

International Studies
— in the field of —
**Food Sciences
and Engineering**

October 2026

EDITOR

Prof. Dr. Arzu KAVAZ YÜKSEL

gece
kitaplığı

İmtiyaz Sahibi / Yaşar Hız
Yayına Hazırlayan / Gece Kitaplığı

Birinci Basım / Ekim 2026 - Ankara
ISBN / 978-625-321-334-3

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CONTENTS

CHAPTER 1

PHYSICAL AND OXIDATIVE STABILITY OF PROTEIN-STABILISED FOOD EMULSIONS: RECENT ADVANCES AND ANALYTICAL APPROACHES

Şelale YALÇINÖZ 7

CHAPTER 2

NOVEL FOODS: EMERGING FOOD SOURCES

Nilgün Başak TECER, Zeynep Görkem DURANTAŞ 21

CHAPTER 3

EMULSION GEL-BASED FAT STRUCTURING STRATEGIES FOR PLANT-BASED MEAT ANALOGUES

Şelale YALÇINÖZ 43

CHAPTER 1

PHYSICAL AND OXIDATIVE STABILITY OF PROTEIN-STABILISED FOOD EMULSIONS: RECENT ADVANCES AND ANALYTICAL APPROACHES

*Şelale YALÇINÖZ*¹

¹ Assistant Professor Food Quality Control and Analysis Programme, Eğirdir Vocational School, Isparta University of Applied Sciences, Isparta, Türkiye ORCID: <https://orcid.org/0000-0003-2503-439X>

1. Introduction

Oil-in-water emulsions are used in many food products, where oil droplets are dispersed in an aqueous phase (Hinderink, Schröder, Sagis, Schroën, & Berton-Carabin, 2021). Animal proteins are commonly used to stabilise oil-in-water emulsions because they can interact with both oil and water (Bisinotto et al., 2025). Plant proteins have also gained interest as more sustainable options (Hinderink et al., 2021). Proteins can stabilise these emulsions by adsorbing at the oil–water interface and helping to prevent droplet aggregation (Chen, Li, Cao, et al., 2022).

Physical stability refers to how well an emulsion maintains its properties and droplet size over time (Kupikowska-Stobba, Domagała, & Kasprzak, 2024). Loss of emulsion stability may involve flocculation, coalescence, creaming, phase separation and etc. (Cerff, Key, & Bladergroen, 2021; Kiokias, Gordon, & Oreopoulou, 2017; Kupikowska-Stobba et al., 2024; Rajbanshi, Hilton, Dreiss, Murnane, & Cook, 2024).

Lipid oxidation is another important concern, particularly in emulsions containing unsaturated oils, as it can reduce sensory quality (Yang et al., 2024). The oil–water interface is important in lipid oxidation because pro-oxidants can reach the oil at this region (Bisinotto et al., 2025). Lipid oxidation also depends on droplet size, interfacial composition, and the presence of antioxidants and pro-oxidants (Bisinotto et al., 2025).

However, experimental studies have shown that physical and oxidative stability do not always follow the same pattern (Chen et al., 2023; Hinderink et al., 2021). Therefore, both physical changes and lipid oxidation need to be considered when evaluating the stability of food emulsions (Ghelichi et al., 2023). Different analytical methods are used to examine emulsion properties and stability (Kupikowska-Stobba et al., 2024). Lipid oxidation is also studied by measuring primary and secondary oxidation products (Ghelichi et al., 2023).

This chapter discusses the physical and oxidative stability of protein-stabilised food emulsions, the factors affecting their stability, and the methods used to evaluate them. It also reviews recent experimental studies and considers current challenges and future research needs.

2. Physical Stability

Emulsion stability is important for maintaining the desired properties and shelf life of food products (Kupikowska-Stobba et al., 2024). Emulsions are thermodynamically unstable because forming an oil–water interface requires energy (Kiokias et al., 2017). Physical instability may involve flocculation, coalescence, creaming, sedimentation, Ostwald ripening and phase inversion (Cerff et al., 2021; Kupikowska-Stobba et al., 2024; Rajbanshi et al., 2024). Figure 1 shows the main emulsion destabilization mechanisms. These processes can occur separately or at the same time (Kupikowska-Stobba et al., 2024).

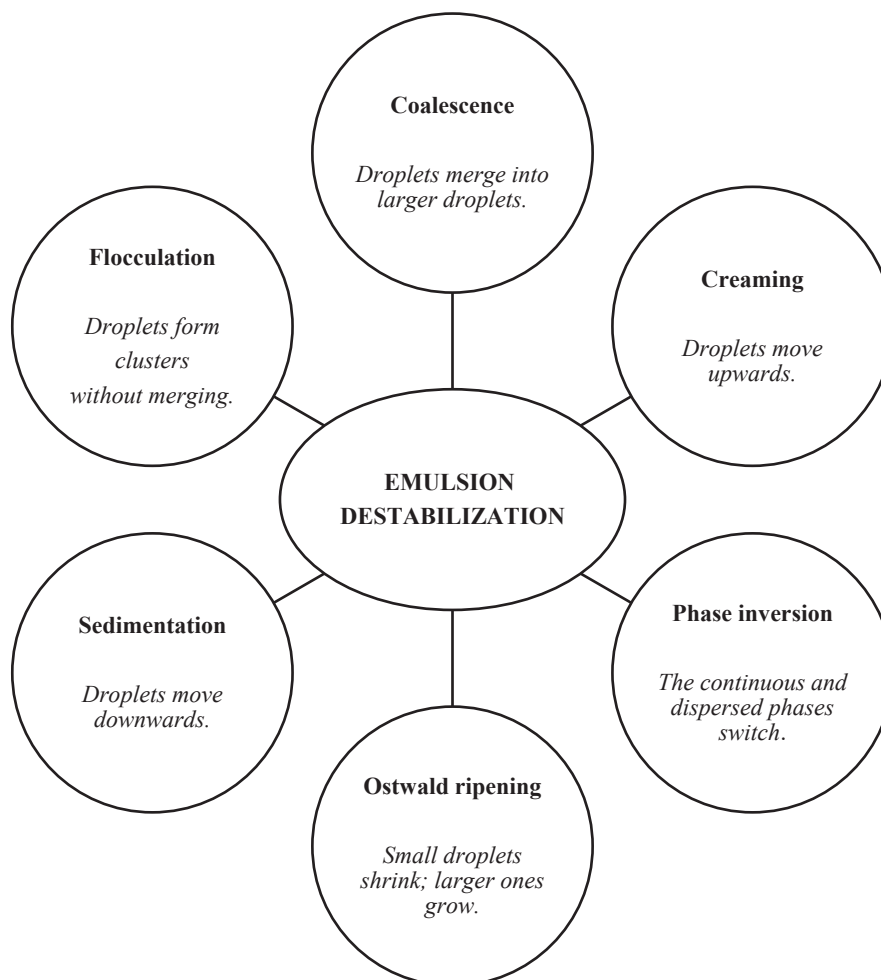


Figure 1. Main emulsion destabilization mechanisms. Developed by the author based on Cerff et al. (2021), Kupikowska-Stobba et al. (2024) and Rajbanshi et al. (2024).

Flocculation occurs when droplets form clusters due to attractive forces, such as van der Waals forces (Kupikowska-Stobba et al., 2024). In flocculation, droplets form clusters but not merge (Cerff et al., 2021). Attractive forces bring the droplets together (Kupikowska-Stobba et al., 2024), but short-range repulsion prevents them from merging (Rajbanshi et al., 2024). Although the droplets change their position within the emulsion, their size distribution generally remains unchanged (Cerff et al., 2021).

During coalescence, two or more droplets combine into a larger one (Kupikowska-Stobba et al., 2024). Brownian motion and attractive interactions can bring droplets into contact and promote their merging (Kupikowska-Stobba et al., 2024). As the droplets approach each other, the thin liquid film between them becomes thinner and eventually breaks, allowing the droplets to merge (Cerff et al., 2021; Kupikowska-Stobba et al., 2024). This process reduces the total oil–water interfacial area (Rajbanshi et al., 2024).

