Food Chemistry: X 27 (2025) 102458

Contents lists available at ScienceDirect

Food Chemistry: X

journal homepage: www.sciencedirect.com/journal/food-chemistry-x

Insoluble dietary fiber stabilized Pickering emulsions as novel food ingredients: Preparation, potential applications and future perspectives

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ARTICLE INFO

Keywords:
Food application
Future perspective
Insoluble dietary Fiber Pickering emulsion
Stabilization mechanism

ABSTRACT

Pickering emulsions (PEs) are valued in the food industry for their biocompatibility and stability. Insoluble dietary fiber (IDF), a sustainable and low-toxicity stabilizer derived from agricultural by-products, has shown great potential for food applications. This paper reviews advancements in IDF extraction and its use in creating IDF-based PEs (IDF-PEs). Key applications in the food sector include food packaging, 3D printing, fat substitution, bioactive delivery, and food stabilization. IDF's natural stabilizing properties and environmentally friendly extraction from agricultural waste are emphasized. While challenges remain regarding the stability and safety of IDF-PEs in complex food systems, their versatility and broad application potential make them a promising area of research. This study provides insights into developing sustainable, multifunctional food ingredients, aiming to expand the use of IDF-PEs and contribute to global sustainability goals.

1. Introduction

In recent years, PEs have been widely used in medical, cosmetic, and food applications due to their excellent biocompatibility, low toxicity, and cost-effectiveness (de Carvalho-Guimarães et al., 2022). Compared with conventional surfactant-stabilized emulsions, PEs exhibit higher stability, not only effectively resisting droplet aggregation (Wei et al., 2018) and Ostwald ripening (Jiang et al., 2020), but also remain stable even under large droplet conditions and without the use of surfactants. The stabilization mechanism mainly relies on the irreversible adsorption of solid particles at the interface to form a strong mechanical barrier ((Kong et al., 2025); Xu et al., 2020). Among many stabilizers, proteins (Jiafei Wang, Lin, Shi, Zhao, Liu, (Liu et al., 2024)), and polysaccharide particles are important materials for the preparation of PEs in multiphase food systems due to their unique properties (Ji & Wang, 2023). However, protein particles (e.g., pea proteins, corn alkyd proteins, and soy proteins) are favored in high internal phase PEs (HIPPEs) for their edibility and safety (Ding et al., 2023). their environmental sensitivities often lead to reduced antioxidant properties and structural instability (F. Cui, Zhao, Guan, McClements, Liu, (Liu et al., 2021)). In contrast, polysaccharide particles, especially IDF, have gradually become a research hotspot for PEs stabilizers due to their excellent stability, environmental friendliness and renewability (Y. (Li et al., 2022); Ren et al., 2024).

As an important component of dietary fiber, IDF is mainly derived from agricultural waste or by-products and has unique nutritional and functional properties (Elleuch et al., 2011). Compared to soluble dietary fiber (SDF), IDF performs better in improving food texture and stability

Abbreviations: AC, acid; BW, beeswax; BSDF, insoluble bamboo shoot dietary fiber; CF, citrus fibers; CIDF, citrus insoluble dietary fiber; CLSM, confocal laser scanning microscopy; CNCs, cellulose nanocrystals; CNFs, cellulose nanofibers; DF, dietary fiber; EE, enzyme; FFAs, free fatty acids; G', storage modulus; GAC, glucose uptake capacity; GIT, gastrointestinal tract; HIPPEs, high internal phase Pickering emulsions; HPH, high-pressure homogenization; HPSIDF, high purity insoluble dietary fiber; IDF, insoluble dietary fiber; IF, intermittent fasting; LNPs, lignin nanoparticles; ISF, insoluble soy fiber; NFC, nanofibrillar cellulose; O/W, water-in-oil; PEs, Pickering emulsions; PIDF, pomelo peel insoluble dietary fiber; PM, plant-based meat; SC, swelling capacity; SDF, soluble dietary fiber; SEM, scanning electron microscope; SPI, soy protein isolate; TEO, thyme essential oil; UV, ultraviolet; WBNC, wheat bran nanocellulose; WHC, water holding capacity; wt, weight; ZCPs, zein colloidal particles.

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https://doi.org/10.1016/j.fochx.2025.102458
Received 25 October 2024; Received in revised form 8 April 2025; Accepted 9 April 2025
Available online 11 April 2025

(Föste et al., 2020), and also possesses significant physiological activities such as promoting intestinal peristalsis and adsorbing and rapidly eliminating fats, oils, and heavy metals(Makki et al., 2018). In addition, IDF has significant advantages in the resource utilization of agricultural waste, which can effectively enhance the added value of by-products, promote economic cycles, and reduce environmental burdens.

In recent years, wastes and by-products rich in polysaccharides, proteins, and fibers generated by the food industry have attracted widespread attention. Studies have shown that IDF as an emulsifier has low environmental sensitivity and high digestibility resistance (Jin et al., 2017; Zhou et al., 2019), its excellent wettability (Qi et al., 2021), electrostatic interactions (Huang et al., 2019), and superior emulsification and interfacial adsorption capabilities (T. (Yang et al., 2019)), making it an ideal material for the preparation of stabilized oil-in-water (O/W) PEs (Table 1). Based on these properties, IDF-PEs has been used in food packaging(Tavassoli et al., 2023), food stabilizers (He, Zhang, et al., 2020), fat replacement (Chen, Zong, Wang, Li, and Han, 2023), active ingredient delivery (Winuprasith et al., 2018), and 3D printing (Wu et al., 2022), among others, show promising applications.

As the resource utilization of agricultural waste and low-cost, stable, and safe PEs preparation technology is increasingly emphasized, the study of IDF-PEs is of great significance. This can not only improve the economic benefits of the food industry but also reduce the environmental impact of waste disposal and promote sustainable development. Focusing on IDF-PEs, this paper reviews the progress of its preparation technology, stabilization mechanism, and application in food-related fields in recent years, aiming to provide a theoretical basis and technical support for future research and fully explore the potential of IDF-PEs in food science.

2. IDF extraction technology, and functional characteristics

IDF is mainly composed of cellulose, hemicellulose, and lignin, which are neither soluble in water nor fermentable by microorganisms in the large intestine (Yegin et al., 2020). Due to its unique physicochemical properties, IDF has a wide range of potential applications in the fields of food, medicine, and functional materials. Agricultural by-products, such as soybean residues and quinoa seeds, are important sources of IDF due to their low cost and high sustainability (Junyao (Wang, Zhang, Wang, et al., 2023)). For example, soybean processing by-products contain up to 55 % DF, of which 90 % is IDF (Bao et al., 2021) Extraction methods have a significant impact on the quality and yield of IDF and its functional properties (e.g., water-holding, oil-holding, and adsorption capacity), so the selection of appropriate technology is crucial (Anjum et al., 2012).

The extraction methods of IDF mainly include chemical, biological, and physical methods. Chemical methods (e.g., acidic and alkaline extraction) are simple and low-cost but may disrupt the chemical

Table 1
Extraction methods, particle sizes, droplet diameters, ζ-potentials of IDF from different sources and their applications in the food industry.

