	Fluorescence or color changes can be observed visually, making them accessible and user-friendly indicators of freshness	Without proper consumer education, fluorescent or color-changing packaging may cause confusion or concern, potentially limiting market acceptance
Compatibility with packaging systems	AIE luminogens can be embedded into polymers, coatings, or labels without loss of function. When combined with nanomaterials, they may also enhance barrier or antimicrobial properties	Many AIE luminogens are synthetic organic compounds or metal complexes, and their safety in direct or indirect food contact is not fully established. Risks of migration or leaching must be addressed before commercialization

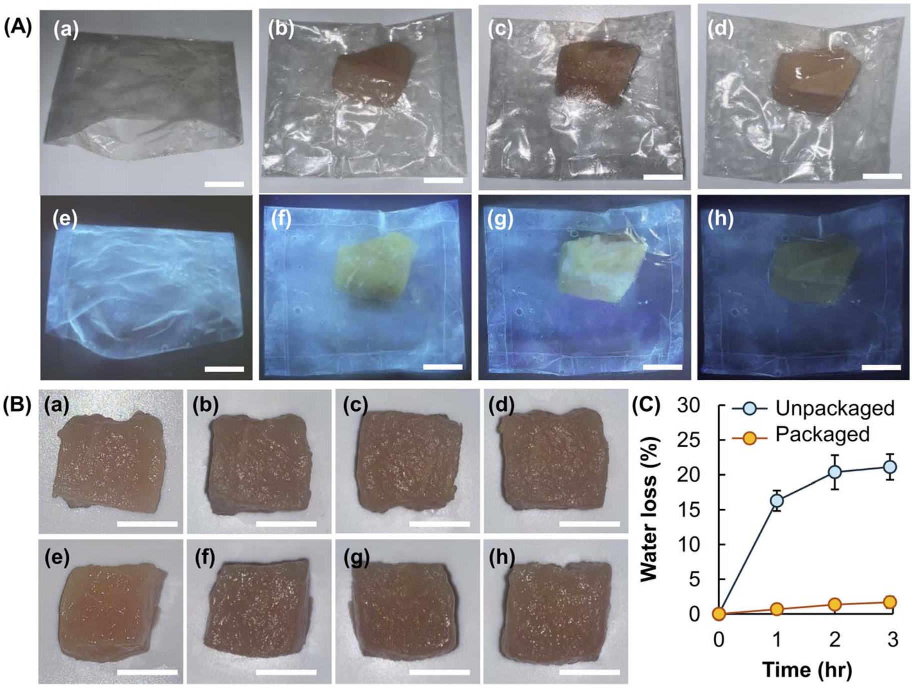

Fig. 4 (A) Photographs of (a and e) a bag made from the clusteroluminogenic cellulose derivative, and the bags containing (b and f) fresh chicken meat, (c and g) frozen chicken meat, and (d and h) thawed frozen chicken meat, shown under (a–d) white light and (e–h) UV light. Scale bar = 1 cm. (B) Photographs of chicken meat (a–d) packaged in, or (e–h) not packaged in, a bag made from the clusteroluminogenic cellulose derivative, after (a and e) 0 h, (b and f) 1 h, (c and g) 2 h, and (d and h) 3 h. Scale bar = 1 cm. (C) Time-dependent changes in the water content of chicken meat with and without packaging in the bag made from the clusteroluminogenic cellulose derivative. Reproduced from ref. 127 with permission from John Wiley & Sons, Inc.