Sedimentation occurs when droplets move downwards and accumulate at the bottom because their density is higher than that of the surrounding liquid (Cerff et al., 2021). This is more commonly seen in water-in-oil emulsions (Kupikowska-Stobba et al., 2024). Although the droplets settle, their size distribution usually remains unchanged (Cerff et al., 2021).

In the same manner, creaming occurs when droplets move upwards and accumulate at the top because their density is lower than that of the surrounding liquid (Cerff et al., 2021). This is commonly observed in oil-in-water emulsions (Cerff et al., 2021). Although the droplets rise, their size distribution usually remains unchanged (Cerff et al., 2021).

During Ostwald ripening, material from smaller droplets dissolves and passes through the continuous phase to larger droplets (Cerff et al., 2021). This process is driven by differences in pressure and solubility between droplets of different sizes (Kupikowska-Stobba et al., 2024). Larger droplets are more thermodynamically stable due to their lower surface area-to-volume ratio (Cerff et al., 2021). As this process continues, small droplets shrink while larger ones grow, changing the droplet size distribution (Cerff et al., 2021; Kupikowska-Stobba et al., 2024). How quickly this happens depends partly on the solubility of the dispersed phase in the continuous phase (Kupikowska-Stobba et al., 2024).

Phase inversion involves a change from one emulsion type to another, such as from oil-in-water to water-in-oil (Cerff et al., 2021). This transition may occur when changes in temperature,

electrolyte concentration or emulsifier solubility favour the opposite emulsion type (Cerff et al., 2021).

Proteins can help maintain the physical stability of emulsions by forming a protective layer around oil droplets (Chen, Li, Cao, et al., 2022). Away from the protein's isoelectric point, the adsorbed protein layer can help prevent physical destabilisation through electrostatic repulsion and steric hindrance (Hinderink et al., 2021). Some proteins, such as β -lactoglobulin, can also form a viscoelastic network at the oil–water interface that protects droplets against coalescence (Hinderink et al., 2021). The structure of the interfacial layer can also vary depending on the protein (Ghelichi et al., 2023). For example, β -lactoglobulin can form a dense interfacial film, whereas caseins can form thicker but less densely packed layers (Ghelichi et al., 2023).

3. Oxidative Stability

Lipid oxidation can negatively affect the quality of oil-in-water food emulsions (Ghelichi et al., 2023). During autoxidation, lipid radicals react with oxygen to form peroxy radicals, which then react with unsaturated fatty acids to produce lipid hydroperoxides (Ghelichi et al., 2023). These hydroperoxides are primary oxidation products and are odourless and tasteless (Ghelichi et al., 2023). Their breakdown can lead to the formation of secondary oxidation products, including aldehydes and ketones, which may cause undesirable odours and flavours (Ghelichi et al., 2023).

The oil–water interface is an important region for the initiation of lipid oxidation (Aslam & Schroën, 2023). In emulsions, a larger interfacial area may allow more interactions between substances in the oil and water phases, increasing the possibility of oxidation (Ghelichi et al., 2023). The movement of metal ions, oxygen and water-soluble antioxidants through the aqueous phase also affects their access to the oil droplets and their interface (Ghelichi et al., 2023). Bröls-Gill, Boerkamp, Hohlbein, and van Duynhoven (2024) found protein–lipid aggregates in the aqueous phase of all the emulsions studied, which were stabilised with legume protein isolates. They observed extensive protein oxidation within these aggregates, together with lipid oxidation (Bröls-Gill et al., 2024).

Proteins can help reduce lipid oxidation in emulsions through their antioxidant properties (Münch, Schroën, & Berton-Carabin, 2024). They can scavenge free radicals and bind metal ions, depending on the pH (Münch et al., 2024). When proteins are present in the aqueous phase,

they may limit lipid oxidation by keeping metal ions away from the oil–water interface (Münch et al., 2024). In contrast, the role of proteins at the oil–water interface in lipid oxidation is more complex (Münch et al., 2024). Overall, their antioxidant activity can vary with protein type and location within the emulsion (Münch et al., 2024).

Hinderink et al. (2021) reported differences in lipid oxidation among emulsions stabilised with different protein fractions. Under oxidative conditions, emulsions stabilised with whey protein showed rapid formation of lipid oxidation products (Hinderink et al., 2021). In contrast, emulsions prepared with whole pea protein isolate showed the lowest accumulation of these products (Hinderink et al., 2021).

The oxidative stability of protein-stabilised emulsions is affected by several factors, including emulsion composition, droplet properties and interfacial composition (Kiokias et al., 2017). Other components in the emulsion may also affect lipid oxidation (Münch et al., 2024). These factors should be considered together when evaluating the oxidative stability of food emulsions.

4. Factors Affecting Physical and Oxidative Stability

Protein properties play an important role in the physical stability of oil-in-water emulsions (Münch et al., 2024). Protein adsorption rate at the oil–water interface depends on molecular size, flexibility and structure (Münch et al., 2024). Rapid protein adsorption during homogenisation helps prevent droplet recoalescence (Münch et al., 2024). Protein solubility can also influence emulsion stability, as even poorly soluble proteins may help stabilise oil droplets (Münch et al., 2024).

The protein layer formed around oil droplets can also influence oxidative stability (Münch et al., 2024). Depending on their molecular structure, proteins may form interfacial layers with different thicknesses and packing densities (Ghelichi et al., 2023). A less permeable interfacial layer may help protect the oil phase by limiting the movement of pro-oxidant substances towards the droplets (Ghelichi et al., 2023).

The fatty acid composition of the oil phase is an important factor in lipid oxidation (Aslam & Schroën, 2023). Fatty acids become more susceptible to oxidation as their degree of unsaturation increases (Aslam & Schroën, 2023). Therefore, the type of oil used should be considered when developing protein-stabilised food emulsions.

The pH of an emulsion can affect both its physical and oxidative stability (Kiokias et al., 2017). Changes in pH can alter the surface charge of proteins and their interactions with metal ions, which may either reduce or promote lipid oxidation (Münch et al., 2024). In protein-stabilised emulsions, lipid oxidation has often been found to increase at pH values above the protein's isoelectric point, when droplets carry a negative charge (Kiokias et al., 2017).

Homogenisation can improve the physical stability of food emulsions by reducing droplet size (Håkansson, 2019). During this process, droplet breakup and protein adsorption influence the formation of the oil–water interface (Berton-Carabin, Sagis, & Schröen, 2018). The composition and structure of this interface may also play a role in lipid oxidation (Berton-Carabin et al., 2018). Processing conditions can also influence lipid oxidation in oil-in-water emulsions (Kiokias et al., 2017).

5. Analytical Approaches for Evaluating Physical and Oxidative Stability

Emulsion stability describes how well an emulsion maintains its physical and chemical characteristics over time (McClements, 2007).

Changes in droplet size can provide information about emulsion instability, as larger droplets tend to undergo faster gravitational separation (Niu et al., 2023). Changes in the creaming index during storage can indicate the extent of cream layer formation in an emulsion (McClements, 2007). Changes in the physical stability of emulsions can also be followed using multiple light scattering methods, particularly to detect creaming and sedimentation (Kupikowska-Stobba et al., 2024).

Microscopy can help visualise structural changes associated with the mechanisms of phase separation, such as flocculation, coalescence and Ostwald ripening (Kupikowska-Stobba et al., 2024).

Zeta potential measurements can help evaluate emulsion stability by revealing the electrical interactions between oil droplets (Kupikowska-Stobba et al., 2024). Repulsive interactions may help keep droplets apart, reducing the likelihood of flocculation and coalescence (Kupikowska-Stobba et al., 2024; Niu et al., 2023).