Source		Extraction Methods	Size of IDF	Droplet diameter	Contact angle	ζ-potential (mV)	Food applications	Reference
Fruits	Pomelo peel	Enzymatic digestion	Length is less than 26 μm	2.35∼ 2.79 μm	68.1° ∼ 88.7°	−24.0∼ −43.0	Stabilizer for frozen foods, beverages, ice cream and sauces	Gao, Liu, et al. (2022)
	Pomelo peel	Enzymatic digestion	25.6∼ 26.4 μm	N/R	54.9° ∼ 68.1°	−18.4∼ −36.1	Can guide the development of natural emulsifiers	Gao et al. (2024)
	Pomelo peel	Enzymatic digestion	57.63∼ 145.21 μm	0.98∼ 5.29 μm	N/R	An absolute value of less than 29	Stabilizes oil-water emulsions as Pickering emulsifiers for the food industry.	K. Yang, et al. (Yang et al., 2024)
	Citrus fiber	Acid hydrolysis	Length is less than 10 μm	9∼ 14 μm	N/R	0∼ −10	Can be used in nutritional supplements and lipid delivery systems.	Yang, Mao, et al. (2023)
	Sugarcane	Enzymatic digestion	19.3∼ 23.1 μm	N/R	N/R	An absolute value of less than 10	Lowering the glycemic index of bread	Yassin, Halim, Taheri, Goh, and Du (Yassin et al., 2023)
	Litchi peels	Alkali extraction	124.37 nm	3.72 μm	N/R	−35.23	Stabilizes oil-water emulsions as a natural stabilizer to form highly stable PEs	Ma, Nie, Bu, Liu, Li, Zhang, et al. (Zhang et al., 2023)
	Longan shell	Alkali extraction	Width 3.23∼ 9.20 nm, height 2.10∼ 4.93 nm	Less than 23.06 μm	45.6° ∼ 77.4°	All absolute values greater than 25.8	To be used as an emulsion fat substitute in cookies	D. Wang, Wang, Zhao, Liu, and Hu (Wang, Wang, Zhao, et al., 2023)
Grains	Soybean hull	Homogenization	Microfiber form	Less than 32.10 μm	N/R	−18.47∼ −28.34	This can be applied to the construction of food emulsion systems.	Yang, Zhu, et al. (2023)
	Rice bran	Enzymatic digestion	Microfiber form	2.93–4.59 μm	N/R	N/R	For delivery of active substances	Wang, Li, et al. (2024)
Vegetables	Carrot pomace	Ethanol extract	216.0 nm	N/R	23.79° ∼ 75.9°	−38.83	Can be used as a functional food ingredient to improve the texture and nutritional properties of food.	Rezvani and Goli (Rezvani & Goli, 2023)
	Flammulina velutiper	Alkali extraction	Width 23.93∼ 30.15 nm, height 4.77∼ 6.77 nm	Less than 10 μm	N/R	−14.5∼ −15.6	Acts as a thickener to increase the viscosity and stability of emulsions.	He, Zhang, Li, Li, and Liu (He, Zhang, et al., 2020)
	Bamboo shoot	Alkali extraction	Width 24.93∼ 32.78 nm, height 5.03∼ 6.77 nm	N/R	N/R	−8.84∼ −17.10	Used as a natural food additive to improve the texture and stability of foods	He, Li, Li, Li, and Liu (He, Li, et al., 2020)

Notes: N/R denotes not reported.

structure of IDF, resulting in the loss of hemicellulose and cellulose, as well as solvent residue and environmental pollution problems (Wang et al., 2022). For example, alkaline hydrogen peroxide treatment significantly improved the water-holding capacity (WHC) and swelling capacity (SC) of bamboo IDF (Ge et al., 2022). In contrast, enzymatic extraction has mild conditions, avoids chemical residues, and is highly environmentally friendly, but it is a complex and time-consuming process with stringent temperature and pH requirements (Siqi (Wang et al., 2022)). Wen et al. (2021) compared acid, alkaline, and enzymatic extraction of blackcurrant IDFs, and found that enzyme-extracted IDFs had higher molecular weights and exhibited more strong water-holding, oil-holding, and swelling ability. Physical extraction methods, such as ultrasound-assisted extraction, have received much attention in recent years due to their high efficiency and protective effects on the IDF structure. For example, ultrasound-assisted alkaline extraction of green pea peels IDF significantly improves its water- and oil-holding properties while reducing the phase transition temperature (Kumari et al., 2022). These methods are particularly suitable for IDF extraction from dense structures such as grapefruit peels and bamboo shoots, where the adsorption capacity of IDF particles at the oil-water interface can be enhanced by physicochemical modification. Liu et al. (2024) (Luo et al., 2018). However, physicochemical modification is usually energy-intensive, costly, and may cause pollution to the environment. Enzymatic modification, on the other hand, provides a low-energy and low-pollution alternative with broad application prospects(Yang et al., 2024).

In addition, the lower lignin content of agricultural wastes compared to woody organisms reduces the dependence on strong chemicals and energy-intensive processes in the extraction process(Junyao (Wang, Zhang, Wang, et al., 2023)). This makes IDF extracted from agricultural waste safer and more sustainable for the preparation of PEs. In recent years, research on modified IDF as a Pickering emulsifier has gradually increased, providing a new avenue for its high-value utilization in the food industry (Cai et al., 2020). Table 1 summarizes the different sources of IDF and their extraction methods, particle sizes, droplet diameters, ζ-potentials, and applications in the food industry for further studies.

In conclusion, the extraction of IDF from agricultural wastes not only contributes to the value of by-products but also meets the goal of sustainable global development. Future research should focus on optimizing the extraction techniques and balancing efficiency, cost, and environmental impact to further promote the application of IDF in food and related fields. By integrating multiple extraction and modification techniques, the efficient utilization of IDF will provide important support for the development of the green food industry.

3. IDF-PEs preparation technology

PEs, as a type of emulsion in which the base particles are stabilizers, have sparked much interest among researchers in the field of food science. PEs require an external high energy to drive the particles to the interface to form an oil-water mixture (McClements, 2004). The current methods for preparing IDF-PEs include microfluidic emulsification (Chen, Xu, et al., 2023), ultrasonic homogenization (Jixuan Gao, Bu, Zhou, Wang, Bilal, Hassan, et al., 2022), colloid milling (K. (Gao et al., 2024)), rotor-stator system (Ramos et al., 2023b), high-pressure homogenization(HPH) (D. (Wang, Wang, Zhao, et al., 2023)), and membrane emulsification (Fig. 1), among which HPH and ultrasonic methods have a better prospect for application among the many Pickering preparation methods.

HPH technology can precisely control the droplet size and achieve fine dispersion by adjusting the pressure and the number of cycles, which is suitable for the continuous treatment of large-volume samples. However, this technique has limitations such as difficulty in cleaning, susceptibility to cross-contamination, and high operating costs, which are particularly affected by pressure and cycling parameters. He, Zhang, Li, Li, and Liu (He, Zhang, et al., 2020) investigated that the IDF of enoki mushrooms not only had increased WHC and stability but also improved interfacial properties after HPH of enoki mushroom IDF. In recent years, HPH has been widely used to prepare IDF-PEs, but due to the limited processing capacity of HPH equipment, it is difficult to meet the demand of large-scale industrial production.

Ultrasonication enhances the stability of PEs by achieving uniform distribution of the dispersed phase without the addition of chemicals, which is in line with the concept of green and sustainable development (Gao et al., 2022). However, its high energy consumption and sensitivity to environmental factors limit its wide application. By optimizing parameters such as amplitude, frequency, and processing time, or combining ultrasound with other technologies, emulsion stability can be