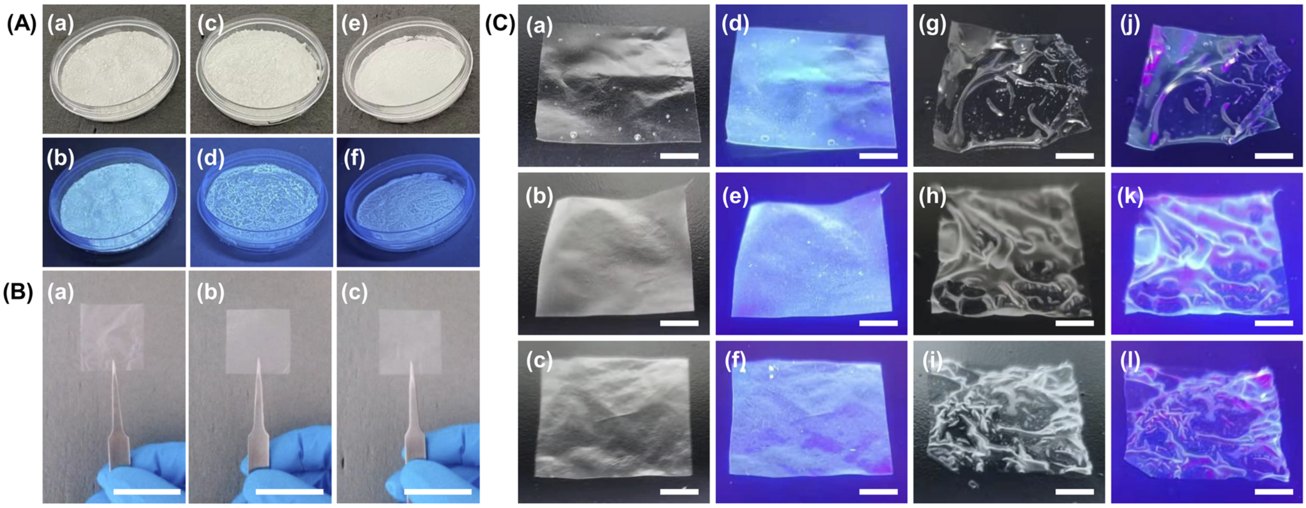

Fig. 5 (A) Photographs of starch samples: (a and b) water chestnut starch (WS), (c and d) maize starch (MS), and (e and f) potato starch (PS) under (a, c and e) white light and (b, d and f) UV light ($\lambda = 365$ nm). (B) Images of films prepared from (a) WS, (b) MS, and (c) PS. Scale bar = 5 cm. (C) Photographs of the films: (a, d, g and j) WS film, (b, e, h and k) MS film, and (c, f, i and l) PS film, captured under (a, b, c, g, h and i) white light and (d, e, f, j, k and l) UV light ($\lambda = 365$ nm). Scale bar = 1 cm. Reproduced from ref. 130 with permission from MDPI.

emission is excitation wavelength-dependent, with longer excitation wavelengths leading to progressively red-shifted emission.[125,126] Importantly, unlike AIE luminogen-loaded films where the incorporated luminogen may migrate into the packaged food and raise safety concerns, clusteroluminogenic polymers themselves can form films with intrinsic AIE-like properties suitable for direct application in smart food packaging.

The feasibility of this approach was corroborated in a previous study,[127] in which packaging films were fabricated from a cellulose derivative. The derivative was synthesized *via* hydroxypropylation and methylation of cellulose, followed by transesterification in a polar aprotic solvent. UV-vis analysis showed that all films were optically transparent, exhibiting a transmittance of approximately 60–85% across the visible spectrum (400–700 nm), while simultaneously demonstrating UV-blocking capability in both the UVA (320–400 nm, long-wavelength) and UVB (280–320 nm, short-wavelength) regions, with a UV block factor ranging from 1.05 to 1.24. As a result, these films significantly reduced UV transmission, and helped mitigate UV-induced degradation of packaged food. Furthermore, both the concentration and molecular weight of the cellulose derivative used in film fabrication were positively correlated with the films' luminescence intensity and also influenced their wettability and permeability. This concentration- and molecular weight-dependent modulation of luminescence endowed the films with self-indicating capability, enabling their optical response to reflect their barrier properties. The films were further applied to the packaging of chicken breast, an especially perishable product sensitive to repeated freeze–thaw cycles during storage and transport.[128,129] It was observed that the luminescence intensity of the packaging remained stable when fresh or frozen chicken was placed inside (Fig. 4). However, upon thawing of the frozen chicken meat, the exudate released caused the film to swell, resulting in a decrease in clusteroluminescence intensity. This change in luminescence serves as a visual indicator, signalling that the frozen food has thawed.