Rheological measurements can be used to determine the viscosity of the continuous phase in food emulsions (McClements, 2007). A higher continuous-phase viscosity can slow droplet

movement and reduce gravitational separation, including creaming and sedimentation (Niu et al., 2023). Several analytical methods are available to examine lipid oxidation in food emulsions (Ghelichi et al., 2023). The formation of primary oxidation products can be examined through lipid hydroperoxide measurements or peroxide value analysis (Ghelichi et al., 2023). Thiobarbituric acid reactive substances (TBARS) and anisidine value (AV) are commonly used to examine secondary oxidation products (Ghelichi et al., 2023). However, the methods used for TBARS and AV determination have limited sensitivity and specificity (Ghelichi et al., 2023). Gas chromatography coupled with mass spectrometry (GC–MS) allows volatile oxidation compounds to be identified and measured with greater confidence (Ghelichi et al., 2023).

6. Selected Experimental Studies

Previous studies have examined the effects of protein characteristics (Hinderink et al., 2021), heat treatment (Chen et al., 2023), and homogenisation methods (Chen, Li, Kong, Chen, & Liu, 2022) on the physical and oxidative stability of food emulsions. Table 1 summarises selected experimental findings and their implications for emulsion stability.

Table 1. Selected Experimental Studies on the Physical and Oxidative Stability of Protein-Stabilised Food Emulsions

Emulsion system/ Experimental conditions	Main findings	Key implication	Ref.
Whey protein isolate, full and insoluble pea proteins; sunflower oil O/W emulsions <i>Protein source and fraction; non-oxidative and pro-oxidant conditions</i>	Whey protein isolate emulsions underwent considerable droplet merging and rapid lipid oxidation; the insoluble pea protein fraction maintained physical stability despite rapid oxidation; full pea protein isolate exhibited physical instability but the lowest levels of oxidation products.	Physical and oxidative stability do not necessarily follow the same trend.	Hinderink et al. (2021)
Soybean oil O/W emulsions stabilised by soybean protein hydrolysates <i>Alcalase hydrolysis (15–180 min)</i>	Among the tested formulations, emulsions prepared with the 90-min hydrolysate showed the highest physical and oxidative stability.	Hydrolysis conditions can affect both physical and oxidative stability.	Tong et al. (2021)
Whey protein isolate-stabilised soybean oil O/W emulsions <i>Ultrasound, high-pressure and microfluidisation homogenisation</i>	Among the homogenisation methods tested, microfluidisation homogenisation emulsions showed smaller droplets and lower lipid oxidation, despite greater oxidation of adsorbed proteins.	Interfacial protein oxidation may accompany improved lipid protection.	Chen, Li, Kong, et al. (2022)
Whey protein isolate- κ -Carrageenan complexes, cod liver oil O/W emulsions <i>κ-Carrageenan concentration (0–0.4 wt%); pH 3–7</i>	Higher κ -carrageenan concentrations improved creaming stability and reduced lipid oxidation, with the effects varying according to pH.	Protein–polysaccharide interactions may influence both stability types.	Ballard, Khouryeh, and Williams (2023)
Grape seed and barley spent grain protein hydrolysates; echium oil O/W emulsions <i>Trypsin and subtilisin hydrolysis; 7-day storage</i>	Trypsin-derived brewer's spent grain hydrolysate gave the smallest droplets and highest physical stability but lower oxidative stability, whereas trypsin-derived grape seed hydrolysate maintained physical stability with larger droplets and less lipid oxidation.	Different protein hydrolysates may exhibit different physical and oxidative stability profiles.	Bisimotto et al. (2025)

Whey protein isolate - stabilised soybean oil O/W emulsions <i>Post-emulsification heating (60–90°C); 10-day storage</i>	All heat-treated emulsions showed lower physical stability, while those heated at 70 or 90°C exhibited less lipid oxidation than the untreated control.	Thermal processing may have opposing effects on physical and oxidative stability.	Chen et al. (2023)
Whey protein isolate - stabilised soybean oil O/W emulsions <i>pH 3, 5, 7 and 9; storage at 37°C</i>	At neutral pH, adsorbed proteins helped protect the lipid phase, whereas pH 9 showed the most pronounced protein–lipid co-oxidation during storage.	At different pH levels, changes in the oil–water interface and droplet aggregation may be associated with protein–lipid co-oxidation.	Chen, Li, Cao, et al. (2022)
Intact and pre-oxidised Whey protein isolate; soybean oil O/W emulsions <i>Peroxyl radical-induced Whey protein isolate pre-oxidation</i>	Emulsions prepared with more extensively oxidised whey protein isolate had larger droplets, lower physical stability and higher lipid oxidation during storage.	Prior protein oxidation may compromise both physical and oxidative stability.	Li et al. (2024)
Pea protein isolate–inulin conjugates; algae oil O/W emulsions <i>Maillard conjugation using ultrasound and/or pH-shift treatments</i>	Pea protein–inulin conjugates improved physical stability and reduced lipid oxidation compared with pea protein alone, with the combined ultrasound and pH-shift treatment showing particularly favourable results.	Protein–polysaccharide conjugation may improve both physical and oxidative stability.	Jiang, Zhang, McClements, Liu, and Liu (2022)

Overall, these studies demonstrate that physical and oxidative stability do not always change in the same direction (Bisinotto et al., 2025; Chen et al., 2023; Hinderink et al., 2021). Both aspects should therefore be considered when evaluating protein-stabilised food emulsions.

7. Conclusion

The physical and oxidative stability of protein-stabilised food emulsions is affected by several factors. These include the type and properties of proteins, processing conditions and changes at the oil–water interface. Proteins help stabilise emulsions by forming a layer around oil droplets. However, the protection they provide depends on the emulsion system and the conditions used.

The studies reviewed in this chapter also show that good physical stability does not always mean low lipid oxidation. Some emulsions remain physically stable even when lipid oxidation occurs. For this reason, both physical and oxidative stability need to be evaluated when studying food emulsions.

More research is needed to understand how protein structure and behaviour at the oil–water interface affect emulsion stability during processing and storage. Measuring droplet stability alongside lipid oxidation may help researchers develop food emulsions with better overall stability.

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CHAPTER 2

NOVEL FOODS: EMERGING FOOD SOURCES

Nilgün Başak TECER¹, Zeynep Görkem DURANTAŞ²

¹ Lecturer, PhD., Ankara University, nbtecer@ankara.edu.tr, ORCID ID: 0000-0001-8724-5585

² Lecturer, Ankara University, zgcerit@ankara.edu.tr, ORCID ID: 0000-0003-3955-9584

1. Introduction

The global food system is undergoing significant transformation due to population growth, climate change, resource limitations, technological advances, and changing consumer expectations. Increasing demand for safe, nutritious, affordable, and sustainable foods has intensified interest in alternative food sources and innovative production systems. These developments are driven partly by the environmental pressures associated with conventional agriculture and livestock production, including land and water use, greenhouse gas emissions, and biodiversity loss (FAO, 2024; Tan et al., 2024). Within this context, novel foods have emerged as an important area of food science and technology. In the European Union (EU), novel foods are defined as foods that were not consumed to a significant degree before 15 May 1997. This category includes foods from new sources, ingredients produced using innovative technologies, and certain traditional foods from countries outside the EU (EFSA, 2025).

The development of novel foods is particularly relevant to diversifying protein sources. In addition to conventional plant proteins, alternative sources include algae, insects, fungi, microorganisms, and animal cells. Technologies such as precision fermentation, cellular agriculture, biotechnology, and advanced food processing have expanded opportunities to develop innovative ingredients and products (Hussain & Li, 2025; Tan et al., 2024). These approaches may also improve food system resilience by diversifying raw materials, supporting more efficient resource utilization, and contributing to circular food systems (Hussain & Li, 2025). Despite their potential, novel foods require careful safety assessment. Potential concerns include microbiological hazards, chemical contaminants, naturally occurring toxins, allergenicity, nutritional imbalances, and risks associated with emerging production technologies. Regulatory evaluation is therefore essential to ensure consumer protection and support responsible commercialization. Consumer acceptance is another key determinant of successful adoption. Familiarity, sensory characteristics, perceived health benefits, environmental considerations, cultural background, and trust in production technologies can influence consumer responses. Food neophobia, unfamiliarity, and limited knowledge may hinder acceptance, whereas perceived health benefits and environmental sustainability may encourage it (Laureati et al., 2024; Mukherjee et al., 2025). This chapter examines novel foods as an emerging component of future food systems, focusing on their sources, production technologies, nutritional and technological properties, safety, sustainability, and consumer acceptance.