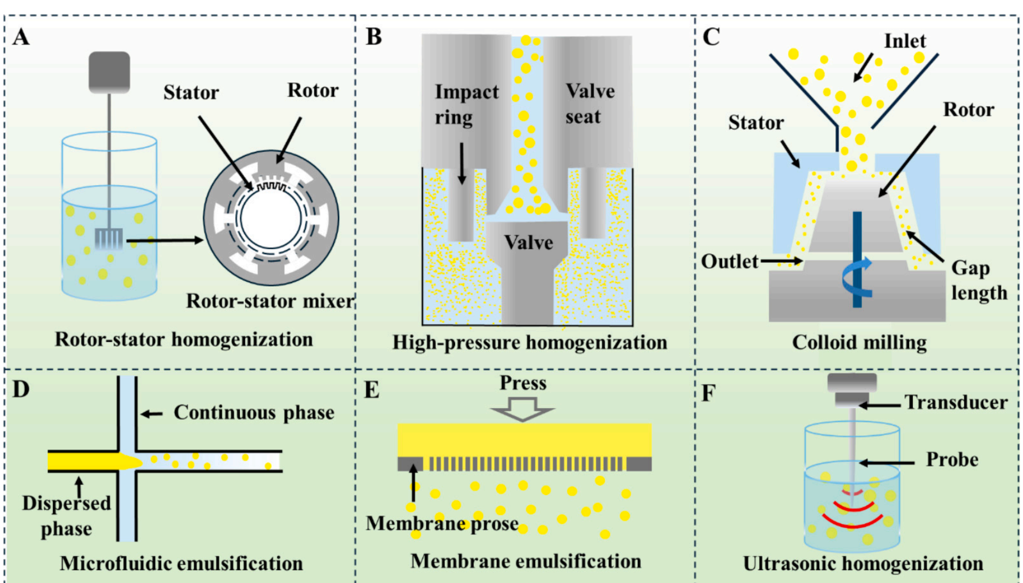

Fig. 1. A. Stator-rotor schematic (adapted from Pang, Liu, and Zhang (Pang et al., 2021)), B. HPH schematic (adapted from Pirozzi, Bettotti, Facchinelli, D'Amato, Scarpa, and Donsì (Pirozzi et al., 2024)), C. Ball milling schematic, D. Microfluidic emulsification schematic (adapted from Ji and Wang (Ji & Wang, 2023)), E. Membrane emulsification schematic (adapted from Piacentini, Drioli, and Giorno (Piacentini et al., 2014)), and F. Ultrasonic emulsification (adapted from J. Yang, Zhu, Lu, Dou, Ning, Wang, et al. (2023)).

improved and energy consumption can be reduced, thus enhancing the feasibility of its industrial application.

The ball milling method stabilizes IDF particles at the oil-water interface through shear and impact forces to form a strong emulsion structure. K. Gao, et al. (Gao et al., 2024) showed that the stability of M-PIDF (pomelo peel IDF) emulsions prepared by the ball milling method stems from the three-dimensional network structure formed by particle accumulation and oil droplet trapping. Although this method can prepare highly stable and environmentally friendly emulsions, its high energy consumption, complex particle selection, and operational difficulties limit practical applications.

The stator-rotor technique is a common method for the preparation of IDF-PEs, which has high efficiency, good emulsification performance, and industrial adaptability (Ramos et al., 2023a). By selecting wear-resistant materials to reduce the wear rate of the stator-rotor equipment, and reasonably controlling the shear rate, time, and temperature, the efficiency and quality of the stator-rotor method for the preparation of PEs can be effectively improved, and the scope of its application can be expanded to enhance the feasibility of its industrial application.

Membrane emulsification is the process of squeezing a dispersed phase (usually oil or water) through a porous membrane into a continuous phase to form an emulsion, which relies on the physical confinement of the membrane pores and hydrodynamic modulation (Shi et al., 2022). However, solid particles may clog membrane pores and reduce efficiency. The efficiency of membrane emulsification for the preparation of IDF-PEs can be improved by improving the membrane material, optimizing the pressure and flow rate, and using appropriate cleaning techniques.

Microfluidic emulsification utilizes designed microchannels in which two-phase fluids meet and disperse to form stable droplets. Despite the method's high accuracy and tunability, its application is limited by equipment complexity, channel clogging susceptibility, and limited throughput (Øye et al., 2023). By improving the microchannel design to minimize the risk of clogging, or by using a parallel design with multiple channels, productivity can be improved and the range of industrial applications can be expanded.

In conclusion, IDF is a novel, green, and environmentally friendly Pickering emulsifier with significant application potential. Despite challenges in scalability, device complexity, and environmental sensitivity, these issues are expected to be resolved through continuous optimization of preparation methods. In terms of energy consumption, ultrasonic treatment and HPH are highly energy-intensive, ball milling is moderately energy-intensive, membrane emulsification is relatively low-energy, and microfluidic emulsification is energy-intensive due to equipment complexity and low throughput (Jafari et al., 2007). By overcoming existing barriers and integrating technological advances, IDF-PEs research and applications will make significant progress, contributing to a global vision of green and sustainable development.

4. Toxicological studies of IDF-PEs in food applications

In the study of food-related materials, the cytotoxicity of IDF should not be ignored. It was found that the cytotoxicity of IDF was restricted by many factors. Fiber length and surface modification have significant effects on its toxicity. Short cellulose nanocrystals (CNCs) induce mitochondrial ROS production and induce apoptosis of the lesion cells, while long cellulose nanocrystals (CNFs) are less toxic due to low cellular uptake (J. Li, Wang, Chang, Jiang, Liu, (Liu et al., 2021)). Unmodified nanofibrillar cellulose (NFC) has pro-inflammatory effects at high doses, but surface modifications can effectively reduce its toxicity (Lopes et al., 2017). Although NFC is not acutely toxic to mussels, it may affect the integrity of cell membranes (Rusconi et al., 2024). These findings suggest that nanofiber cellulose has the potential to improve food texture and develop high-performance packaging materials, but the risk of toxicity needs to be reduced through optimized formulation, controlled dosage, and surface modification.

In the toxicological study of IDF-PEs, its toxicity is mainly affected by material properties, formulation, and environmental factors. Studies have shown that low concentrations (0.4–2 μL/mL) of polysaccharide nanofibre-stabilized IDF-PEs induce pro-death of hepatocytes and diseased cells and that this effect persists after long-term storage (Q. (Li, Hatakeyama, & Kitaoka, 2023)). This property provides a new idea for the development of functional foods with immune regulation and metabolic promotion functions. For example, in vivo, experiments showed that IDF-PEs stabilized yam polysaccharide PLGA nanoparticles did not cause tissue damage or inflammation, and serum biochemical markers remained normal (Zhang et al., 2022). In addition, chitosan nanoparticle-stabilized IDF-PEs were converted to polymer chain-stabilized form in an acidic environment, which promoted antigen uptake and did not exhibit significant toxicity or inflammatory response (Zou et al., 2023). These findings suggest that the stability of IDF-PEs under acidic conditions and its ability to enhance antigen uptake make it promising as an efficient delivery vehicle for bioactive ingredients such as vitamins, probiotics, or antioxidants in foods.

In conclusion, IDF-PEs have promising applications in functional foods, additives, packaging, and delivery systems. However, their dual properties, which are beneficial at low concentrations and potentially toxic at high doses, need to be treated with caution. Future studies should prioritize understanding how material properties influence toxicity, optimizing formulations, and conducting comprehensive long-term safety evaluations. With the improvement of toxicological studies and regulatory frameworks, IDF-PEs are expected to promote the innovative development of efficient and low-toxicity food products and materials.

5. Prospects for IDF-PEs in food applications

Food particle-based PEs have attracted attention due to their excellent stability, safety, biocompatibility, sustainability, and economic benefits. Among them, IDF-PEs have significant natural benefits, IDF extraction method is simple, easy to prepare, and belongs to green and renewable resources. IDF-PEs are beneficial for human digestion and absorption and have the advantages of high biocompatibility and better interfacial properties. Therefore, IDF-PEs have great application prospects in food. The current research work on PEs in food mainly focuses on packaging materials, delivery of bioactive substances, 3D printing of food, fat substitutes, and so on (Fig. 2).

5.1. Food packaging materials

The core objective of developing food packaging is to prevent external microorganisms from coming into direct contact with the food, ensuring food safety and prolonging shelf life. PEs offer a safer alternative to conventional emulsions in active food packaging due to their surfactant-free composition and eco-friendly nature (Choi et al., 2020). IDF-PEs offer several advantages such as availability, low cost, renewability, environmental friendliness, and biodegradability. During film formation, these emulsions form interconnected network structures via intermolecular interactions. This structural property enhances their potential for developing biopolymer-based packaging films (Zhao et al., 2023).