Similar to the cellulose derivative described above, starch was also used to produce smart food packaging films that exhibited clusteroluminescence.[130] The clusteroluminogenic properties of starch films derived from different botanical sources (*e.g.*, water chestnut, maize, and potato) varied (Fig. 5).[130] This was attributed to differences in the intrinsic properties of the starches (such as molecular weight, degree of branching, and amylose-to-amylopectin ratio) which influenced molecular entanglement and, consequently, clusteroluminescence.[130] These films demonstrated a dual capacity to indicate their barrier properties and to detect the thawing of packaged frozen food. Recently, chitosan-based composite films derived from clusteroluminogenic polymers were reported to possess self-indicating capabilities, enabling visualization of their composition. A representative example was a film prepared from a Pickering emulsion loaded with lemon myrtle (*Backhousia citriodora*) essential oil (LEO).[131] The emulsion, stabilized by chitosan-coated alkali lignin colloidal particles, was incorporated into a chitosan-based film-forming solution to produce the final film. Notably, the film exhibited AIE-like luminescence whose intensity varied with the essential oil content.[131] All these highlight the promising potential of clusteroluminogenic polymers for developing smart packaging materials with aggregation-enhanced luminescence in future studies.

6. Conclusions and outlook

Over the past decades, considerable research has demonstrated the practical feasibility and potential of biodegradable polymer films incorporating AIE luminogens for smart food packaging. The unique optical properties of AIE luminogens allow for sensitive detection of environmental changes or food spoilage, enabling consumers and manufacturers to monitor product freshness more effectively. In addition, the tunable mechanical, thermal, and barrier characteristics of the films provide opportunities to tailor packaging materials for specific food products, ensuring both protection and functionality. Despite these promising features, several challenges remain that require further research. For instance, the optimal loading of AIE luminogens must be carefully controlled to maintain both high fluorescence efficiency and desirable film properties (such as transparency, flexibility, and mechanical strength). Potential migration of luminogens into the food matrix, as well as possible effects on taste or odour, also necessitate careful consideration to ensure consumer safety and acceptability. Furthermore, most AIE-active food packaging films reported to date remain at a proof-of-concept stage and are typically fabricated using laboratory-scale methods such as solution casting or small-area coating. Consequently, their industrial readiness remains limited, as systematic studies addressing large-scale production, continuous processing, or integration into existing packaging manufacturing lines are largely absent. From a scalability perspective, key challenges include the thermal and chemical stability of AIE luminogens during high-temperature processes such as melt extrusion, the maintenance of uniform dispersion and controlled aggregation within polymer matrices, and the reproducibility of optical response during extrusion or lamination. Addressing these challenges through process-oriented studies under industrially relevant conditions will be crucial in the coming decades before the widespread commercial application of AIE-based smart food packaging films can be realized.

Nonetheless, the body of existing literature provides a solid foundation that underscores the feasibility of integrating AIE luminogens into biodegradable polymer films. The combination of functional performance, adaptability, and sensory feedback offered by these materials positions them as highly promising candidates for the next generation of food packaging solutions. While further optimization and systematic studies are needed to address current limitations, the overall outlook for such films is optimistic. Along with the possibility of transforming conventional luminogens that exhibit ACQ into AIE luminogens—as demonstrated by the success of rendering an ACQ molecule AIE-active by modifying its 2,3,4,5,6-penta(9H-carbazol-9-yl) benzonitrile core through decoration with alkyl chain–linked spirobifluorene dendrons[132]—more novel AIE luminogens applicable for food-related applications are expected to continue to emerge. The concept of AIE is anticipated to hold considerable future potential for enhancing food safety, quality monitoring, and consumer confidence in packaged products.

Conflicts of interest

There are no conflicts to declare.

Data availability

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

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