2. Definition, Classification, and Regulatory Framework of Novel Foods

Novel foods are foods or ingredients that differ from those traditionally consumed in a given region. Their classification depends on consumption history, origin, composition, and production methods. In the European Union (EU), Regulation (EU) 2015/2283 defines novel foods as those not consumed to a significant degree before 15 May 1997 and requires authorization before marketing when applicable (European Parliament and Council of the European Union, 2015; EFSA, 2025). In Türkiye, the relevant regulation considers foods not consumed to a significant degree before 31 December 2025, as well as foods included in the official novel foods list and falling within specified categories (Ministry of Agriculture and Forestry of Türkiye, 2026).

Novel foods encompass products derived from plants, animals, microorganisms, fungi, algae, and cell or tissue cultures, as well as ingredients obtained through innovative processes such as precision fermentation and cellular agriculture. Other categories include foods containing engineered nanomaterials and certain ingredients produced through novel technologies (Hussain & Li, 2025). Novelty does not necessarily imply a safety risk. Rather, regulatory frameworks establish procedures to evaluate the identity, composition, production methods, intended uses, nutritional characteristics, and potential toxicological or allergenic risks of these foods. EFSA assesses the available scientific evidence to determine whether proposed uses are safe (EFSA, 2025). This assessment is particularly important for emerging technologies involving genetically modified microorganisms, new substrates, and unconventional processing methods. Traditional foods from countries outside the EU may follow a simplified notification procedure if they have a documented history of safe consumption by a significant number of people for at least 25 years. However, further assessment may be required if safety concerns arise (EFSA, 2025). Because definitions, consumption thresholds, and authorization procedures differ internationally, a food may be considered novel in one country but not in another. Regulatory systems must therefore adapt to technological advances while maintaining consumer protection (Tan et al., 2024; FAO, 2024). Clear definitions, transparent authorization procedures, and science-based safety assessments are essential for balancing innovation with food safety, nutritional quality, and consumer confidence.

3. Plant-Based Novel Foods

The development of plant-based foods has moved beyond the traditional consumption of whole grains, legumes, fruits, and vegetables toward the design of food products with specific nutritional, sensory, and technological functions. This transformation has been supported by advances in plant protein extraction, ingredient fractionation, food structuring, fermentation, and formulation technologies. As a result, a new generation of plant-based foods has emerged, including products intended to provide alternatives to meat, milk, dairy products, and eggs. These developments have positioned plant-derived ingredients as important resources within the broader novel food sector (McClements & Grossmann, 2024). Plant-based novel foods can be developed from established sources such as soybean, wheat, and pea, as well as underutilized crops including chickpeas, lentils, faba beans, lupin, oats, quinoa, buckwheat, hemp, and sunflower. These alternative sources offer opportunities to diversify raw materials and develop foods with distinctive nutritional profiles. The suitability of plant materials depends not only on their nutrient composition but also on functional properties such as solubility, emulsification, foaming, gel formation, and thermal behavior. Plant materials can also be fractionated into protein concentrates, isolates, starches, fibers, and oils to meet specific formulation requirements. Understanding the relationship between composition and functionality is therefore essential for developing plant-based foods with desirable nutritional and physicochemical characteristics (McClements & Grossmann, 2024).

The nutritional profile of plant-based novel foods depends on raw material composition, processing, and formulation. Plant ingredients can provide proteins, dietary fiber, unsaturated fatty acids, vitamins, minerals, and bioactive compounds, although their nutritional characteristics vary considerably among sources and products (Schweiggert-Weisz et al., 2024). Protein quality is particularly important when plant-based foods replace animal-derived products. Plant proteins may differ in essential amino acid composition and digestibility, which can be improved through complementary protein combinations and appropriate processing techniques (Munialo, 2024). Plant-derived polyphenols, flavonoids, and carotenoids may also contribute functional properties, although processing can alter their levels. Conversely, antinutritional compounds such as phytates, tannins, and protease inhibitors may affect nutrient availability and digestibility. The nutritional and health effects of plant-based novel foods cannot be generalized across all products because composition and processing vary substantially (Nájera Espinosa et al., 2025). Similarly, the nutritional quality of plant-based

meat alternatives depends on their specific formulation rather than their plant-based origin alone (El Sadig & Wu, 2024).

3.1. Plant-Based Meat Alternatives

Plant-based meat alternatives are designed to replicate the texture, juiciness, appearance, and cooking properties of conventional meat. They commonly contain proteins from soybean, pea, wheat, or faba bean, combined with oils, flavorings, colorants, and texturizing agents. High-moisture extrusion is particularly important for developing fibrous structures by promoting protein unfolding, aggregation, and alignment under controlled processing conditions (Zhang et al., 2024). The nutritional quality of these products varies according to formulation, including protein content, amino acid balance, micronutrients, fat profile, and sodium levels. Therefore, their nutritional value should be evaluated individually rather than inferred solely from their plant-based origin (El Sadig & Wu, 2024). Environmental impacts also vary depending on raw materials, agricultural practices, processing energy, packaging, and transportation. Consequently, sustainability should be assessed across the entire production system rather than assumed to be uniform across all meat alternatives (Lindberg et al., 2024). Consumer acceptance depends on sensory quality, familiarity, perceived health benefits, environmental concerns, price, and attitudes toward food technologies. Thus, successful product development requires balancing technological performance and nutritional quality with consumer expectations (Tahseen et al., 2024).

3.2. Plant-Based Dairy and Egg Alternatives

The Plant-based dairy alternatives are produced from legumes, cereals, oilseeds, nuts, and other plant materials, with soy, oats, almonds, peas, and rice being commonly investigated sources. Raw material selection and processing conditions influence their nutritional composition, physicochemical properties, stability, and sensory quality (Daryani et al., 2024). Compared with dairy milk, these beverages may differ in protein content, amino acid profile, digestibility, and micronutrient composition. Fortification with vitamins, minerals, or additional proteins can help improve their nutritional value. Plant-based yogurt, cheese, and cream alternatives present additional technological challenges because viscosity, gel formation, emulsion stability, mouthfeel, and flavor must be achieved without the interactions characteristic of conventional dairy systems. Plant proteins, starches, and hydrocolloids can help develop the desired properties (McClements & Grossmann, 2024). Fermentation is also increasingly used to modify

acidity, flavor, texture, and stability, while potentially improving selected nutritional and functional characteristics. However, fermentation conditions and substrate pretreatment strongly influence sensory quality and consumer acceptance (Ueda et al., 2025). Plant-based cheese alternatives require specific strategies to reproduce firmness, elasticity, spreadability, and meltability. Combinations of plant proteins, starches, hydrocolloids, and structured lipids, alongside fermentation and other processing techniques, can help improve these characteristics. Plant-based egg alternatives represent another emerging category. Their development requires the simultaneous reproduction of key techno-functional properties, including emulsification, foaming, gelation, binding, and water retention. Formulations combining plant proteins, starches, hydrocolloids, and lipids can be tailored to specific food applications, while processing conditions influence viscosity, gel strength, and thermal stability (Khalifa et al., 2025).