With its unique advantages, IDF-PEs have also been explored as a reinforcing agent or coating to significantly improve the moisture resistance, mechanical properties, and antimicrobial properties of the film. Huang, et al. (Huang et al., 2019) showed that insoluble soybean fiber (ISF) improved the stability of soybean isolate protein (SPI) emulsions and facilitated the adsorption of proteins on the surface of the oil droplets, enhancing the interfacial protective layer (Fig. 3A). In addition, the incorporation of IDF-PEs can enhance the barrier properties and bioactivity of the film, expanding its application in food preservation (Zhao et al., 2023). For example, Bangar, Whiteside, Ozogul, Dunno, Cavender, and Dawson (Bangar et al., 2022) found that PEs

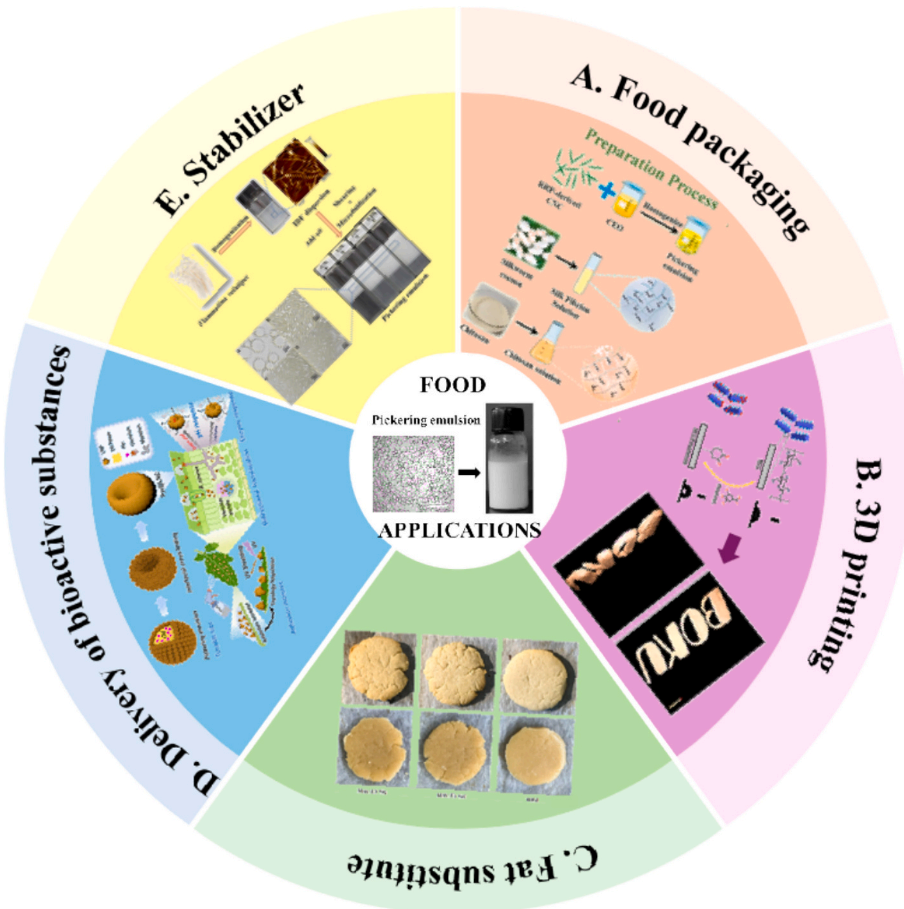

Fig. 2. Overview of applications of O/W-PEs with IDF as a stabilizing extrusion: A. Food packaging (J.-D. Wang, Yang, Liu, Zhou, Fu, Gu, et al., 2024). B. 3D printing (Shahbazi et al., 2021). C. Fat replacement (Genc et al., 2024). D. Delivery of bioactive substances (Hong, 2022b). E. Stabilizers (He, Zhang, et al., 2020).

enhanced with clove oil and stabilized with Pueraria Mirifica CNCs were able to maintain the weight, hardness, and soluble solids of grapes during storage (Fig. 3B).

IDF-PEs can also be compounded with functional materials (e.g., nanocellulose, natural antimicrobials, or antioxidants) to further enhance their antimicrobial properties. Aguado, Saguer, Fiol, Tarrés, and Delgado-Aguilar (Aguado et al., 2024) demonstrated that stabilized emulsions of Thyme essential oils (TEOs) and CNFs inhibited the growth of both Gram-negative and Gram-positive bacteria, and possessed excellent antioxidant properties, which has a significant potential for use in active food packaging (Fig. 3C). Similarly, Wardana, Wigati, Van, Tanaka, and Tanaka (Wardana et al., 2023) investigated the antifungal properties of alginate/lemongrass oil/ CNFs PEs coatings and found that 0.75 % lemongrass oil (LGO) significantly inhibited the spore germination and mycelial growth of citrus pathogens (such as Penicillium digitatum and *P. italicum*). The potential of IDF-PEs in antimicrobial packaging was further confirmed (Fig. 3D).

Although IDF-PEs show significant advantages in food packaging, their application still faces some challenges. First, its stability and film-forming properties are susceptible to environmental conditions (e.g., temperature, humidity), and there are technical difficulties in large-scale production. To overcome these shortcomings, the stability of insoluble dietary fibers under different environmental conditions can be enhanced by optimizing their particle size, surface modification, and the oil-water ratio in the emulsion. In addition, compounding IDF-PEs with other functional materials (e.g., nanocellulose, natural antimicrobial agents, or antioxidants) can further enhance its mechanical properties, antimicrobial effect, and antioxidant capacity, thus expanding its application scope.

In conclusion, IDF as a Pickering emulsifier can significantly enhance the interfacial protection, antimicrobial, and emulsification properties of films. The application of IDF-PEs in a biopolymer film matrix can form biofilms with excellent mechanical strength, gas barrier, and antimicrobial properties, which can effectively prolong the shelf life of food products. IDF-PEs, as carriers of oil-soluble bioactive compounds, have great potential for application and a broad development prospect in the field of active food packaging. However, further research is required to optimize IDF-PEs' performance, particularly by improving particle formulations, refining preparation processes, and exploring the incorporation of functional materials. These efforts are essential to fully harness its potential in active food packaging applications.

5.2. Food 3D printing

3D printing technology, as an emerging food processing method, can produce food products with diverse shapes and balanced nutrition, owing to its flexibility and ease of operation (Y. Cheng, Fu, Ma, Yap, Losic, (Wang et al., 2022)). In 3D printing, food gels, starches, proteins, and PEs are commonly employed as "inks" (Guo et al., 2022), with PEs, being considered highly promising materials due to their capacity to encapsulate and deliver functional ingredients (Tavasoli et al., 2022).

IDF-PEs, a vital type of food-grade PEs, exhibit distinctive advantages for application in 3D printing. Its interfacial stabilizing properties enhance the stability of the emulsion and prevent oil droplet merging and precipitation, thus ensuring the quality of the printed material. For example, Y. Liu, Yi, Ye, Leng, Hossen, Sameen, et al. (2021) modified IDF from soybean dregs by ultrasonic and high-speed shear techniques to obtain IDF with smaller particle size and higher thermal stability,