3.3. Processing Technologies for Plant-Based Novel Foods

The development of plant-based novel foods relies on processing technologies that modify ingredient structure, functionality, and sensory properties. Conventional methods, including milling, heating, drying, homogenization, and fractionation, are complemented by advanced techniques such as extrusion, fermentation, enzymatic treatment, high-pressure processing, and ultrasound. Extrusion is particularly important for plant-based meat alternatives, as controlled temperature, moisture, pressure, and mechanical shear promote protein restructuring and the formation of fibrous, meat-like textures (Zhang et al., 2024). Fermentation can modify proteins, carbohydrates, and flavor compounds while potentially reducing antinutritional factors. Enzymatic treatments, high-pressure processing, and ultrasound offer further opportunities to improve ingredient functionality (McClements & Grossmann, 2024). The key processing technologies for plant-based novel foods and their applications are presented in Figure 1. The nutritional quality, environmental performance, and consumer acceptance of plant-based novel foods vary according to raw materials, processing methods, and formulation (Lindberg et al., 2024; Nájera Espinosa et al., 2025). Therefore, their successful development requires an integrated approach that considers ingredient selection, processing technology, product quality, and sustainability.

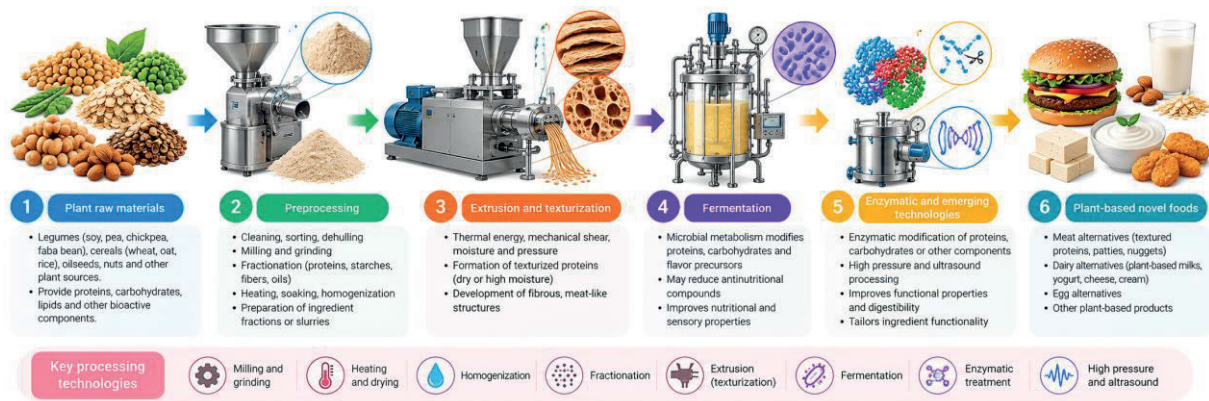


Figure 1. Key processing technologies for plant-based novel foods and their applications.

4. Algae and Seaweed as Emerging Food Sources

Algae and seaweeds are promising food resources due to their nutritional composition, functional properties, and potential contribution to sustainable food production. Depending on the species, they provide proteins, dietary fibers, lipids, minerals, vitamins, pigments, and bioactive compounds, making them valuable ingredients for innovative food products (Eladl et al., 2024). Algae are broadly classified into microalgae and macroalgae (seaweeds). Microalgae such as *Spirulina* (*Arthrospira*) and *Chlorella* are particularly valued for their protein content, whereas green, red, and brown seaweeds offer diverse nutritional and functional characteristics.

Algae provide proteins, essential amino acids, dietary fiber, lipids, minerals, vitamins, pigments, and bioactive compounds. Microalgae can enrich foods with protein, while seaweeds are notable for their minerals and polysaccharides. Algal pigments and phenolic compounds may also contribute antioxidant properties. In addition to their nutritional value, algal components offer technological functions. Proteins can support emulsification, foaming, and gel formation, whereas seaweed-derived polysaccharides, including alginate, agar, and carrageenan, are widely used as thickening, stabilizing, and gelling agents (Salido et al., 2024).

Algae can be incorporated into foods as whole biomass, powders, extracts, or purified ingredients. Applications include beverages, bakery products, snacks, protein-enriched foods, and plant-based formulations (Bhatnagar et al., 2024). Processing methods such as drying, cell disruption, extraction, fractionation, and fermentation can improve the recovery and functionality of algal components. Appropriate processing conditions are important for maintaining protein solubility, emulsification, gelation, and digestibility. The main algal sources, processing technologies, and food applications are presented in Figure 2. Despite their

potential, algae-based foods require careful safety assessment because composition varies with species, cultivation conditions, and environmental factors. Potential hazards include heavy metals, excessive iodine, and species-specific toxins. Species identification, cultivation control, and quality assessment are therefore essential. Regulatory requirements also differ among countries according to the species, intended use, and history of consumption.

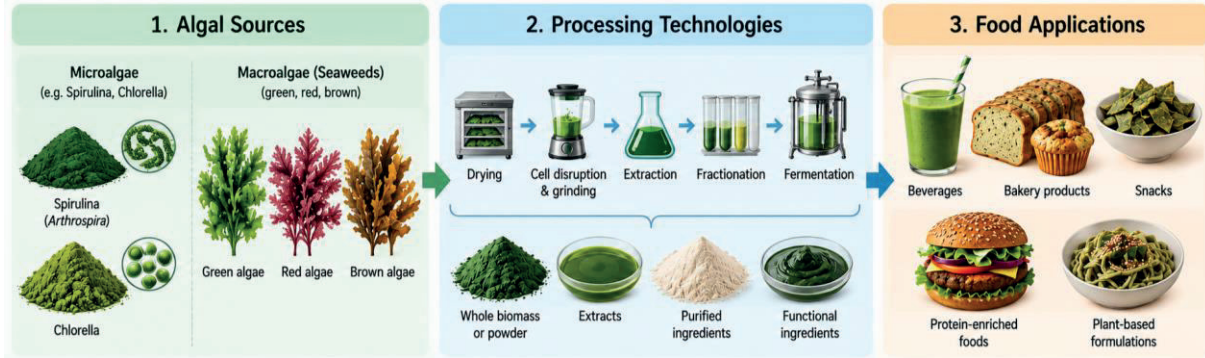


Figure 2. Algal sources, processing technologies, and food applications.

5. Insect-Based Foods

Edible insects have attracted interest as alternative food sources due to their protein content, amino acid profiles, lipids, minerals, vitamins, and bioactive compounds. Their nutritional composition varies according to species, feeding conditions, developmental stage, and processing methods (Psarianos et al., 2025). Insects can be consumed whole or processed into powders, flours, protein concentrates, and oils for use in bakery products, snacks, and protein-enriched foods (Liang et al., 2024; Kozlu et al., 2024). In addition to proteins, edible insects can provide unsaturated fatty acids, minerals, vitamins, and chitin, which may contribute to the functional properties of insect-derived ingredients (Psarianos et al., 2025). Insect proteins exhibit water-holding, emulsifying, foaming, and gelation properties, making them suitable for various food applications. However, these characteristics, along with protein digestibility and nutrient bioavailability, depend on the insect species, extraction methods, and processing conditions (Liang et al., 2024).

Insect-derived ingredients can be incorporated into different foods following processing methods such as drying, grinding, thermal treatment, and fermentation. These methods influence their nutritional, physicochemical, and sensory characteristics (Liang et al., 2024; Kozlu et al., 2024). The main edible insect sources, processing technologies, and food applications are presented in Figure 3. Safety considerations include microbial contamination,

heavy metals, and allergenicity, particularly the potential cross-reactivity between insect proteins and allergens from other arthropods. Appropriate rearing practices, processing, and quality control are therefore essential (Liang et al., 2024). Consumer acceptance remains a major challenge and is influenced by familiarity, food neophobia, sensory expectations, cultural attitudes, and perceived safety. Incorporating insects as powders or protein ingredients and improving flavor and texture may help overcome some barriers to acceptance (Okaiyeto et al., 2024).

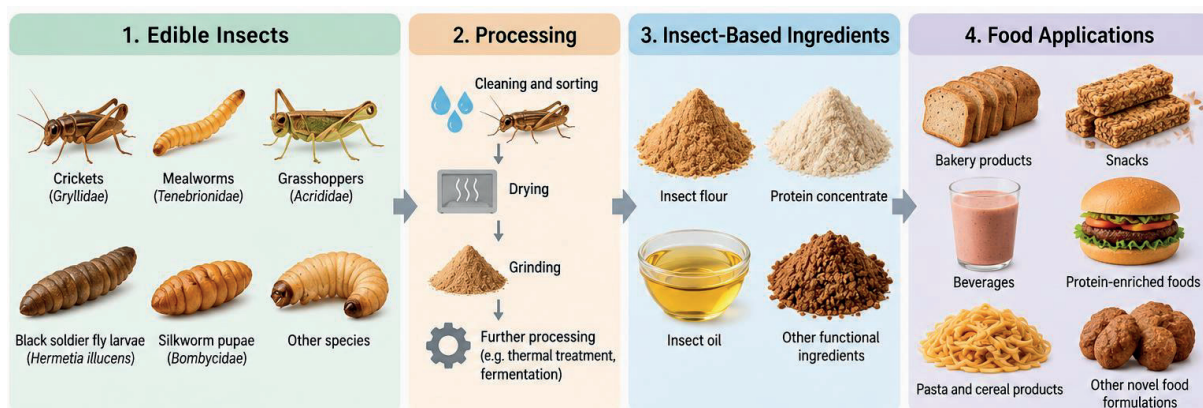


Figure 3. Edible insect sources, processing technologies, and food applications.

6. Cultivated Meat and Cellular Agriculture

Cellular agriculture combines cell culture, tissue engineering, biotechnology, and bioprocess engineering to produce food through controlled biological systems. Cellular production cultivates animal cells for meat and other animal-derived materials, whereas acellular production uses microorganisms or other biological platforms to generate ingredients such as proteins, lipids, and enzymes. Cultivated meat is produced by expanding animal cells *ex vivo* and differentiating them into muscle, adipose, and, where needed, connective-tissue components. Bioreactors, scaffolds, and tissue-engineering approaches can help reproduce selected characteristics of conventional meat (Cedeno et al., 2025; Kirsch et al., 2023; Wood et al., 2023).

Scale-up remains constrained by cell senescence, cell-line stability, capital investment, mass transfer, and culture-medium costs. Research therefore investigates pluripotent stem cells, immortalised cell lines, serum-free media, recombinant growth-factor alternatives, and nutrient sources derived from agricultural by-products (Malila et al., 2024; Cedeno et al., 2025; Wood et al., 2023). Shear-cell structuring, edible scaffolds, and 3D bioprinting aim to reproduce muscle-fibre organisation and meat-like texture. Commercial potential must nevertheless be

assessed alongside cost, energy use, nutritional quality, food safety, regulation, sensory performance, and consumer acceptance (Chodkowska et al., 2022; Wood et al., 2023; Hwang et al., 2026).

6.1. Production Principles and Processing Technologies

Cultivated meat production typically comprises cell sourcing and characterisation, cell-line establishment, proliferation, differentiation, harvesting, and downstream processing. Muscle satellite cells, myoblasts, and other progenitor or stem cells are evaluated for growth, differentiation capacity, genetic stability, and suitability for food production. Characterised cell banks support reproducibility, while prolonged cultivation requires monitoring for phenotypic or genetic changes (Lee et al., 2024; Kang et al., 2024).

Culture media supply amino acids, carbohydrates, vitamins, minerals, and, where required, growth factors and signalling molecules. Their composition affects cell yield, metabolism, differentiation, and biomass composition. Serum-free, chemically defined media may improve consistency and reduce animal-derived inputs, but affordable formulations that support both proliferation and differentiation remain a key challenge (Lee et al., 2024; Goodwin et al., 2024).

Bioreactors regulate temperature, pH, dissolved oxygen, nutrient delivery, mixing, and metabolite accumulation. Scale-up requires efficient oxygen and nutrient transfer while limiting shear stress. Adherent cells may require microcarriers or matrices, whereas suspension-adapted cells have different cultivation requirements; therefore, reactor design, cell density, mixing, and mass transfer must be optimised together (Lee et al., 2024; Goodwin et al., 2024).

Differentiation promotes muscle-cell and adipocyte development. For structured products, edible plant-derived scaffolds or food-grade biopolymers, 3D bioprinting, and other biofabrication methods can support cellular organisation. Unstructured biomass can instead be blended with other ingredients for minced or restructured products. Scaffold choice must consider edibility, functionality, process compatibility, and regulatory requirements (Chodkowska et al., 2022). Harvested biomass may undergo washing, separation, blending, forming, seasoning, thermal processing, and packaging. Whole-cut products require more complex organisation of muscle, fat, and supporting structures than products based on dispersed cells (Kang et al., 2024).

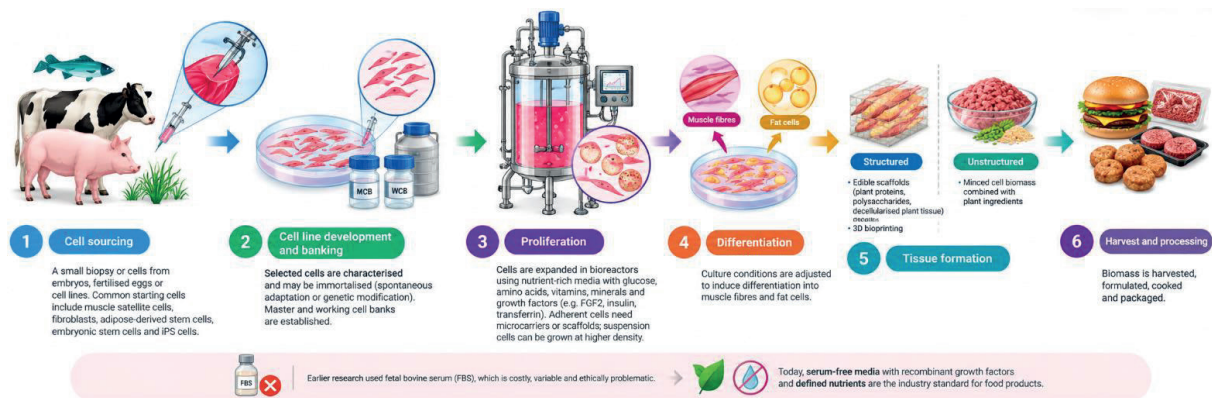


Figure 4. Cultivated meat production steps.

6.2. Nutritional Composition and Food Safety

The nutritional composition of cultivated meat depends on species, cell type, medium, cultivation and differentiation conditions, and downstream processing. Protein and amino-acid profiles may be comparable to conventional meat in some formulations, but equivalence cannot be assumed across products. Lipids, micronutrients, tissue structure, and nutrient bioavailability may differ; therefore, assessment should be performed on the final product (Fraeye et al., 2020; Kang et al., 2024).

Controlled cultivation may offer opportunities to influence fatty-acid profiles through adipose-tissue development and precursor availability. Such changes must be confirmed analytically and assessed alongside oxidative stability, flavour, and overall quality. Iron, zinc, and vitamin B12 also require product-specific evaluation because their presence in the medium does not guarantee cellular uptake, retention, or bioavailability in the final food (Fraeye et al., 2020; Kang et al., 2024).

Safety assessment should address microbial contamination, residues from media or processing aids, and changes in cell characteristics during extended cultivation. Closed systems do not eliminate these hazards. Controls should cover cell banks, raw materials, media inputs, environmental monitoring, harvesting, processing, traceability, packaging, and storage. Risk assessment must be tailored to the process and product, including the safety of cells, scaffolds, and formulation ingredients (FAO & WHO, 2023).

6.3. Technical and Commercial Challenges

Major barriers include the cost of recombinant growth factors and purified media ingredients, the scale-up of high-density cultures, and the need to maintain oxygen and nutrient transfer while controlling waste and shear stress. Food-compatible serum-free media and validated

alternative nutrient sources, including agricultural by-products, may reduce costs, provided their safety, consistency, and capacity to support cell growth are demonstrated (Lee et al., 2024; Goodwin et al., 2024).