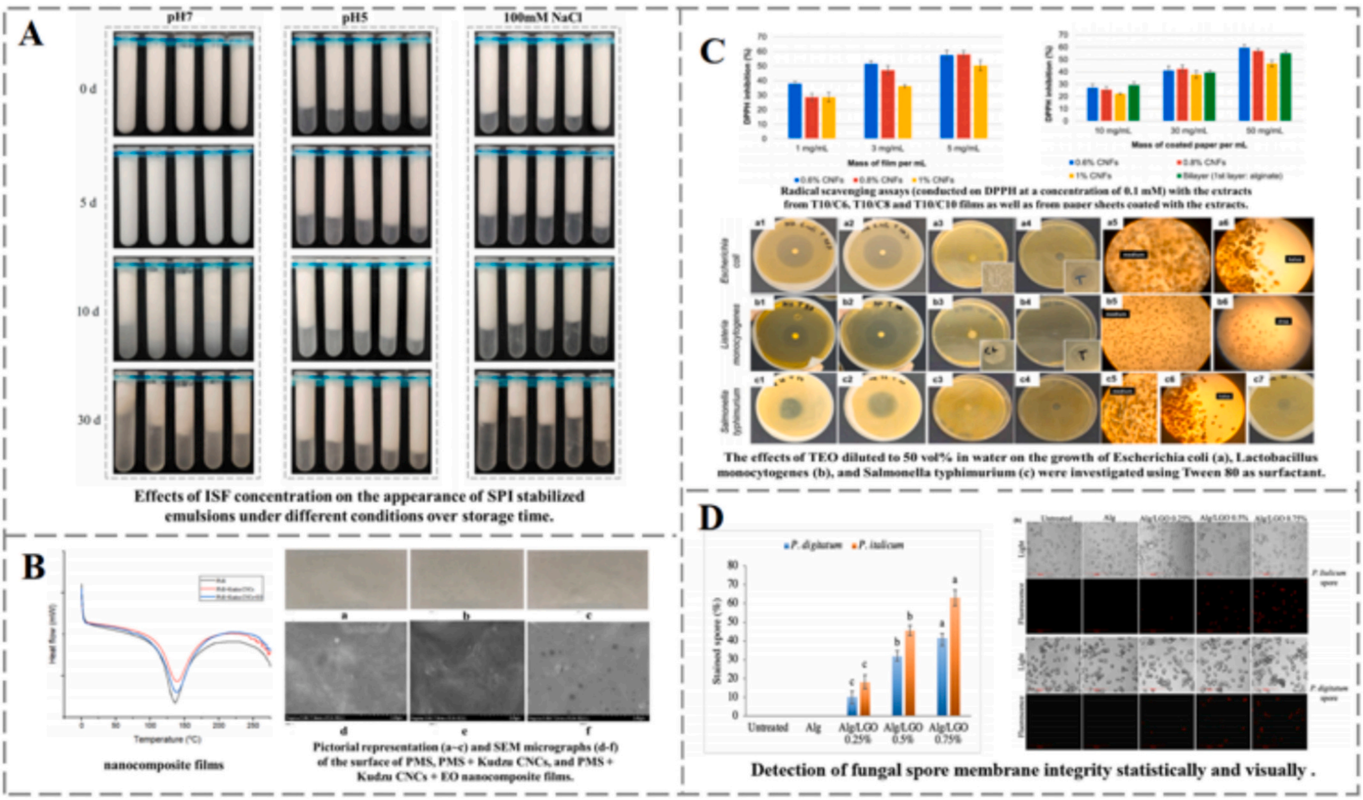

Fig. 3. A. Effect of ISF concentration on the appearance of SPI-stabilized emulsions during storage time under different conditions (Huang et al., 2019). B. DSC analyses of the complexes at 0–300 °C, as well as graphical and SEM micrographs of the surfaces of the composite films (Bangar et al., 2022). C. Free radical scavenging test and bacteriostatic effect of film extracts (Aguado et al., 2024). D. Statistical and visual methods for assessing the integrity of fungal spore membranes (Wardana et al., 2023).

which significantly improved water- and oil-holding properties. After the addition of 6 % modified IDF, the cookie dough exhibited the best printing performance and successfully printed high-quality 3D cookies after optimizing the parameters (30 % filling ratio, 0.8 mm nozzle diameter, and 50 mm/s printing speed) (Fig. 4A). This indicates that IDF-PEs significantly improves the rheological properties and printing accuracy of the material, which plays a key role in 3D printing.

However, current PEs still face challenges in achieving adequate stability and mechanical support. To address these issues, Teng, Zhang, and Mujumdar (Teng et al., 2022) nanotechnologically treated soybean dregs-derived IDFs to significantly improve their dispersion and stability. This modified IDF improved the structural integrity and printing accuracy of printed food products. For example, the treated IDF optimized the material properties by enhancing water-holding and oil-holding properties, enabling the successful printing of high-quality 3D food products (Fig. 4B).

Building on these advancements, nanotechnology processing, and material formulation optimization have further demonstrated the potential of IDF-PEs in functional food development. Cheng et al. (2024) showed that the tensile strength, elongation at break, and post-cooking textural properties of SPI (soy protein)-WG (wheat protein) composites were optimized at an IDF content of 10 %, and that their shear thinning behavior and solid-state viscoelasticity were highly compatible with 3D printing requirements (Fig. 4C). This demonstrates that IDF-PEs excels in improving the texture and mechanical properties of food products and is particularly suitable for enhancing the printability and structural stability of food products.

In food-grade 3D printing, safe IDF materials are crucial. Processed through ultrasound, high-speed shear, and other modification techniques, the IDF for agricultural by-products has high stability and meets food safety standards, while significantly improving food texture, mechanical properties, and printing adaptability. Its competitive water absorption also reduces water evaporation during the printing process, further optimizing product quality. As a multifunctional material, IDF-PEs provide reliable support for food 3D printing with their excellent rheological properties, stability, and environmental friendliness.

In the future, the development of IDF-PEs 3D printing will focus on functionalized design, material diversification, and environmental sustainability. This can be achieved by loading bioactive ingredients (e.g., vitamins, minerals, etc.) to meet individualized nutritional needs, developing efficient composites by combining proteins (e.g., whey protein isolate or gelatin) or polysaccharide matrices (e.g., alginate or carrageenan), and utilizing agricultural by-products (e.g., soybean dregs, wheat gluten, or fruit pomace) to lower costs and reduce resource waste. These innovations will open new avenues for sustainable, nutrient-dense 3D-printed food products to address the increasing demand for personalized nutrition and sustainable production practices.

5.3. Fat substitutes

A fat substitute is a substance that can replace all or part of the fat in food while having the same physiological properties (Colla et al., 2018). In recent years, IDF has become an important choice for fat substitutes due to their unique physical and chemical properties. IDF not only effectively reduces fat intake but also improves the texture and stability of food products, showing their great potential in low-fat foods.

Studies have shown that IDF has a potentially positive effect on obesity caused by a high-fat diet (J. Zhang, Wang, Wang, Liu, Gong, (Zhang et al., 2023)), and is effective in increasing fecal output and improving hyperglycemia (G. (Zhang, Wang, et al., 2024)). Sainan Wang et al. (2023) used high-purity IDF (HPSIDF) extracted from soybean dregs to investigate the mechanism of obesity prevention by combining