Sensory quality depends on muscle organisation, fat distribution, water-holding capacity, and flavour precursors involved in cooking reactions. Scaffolds and biofabrication may improve structure, but reproducible whole-cut architecture and desirable flavour remain challenging (Kang et al., 2024). Environmental performance also depends on energy supply, media manufacture, facility operation, equipment utilisation, and waste management. Life-cycle assessment (LCA) and techno-economic analysis (TEA) should therefore use transparent assumptions and realistic process data rather than presuming cultivated meat is inherently more sustainable or cost-competitive (Goodwin et al., 2024; Malila et al., 2024).

7. Fermentation-Derived and Microbial Foods

Microbial biomass and precision fermentation use microorganisms to produce food biomass and targeted ingredients (Wang et al., 2024). Filamentous fungi can generate fibrous mycoprotein, potentially using suitable agro-industrial substrates; engineered yeasts and bacteria can produce proteins such as β -lactoglobulin and casein; and controlled fermentation can reduce beany off-flavours in plant-protein bases. Microalgae and bacteria are also investigated as sources of protein, polyunsaturated fatty acids, and bioactive compounds (Cedeno et al., 2025; Malila et al., 2024; Wood et al., 2023).

7.1. Fermentation as a Platform for Novel Food Production

Fermentation has traditionally supported food preservation, digestibility, flavour development, and nutritional modification. Advances in microbial biotechnology and process control have extended its applications to microbial biomass, alternative proteins, enzymes, vitamins, pigments, and functional ingredients. Three overlapping categories are commonly distinguished:

- Traditional fermentation transforms food substrates through microbial activity, as in yoghurt, sourdough, tempeh, miso, and kimchi. These products are not necessarily novel foods, although new cultures and processes can create novel characteristics.
- Biomass fermentation grows microbial cells as the main ingredient, including protein-rich yeast, bacterial, fungal, or other biomass. Mycoprotein is a prominent example.

- Precision fermentation uses selected or engineered microorganisms to produce specific compounds, including animal-identical or similar proteins, enzymes, vitamins, and flavour ingredients, which are then recovered or formulated for food use. Recent reviews describe its potential and the scale-up and regulatory challenges that remain (Knychala et al., 2024; Hilgendorf et al., 2024).

7.2. Microbial Biomass and Alternative Protein Production

Microorganisms can grow rapidly in compact systems using suitable carbohydrate feedstocks, agricultural residues, or food-processing by-products. Yeasts provide food ingredients and protein-rich biomass; filamentous fungi produce fibrous mycoprotein; bacteria are studied for high-protein biomass and specialised ingredients; and microalgae provide proteins, pigments, lipids, and other bioactives. Production generally involves strain selection, medium formulation, fermentation, biomass recovery, and processing such as washing, dewatering, drying, heat treatment, or flavour modification.

Composition depends on the organism, growth conditions, and processing. Protein quality should be assessed through amino-acid composition and digestibility, not crude protein alone. Nucleic-acid content may increase purine exposure, while fungal cell-wall components can influence digestibility and functionality; these factors should inform product applications and consumption levels.

7.3. Precision Fermentation and Functional Food Ingredients

Precision fermentation can produce dairy and egg-related proteins, enzymes, vitamins, pigments, and flavour compounds. Recombinant milk proteins may contribute to emulsification, foaming, gelation, and heat-induced structuring, although performance depends on protein structure, relevant post-translational modifications, formulation, and interactions with other ingredients. Fermentation-derived enzymes are also used in baking, cheese manufacture, beverage clarification, and plant-material processing.

Controlled production may improve consistency, but functionality must be assessed in the intended food matrix: performance in a purified system may not predict behaviour in formulations containing salts, carbohydrates, lipids, and other proteins. Precision fermentation primarily targets defined molecules, whereas traditional fermentation generally transforms a substrate through selected cultures or microbial communities (Knychala et al., 2024; Hilgendorf et al., 2024).

7.4. Food Safety, Quality Control, and Regulatory Considerations

Safety and quality control should cover strain identity and purity, genetic stability where relevant, contamination, residual production organisms, unintended metabolites, and ingredient purity. For precision-fermentation products, assessment should consider the production organism, genetic modifications, target substance, potential impurities, intended use, and allergenicity especially when proteins resemble known food allergens. Microbial biomass may additionally require evaluation of cell-wall components, nucleic acids, relevant toxins, digestibility, and nutritional quality.

Temperature, pH, oxygen transfer, substrate concentration, agitation, and fermentation time affect yield and metabolite formation. Validated monitoring and standardised analytical methods are therefore essential. Low-cost substrates may reduce material expenses, but agricultural residues and processing by-products require characterisation for variability and contaminants. Safety and sustainability must be assessed for each organism, process, ingredient, and application rather than assumed from fermentation alone (FAO & WHO, 2023; Malila et al., 2024).

8. Comparing Alternative Protein Platforms

The optimal alternative protein platform depends on its intended application. For beverages, high solubility and minimal sedimentation are essential, whereas meat analogues require adequate water-holding capacity, gel-forming ability, and fibrous texture. Therefore, platform selection should be guided not only by protein content but also by functional performance and nutritional requirements. Table 1 presents a comparative overview of the major alternative protein platforms, highlighting their key characteristics and potential applications. These characteristics may vary depending on the species, ingredient composition, and production system employed.

Table 1. Comparative overview of major alternative protein platforms. Characteristics vary by species, ingredient, and production system.

Protein source	Main opportunities	Principal limitations
Plant proteins	Established supply chains; versatile processing; potential environmental benefits	Variable protein quality; flavour and texture limits; formulation-dependent sodium and micronutrients
Microbial biomass	Rapid growth; compact production potential; high protein in some species	Substrate needs; nucleic acids; sensory and downstream-processing challenges
Precision-fermentation proteins	Targeted functional proteins; potential consistency	Fermentation and purification costs; regulation; possible allergenicity
Cultivated meat	Animal-cell biomass produced under controlled conditions	Scale-up, cost, structuring, energy, and regulatory challenges
Edible insects	Protein and lipid resources; food-system diversification	Allergens, acceptance, species-specific safety, and feed quality
Algae and aquatic plants	Potential sources of protein, lipids, pigments, and polysaccharides	Species variability, contamination, cultivation and harvesting costs

9. Integrating Nutrition, Technology, and Sustainability

Novel-food development must balance nutritional value, technological functionality, sensory acceptance, safety, affordability, and environmental impact. These dimensions interact: intensive fractionation may improve protein functionality but increase energy and water use; flavour additions may increase costs or sodium; and fortification can improve nutrient adequacy while creating stability, bioavailability, and labelling challenges. Evaluation should therefore be multidimensional and application-specific as shown in Table 2.

Table 2. Integrated criteria for developing and evaluating novel foods.

Evaluation dimension	Key indicators	Main objective
Nutritional quality	Protein quality, digestibility, essential amino acids, micronutrients	Support nutrient adequacy
Technological functionality	Solubility, gelation, emulsification, texture, thermal stability	Ensure processability and product quality
Sensory performance	Flavour, aroma, appearance, texture, consumer acceptance	Improve product appeal
Food safety	Microbial hazards, contaminants, allergens, residues	Protect consumers
Environmental performance	GHG emissions, land, water, energy, waste	Reduce life-cycle impacts
Economic feasibility	Yield, input and processing costs, scalability	Support affordability and viability
Regulatory compliance	Safety evidence, classification, labelling, authorisation	Enable responsible market access

The objective is not to maximise one indicator in isolation, but to identify products with demonstrable nutritional or environmental benefits while maintaining safety, quality, accessibility, and consumer trust.

10. Future Perspectives and Conclusion

The development of novel foods has shifted from initial enthusiasm and rapid investment toward a more realistic assessment of their technical, economic, and social challenges. Future progress is likely to depend on diversification rather than the complete replacement of conventional animal products, with hybrid foods, functional ingredients, and fermentation-derived components offering promising opportunities. Scaling up production will require investment in food-grade bioprocessing infrastructure, access to affordable low-carbon energy, and more efficient regulatory frameworks that maintain rigorous safety standards. Meanwhile, further research into nutritional quality, digestibility, bioavailability, allergenicity, and long-term health effects will be essential to ensure that technological advances translate into meaningful dietary benefits.