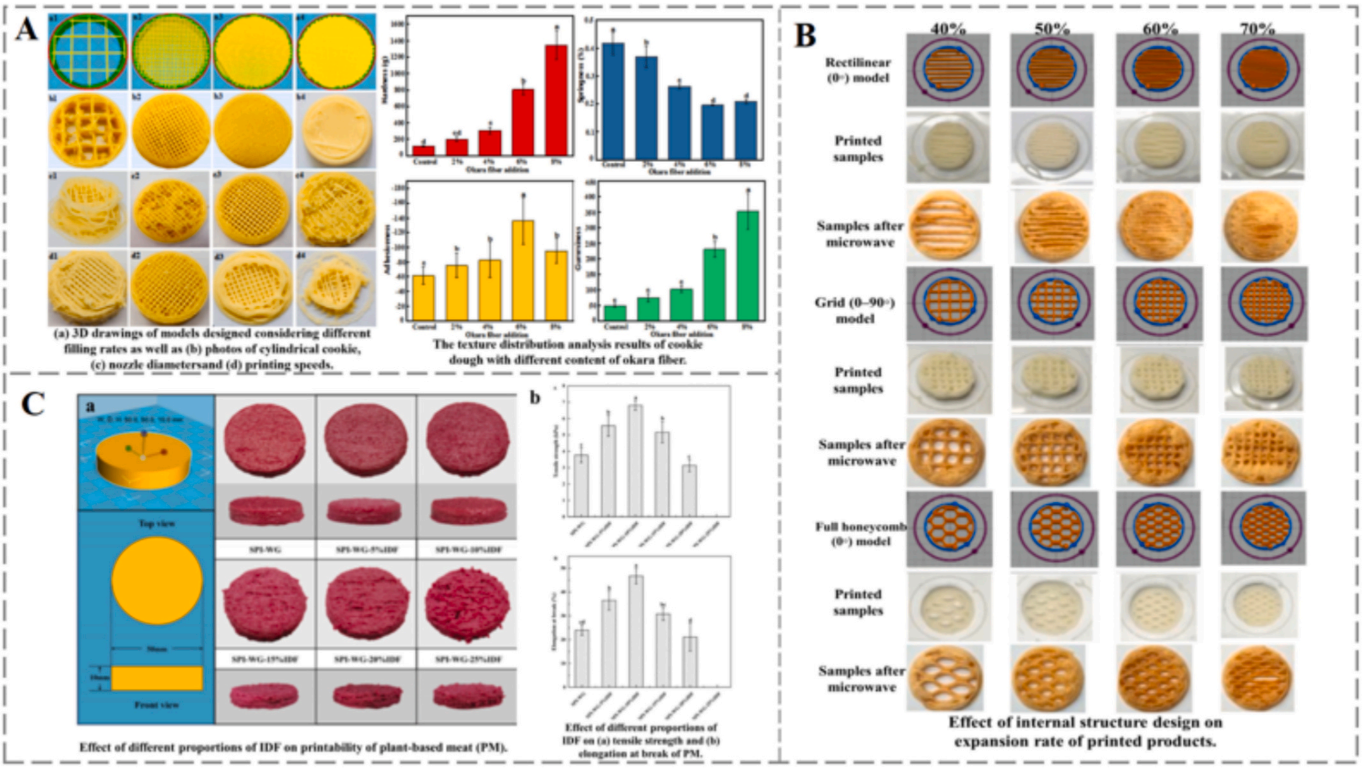

Fig. 4. A. (a) 3D modeling with different filling rates (10 %–70 %); (b) physical drawings of cylindrical cookies; (c) printing results with different nozzle diameters (0.4–1 mm); and (d) printing results and texture analysis of cookie dough with different printing speeds (25–100 mm/s) (Y. (Liu et al., 2021)). B. Swelling and print quality of 3D printed potato gels after microwave treatment with 50 % filler and the effect of added soy IDF and particle size on the rheology and gel properties of 3D printed potato gels (Teng et al., 2022). C. The effect of different IDF ratios on the printability and print deviation of PM (plant-based meat) inks as well as the rheological and mechanical properties of PM inks (Z. (Cheng et al., 2024)).

HPSIDF with intermittent fasting (IF) therapy. The results showed that the combination of HPSIDF and IF therapy could significantly improve the anti-obesity efficacy by regulating the intestinal microbiota and its metabolites.

Pickering emulsifiers have been receiving increasing attention as fat substitutes in the food industry. Pickering emulsifiers are emulsions stabilized by solid particles, making them ideal for fat replacement due to their excellent stability and low energy density. Due to the small particle size and stability of IDF-PEs, and the fact that IDF is not easily digested and absorbed by the body, it delays lipid digestion, effectively reducing the calorie content of food. It has been reported that IDFs with different particle sizes lead to aggregation and flocculation of droplets, thus delaying the rate and speed of lipid digestion (Yu et al., 2023) (Fig. 5A). In addition, the concentration of IDF increases, the structure of the oleogel becomes denser and firmer, and its oil retention improves significantly, showing the potential to be an effective alternative to palm oil (Genc et al., 2024) (Fig. 5B). Therefore, the application of IDF-PEs in lipid-lowering foods can reduce caloric intake and increase the dietary fiber content of foods, showing great potential as a fat substitute.

In recent years, significant progress has also been made in the application of IDF in PEs. For example, Q. Zhang, Shen, Meng, Liu, Wang, Zhang, et al. (2024) investigated the application of PEs stabilized by wheat bran nanocellulose (WBNC) in low-fat emulsified sausages. It was shown that the use of WBNC-stabilized PEs in place of animal fat significantly reduced the fat content and theoretical calorie content of emulsified sausages while improving their texture and color. Specifically, the fat content of emulsified sausages was reduced from 22.41 % to 12.47 % and the theoretical calorie content was reduced from 2541.5 kcal/kg to 1608.6 kcal/kg when 100 % fat was replaced by the PEs (Fig. 5C). In addition, PEs addition significantly improved the firmness, elasticity, chewiness, and recovery of emulsified sausages, and reduced the water loss during cooking (Q. Zhang, et al., 2024). Similarly, the application of palm-based nanofibrillar cellulose (NFC)-stabilized PEs in low-fat margarine showed the potential of IDF-PEs as a fat substitute. It was shown that NFC PEs significantly enhanced product hardness and color at a concentration of 0.6 % (Bernice et al., 2024).

Currently, IDF-PEs are gaining increasing importance as a fat substitute, though they may still fall short in terms of flavor and texture compared to conventional fat substitutes, which may impact sensory properties. However, the taste and texture of fats can be effectively optimized by blending multiple dietary fibers or adding natural flavors (Vilcapoma et al., 2023). To meet the market demand, the development of multifunctional products combining proteins (Li et al., 2023) or antioxidants (W. (Wang, Sun, et al., 2024))can better fit the diversified needs of the health food market.

IDF-PEs have low-calorie properties that retard lipid digestion and reduce calorie intake, making it ideal for weight management and low-fat diets. In addition, its wide application provides new ideas for extracting dietary fiber from agricultural waste, further expanding its potential in regulating lipid metabolism and promoting healthy diets. With the continuous optimization of the preparation technology, IDF-PEs are expected to play a greater role in the food industry and provide important support for the development of healthy and sustainable low-fat foods.

5.4. Bioactive substance delivery

In the food industry, O/W emulsions and nanoemulsions are commonly used to encapsulate hydrophobic bioactive compounds, owing to their ease of production and compatibility with existing food processing technologies (Winuprasith et al., 2018). However, conventional emulsions often face problems such as foaming and irritation

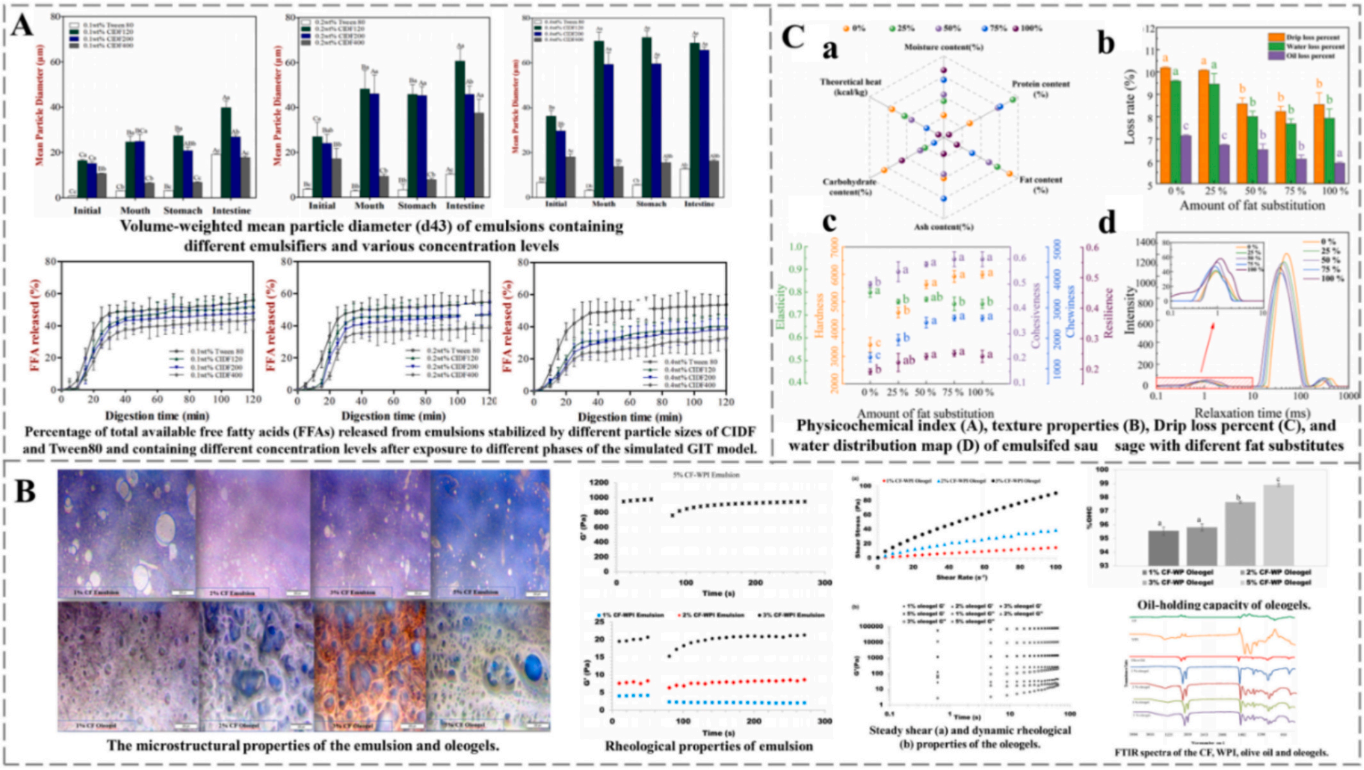

Fig. 5. A. Volume-weighted mean particle size (d43) and percentage of total free fatty acids (FFAs) released from emulsions stabilized at different concentration levels of CIDF with different particle sizes and Tween 80 (control) (Yu et al., 2023). B. Volume-weighted average particle size at 0.4 wt% concentration, percentage of total FFAs released from the emulsion, and microstructure and visual appearance of the emulsion (Genc et al., 2024). C. Microstructural properties, emulsification properties, and oil storage capacity of emulsions and oil gels (Q. Zhang, et al., 2024).

caused by surfactants. Particle-stabilized PEs offer a promising alternative due to their anti-aggregation, anti-flocculation, and prevention of Ostwald ripening (F. D. (Liu & Shenghua., 2021)). These properties give PEs the potential for a wide range of applications in food and pharmaceuticals.

IDF particles, such as cellulose and lignin, are derived from agro-processing waste and are inexpensive, safe, non-toxic, environmentally friendly, and have excellent biodegradability and biocompatibility. These properties make IDF an ideal alternative to inorganic particles and other biopolymer stabilizers. IDF-PEs excel in encapsulating and protecting hydrophobic nutrients and functional ingredients, significantly improving encapsulation efficiency and bioavailability (X. (Zhang, Wang, et al., 2022)).

Studies have highlighted the significant role of IDF-PEs in delivery systems. Jianbiao Gao, Qiu, Chen, Zhang, Wei, An, et al. (Gao et al., 2023) prepared cellulose nanofibres (CNFs) and CNCs-PEs from grapefruit peels and verified their effects through vitro digestion experiments. The experiments showed that the release trend of lycopene from IDF-PE was like that of free fatty acids (FFAs), indicating that the high oil content helps to control the release of bioactive compounds during gastrointestinal digestion (Fig. 6A). This controlled release mechanism is essential for improving the bioavailability of hydrophobic nutrients.

Although IDF-PEs have many advantages in drug delivery, emulsion delamination or drug degradation leads to a decrease in stability during long-term storage or under extreme conditions (e.g. high temperature, high salt, acidic environment). The stability of IDF-PEs can be further improved by optimizing the surface modification of IDF particles (e.g., chemical or physical treatments) or by combining them with other stabilizers (e.g., proteins, polysaccharides). For example, Wei et al. (2021) significantly improved the stability of β-carotene by combining zein colloidal particles (ZCPs) with CNCs (Fig. 6B).

Second, the encapsulation efficiency of certain hydrophobic actives may be limited by the surface properties of the IDF particles or the emulsion preparation process. The encapsulation efficiency can be improved by adjusting the particle size, surface charge, and hydrophobicity of the IDF particles or optimizing the emulsion preparation process (e.g., ultrasonication, high-pressure homogenization). Aw, Lim, Low, Singh, Chan, and Tey (Aw et al., 2022) prepared O/W-PEs stabilized by CNCs by using ultrasound waves. The prepared CNCs-PEs remained stable for over a month, with an encapsulation efficiency of more than 99 % for curcumin. In addition, the curcumin-loaded CNCs-PEs were nearly 20 times more stable than other emulsion systems under dark storage conditions (Fig. 6C), highlighting the potential of IDF-PEs in improving the stability and bioavailability of bioactive compounds.

In addition to CNCs, various other IDF materials can serve as stabilizers for emulsion delivery. For example, lignin particles are hydrophobic and oxidation-resistant, making them suitable for stabilizing emulsions and protecting active ingredients. Hong (Hong, 2022a) prepared PEs using alkyl chain-bridged lignin polymers and achieved encapsulation rates of up to 10 % in sustained release experiments with ibuprofen (Fig. 6D). This suggests that IDF-PEs can be tailored for targeted and controlled release of drugs, further broadening its application.

In summary, IDF-PEs offer notable advantages in drug delivery, including efficient encapsulation, excellent stability, and controlled release properties, making it highly valuable for applications in both the food and pharmaceutical industries. Optimization of the surface modification of IDF particles (or use in combination with other stabilizers (e.g. proteins, polysaccharides) to improve stability and functionality. By exploring multilayer emulsions (Aktaş et al., 2024) or smart responsiveness (Cui et al., 2017), IDF-PEs can achieve precisely controlled release under pH, temperature, and other environmental factors, thus meeting the specific needs of different populations and diseases and greatly expanding its prospects for application in the food and pharmaceutical fields. This significantly expands its application prospects in

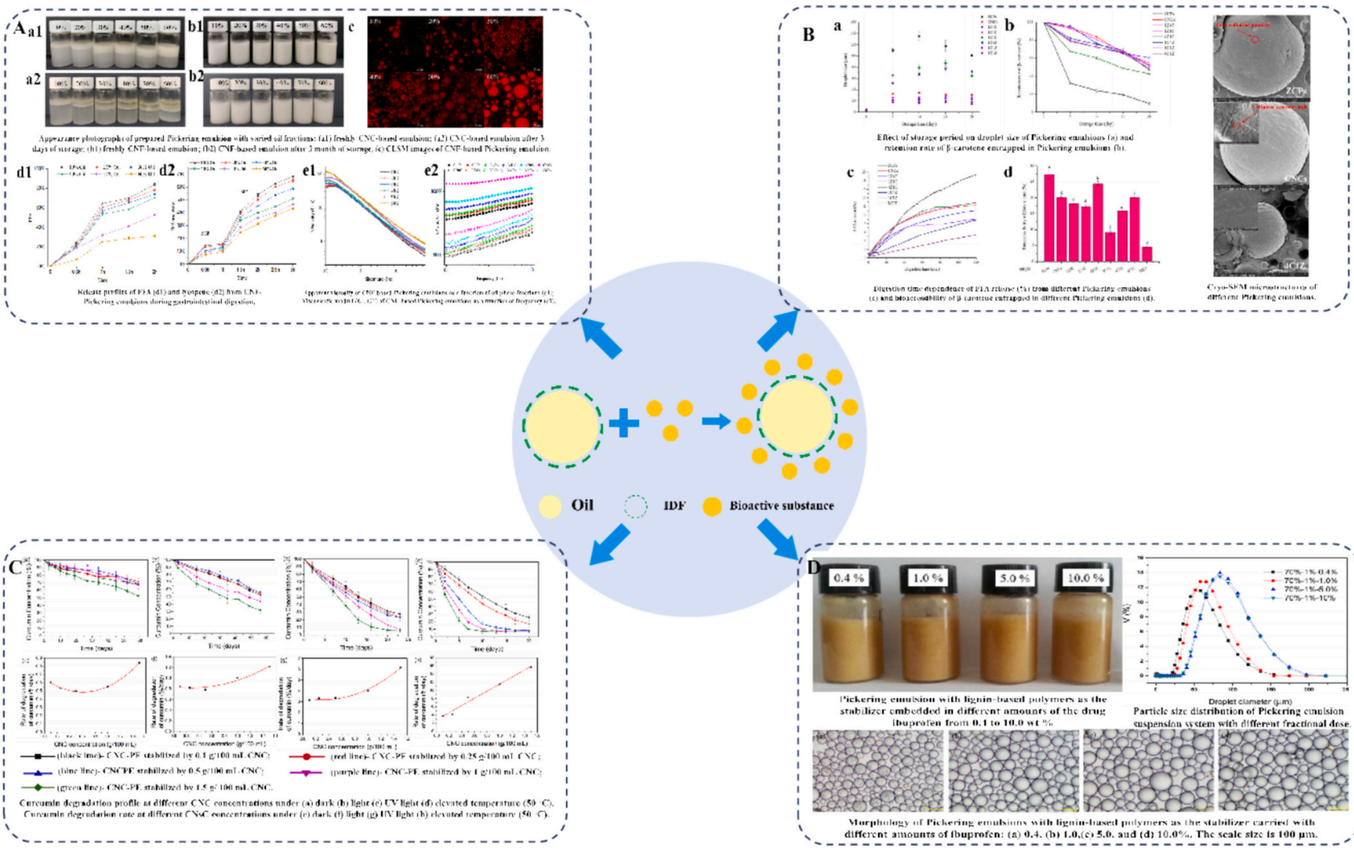

Fig. 6. A. Appearance of PEs Prepared with Different Oil Components, CLSM Images of CNFs-Based PEs, Variation of Apparent Viscosity with Oil Phase Fraction and Viscoelastic Modulus with Frequency, and FFAs and Lycopene Release Spectra During Gastrointestinal Digestion (Jianbiao (Gao et al., 2023)). B. Effect of storage period on droplet size and β-carotene retention of PEs and digestion time dependence of FFAs release, bioaccessibility of β-carotene and microstructure under cryo-SEM in different PEs (Wei et al., 2021). C. Degradation profiles of curcumin under dark, light, UV (ultraviolet), and high temperatures (50 °C) at different CNCs concentrations and the effect of different CNCs concentrations on the rate of curcumin degradation under these conditions (Aw et al., 2022). D. Particle size distribution of suspension systems of PEs at different doses and microstructure of ibuprofen in lignin-stabilized PEs (Hong, 2022a).

the food and pharmaceutical fields.

5.5. Food stabilizers

IDF-PEs have significant advantages as an emerging food stabilizer. It can significantly improve the stability, texture, and shelf life of food products. Its stabilization mechanism relies on the formation of a dense adsorption layer of solid particles at the oil-water interface, which effectively prevents droplet aggregation and phase separation, thus enhancing the physical and chemical stability of the emulsion. Compared with conventional emulsifiers, IDF-PEs have better water and oil retention capacity, which improves the structure and functionality of food products and avoids droplet aggregation and drainage by forming a high-strength interfacial layer through irreversible particle adsorption (Parker & Krog, 1987). The high resistance to agglomeration and high adsorption of IDF particles, compared with conventional low-molecular-weight emulsifiers, make them better maintain the stability of the emulsion during production and storage than conventional low molecular weight emulsifiers.

The advantages of IDF-PEs have been further confirmed by numerous research literature. He, Zhang, Li, Li, and Liu (He, Zhang, et al., 2020) showed that the water retention capacity and stability of golden mushroom IDF treated with high-pressure homogenization increased 21-fold compared to untreated samples, and the interfacial properties were significantly improved. He, Li, Li, Li, and Liu (He, Li, et al., 2020) indicated that insoluble bamboo shoot dietary fiber (BSDF) as a PEs stabilizer also showed excellent emulsification capacity and stability, which makes it suitable for use as a stabilizer in the food industry. Sanchez-Salvador, Balea, Monte, Blanco, and Negro (Sanchez-Salvador et al., 2019) found that cellulose microfibers can effectively stabilize water-in-oil (O/W) emulsions, forming a dense network structure and preventing droplet agglomeration, and its amphiphilicity enables self-assembly at the oil-water interface, which significantly enhances the emulsion stability, even at low concentrations. Even at low concentrations, it can significantly enhance the stability of emulsions.

Further studies showed that mixtures of carboxylated CNCs with lauroyl arginine ethyl ester significantly improved foam stability, especially at low concentrations, over sulfated CNCs. CNCs retarded foam drainage and agglomeration by reducing surface tension and enhancing interfacial viscoelasticity (Czakaj et al., 2022). In addition, Agustin et al. (2023) found that lignin nanoparticles (LNPs) combined with CNFs reduced oil droplet size and slowed down emulsion precipitation, especially at pH 5 and 8. The amphiphilic nature of LNPs enhances the stability of the emulsion, and their lyophilized foams have the ability to adsorb pharmaceutical contaminants, which expands the applications in food and environmental fields.

Currently, the quality of IDF-PEs in some special environmental food systems still needs to be improved, for example, the stability of IDF-PEs is affected in some food products with extremely stringent pH requirements (Ebrahimi et al., 2024). To improve this deficiency, the molecular structure of IDF-PEs can be adjusted by chemical modification (Cai et al., 2021) to enhance its stability in special environments.

In summary, IDF-PEs will play a wider role as a food stabilizer. With the increasing demand for health, safety, and sustainability in the food industry, it is expected to drive the innovation and development of food processing technology through its unique stabilizing mechanism and excellent physicochemical properties. IDF-PEs can be widely used in ready-to-eat food products, such as ketchup and mayonnaise (Taghavi et al., 2024), and are effective in improving the refrigeration stability to ensure product quality. In addition, IDF offers new directions for the development of functional ingredients and the commercialization of food additives, with great market potential.

6. Conclusions and perspective

In recent years, IDF-PEs have shown great potential for application in the food industry. Its morphology and emulsifying ability are closely related to its source, extraction method, and preparation technique, while synergistic stabilization can further enhance its performance. IDF-PEs have demonstrated multiple advantages in the food field, such as enhancing the stability and controlled release of bioactive compounds, producing high-performance food packaging films, and providing excellent rheological properties for 3D food printing. These properties make it a versatile and valuable material with promising applications in food packaging, 3D printing, fat replacement, and bioactive delivery. However, there are still some limitations in the current research, including insufficient mechanistic studies, lack of large-scale production technology, incomplete safety assessment, and limited application scenarios, which limit its further optimization and promotion.

Future research should focus on the following directions: first, in-depth elucidation of the molecular mechanism of IDF-PEs and improvement of its functional properties through structural optimization; second, development of efficient and low-cost large-scale production technology to promote its industrial application; third, systematic safety assessment to ensure its long-term reliability in food; fourth, expansion of its diversified applications in functional food, dietary supplements and other fields; and fifth, strengthening interdisciplinary cooperation and technological innovation, combining artificial intelligence and big data technology to realize precise development. Through the above efforts, IDF-PEs are expected to realize broader applications in the food industry, strongly support the innovation of food science and technology, and at the same time open new ways for the sustainable development of the food industry in the future.

CRediT authorship contribution statement

Yaomei Ma: Writing – original draft, Software, Funding acquisition, Conceptualization. **Nan Zheng:** Formal analysis, Conceptualization. **Yue Wang:** Visualization, Resources, Methodology. **Hongyu Lei:** Investigation, Data curation. **Xinyu Zhen:** Visualization, Supervision, Formal analysis. **Ruining Zhang:** Visualization, Supervision. **Tong Liu:** Writing – review & editing, Validation, Supervision, Resources, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research was funded by the Jilin Province Science and Technology Development Project (20230202060NC), and Study Abroad Fund Project [2023] No. 43 (202308220123).

Data availability

No data was used for the research described in the article.

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