Equitable development will also be critical, particularly in low- and middle-income countries, where traditional foods, underutilised crops, algae, insects, and fermented products may offer locally appropriate alternatives. Respecting traditional knowledge, strengthening regional production capacity, and adapting innovations to local needs will help ensure that the benefits of novel foods are widely shared. Overall, novel foods encompass diverse sources and technologies with varying nutritional, technological, economic, environmental, and cultural implications. Although they offer considerable potential to diversify protein supplies and improve food-system sustainability, their benefits depend on formulation, processing, production conditions, regulatory oversight, and consumer acceptance. Their successful integration into the food system will therefore require a diversified approach that combines conventional agriculture with plant-based, aquatic, insect-derived, microbial, and cell-based alternatives, supported by interdisciplinary research, effective regulation, infrastructure investment, and equitable, consumer-oriented innovation.

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CHAPTER 3

EMULSION GEL-BASED FAT STRUCTURING STRATEGIES FOR PLANT-BASED MEAT ANALOGUES

*Şelale YALÇINÖZ*¹

¹ Assistant Professor Food Quality Control and Analysis Programme, Egirdir Vocational School, Isparta University of Applied Sciences, Isparta, Türkiye ORCID: <https://orcid.org/0000-0003-2503-439X>

1. Introduction

Plant-based meat analogues have gained increasing attention as alternatives to conventional meat products (Kothuri et al., 2025). To achieve meat-like properties, both fibrous and fat-like structures are needed (Fu et al., 2025). The fat-like phase should be integrated into the fibrous protein matrix to provide mouthfeel, flavour release, and juiciness (Fu et al., 2025).

Native adipose tissue has a complex structure (van der Sman & Marangoni, 2026). Its lipid-rich regions are supported by connective tissue (van der Sman & Marangoni, 2026). This structure contributes to tissue integrity, deformability, and thermal stability (van der Sman & Marangoni, 2026). It also helps control lipid release during eating (van der Sman & Marangoni, 2026).

While designing meat analogues, direct addition of liquid vegetable oils can cause phase separation, oil leakage during cooking, and undesirable changes in texture (Ali et al., 2026). Emulsion gels can provide a semi-solid structure for liquid plant oils, allowing them to be used as fat replacers (Niu et al., 2025).

Emulsion gels are particularly relevant because a biopolymer framework constrains the dispersed lipid phase and converts a fluid emulsion into a tunable soft-solid material (Wan, Cheng, Zeng, & Huang, 2023). Particle adsorption at the oil–water interface can improve emulsion stability by creating a strong barrier against droplet coalescence (Ali et al., 2026). In densely packed emulsions, close packing of oil droplets restricts their movement and gives the system solid-like properties (Niu et al., 2025). Hybrid lipid architectures combine different structuring strategies within a multi-component system (Ali et al., 2026). Figure 1 shows the progression from liquid plant oil to more structured fat-like architectures.

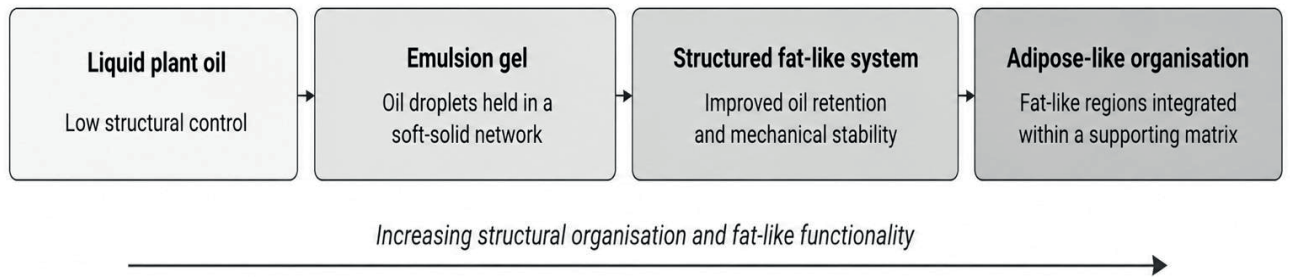


Figure 1. Simplified progression from liquid plant oil to more structured fat-like systems with adipose-like organization. Conceptual synthesis based on Ali et al. (2026), Niu et al. (2025), Wan et al. (2023), Fu et al. (2025) and van der Sman and Marangoni (2026).

The performance of a fat analogue should be evaluated during processing, heating, and deformation in the mouth (van der Sman & Marangoni, 2026). Its mechanical and sensory functions should also be considered, rather than oil retention alone (van der Sman & Marangoni, 2026).

The formation, processing, and use of emulsion gels have been reviewed in detail elsewhere (Niu et al., 2025; Wan et al., 2023; Yiu et al., 2023). This chapter focuses specifically on their use as structured-fat systems in plant-based meat analogues.

2. Why Fat Structuring Matters in Plant-Based Meat

2.1. Structural and sensory role of the lipid phase

Animal fat affects cooking loss, texture, juiciness, flavour, and appearance in meat products (Ren et al., 2022). In plant-based meat, the fat-like phase may provide similar structural and sensory functions (van der Sman & Marangoni, 2026).

Consequently, replacing one lipid source with another is not enough. The fat phase should be structurally organised to mimic important features of adipose tissue (van der Sman & Marangoni, 2026).

A realistic plant-based meat product requires both fibrous and fat-like structural components (Fu et al., 2025). The fat-like phase contributes to important textural and sensory properties and should be integrated with the fibrous protein matrix (Fu et al., 2025). Based on the findings of Hu, Xiang, Cao, Li, and McClements (2025), the spatial organisation of fat-like and lean-like regions can be considered important for reproducing the appearance and texture of marbled meat products. Moreover, based on the findings discussed by van der Sman and Marangoni (2026), it can be inferred that a fat analogue should retain lipid during heating and release it in a controlled manner during eating to support juiciness.

2.2. Nutritional reformulation without losing functionality

Vegetable oils contain high amounts of monounsaturated and polyunsaturated fatty acids (Jiaxin Guo, Cui, & Meng, 2023). Therefore, they may have greater nutritional value than animal fats (Jiaxin Guo et al., 2023). Using these oils in emulsified form can also improve the lipid profile of reformulated meat products (Jiaxin Guo et al., 2023).

Reducing fat content can improve the nutritional quality of reformulated meat products

(Domínguez et al., 2023). For instance, in their study, Botella-Martínez et al. (2021) reported lower fat content in beef burgers when pork backfat was replaced with a gelled emulsion. The pork backfat contained 74.41 g/100 g lipid, compared with 40 g/100 g oil in the emulsion (Botella-Martínez et al., 2021). This difference shows how an emulsion gel containing a large aqueous fraction can help in reducing the total fat content of the product (Botella-Martínez et al., 2021).

However, directly replacing animal fat with unsaturated plant oils can reduce product quality, particularly juiciness and hardness (Ren et al., 2022). Unsaturated plant oils are also more prone to oxidation, which may shorten shelf life (Ren et al., 2022). They may also reduce product plasticity and negatively affect texture and nutritional quality (Ren et al., 2022).

To overcome these problems, the oil phase needs structural support. Well-designed emulsion gels can turn liquid plant oils into semi-solid fat replacers with rheological properties similar to animal fat (Niu et al., 2025). Lei et al. (2025) reported better processing and sensory properties when vegetable oils were structured as emulsion gels in plant-based meat. These gels reduced cooking and thawing losses (Lei et al., 2025). Replacement levels of 75% or higher also received higher sensory scores than direct oil addition (Lei et al., 2025).

These findings suggest that fat replacement is not just about reducing animal fat. Lipid quality, structural stability, processing performance, and sensory properties should also be considered (Lei et al., 2025; Niu et al., 2025; Ren et al., 2022).

2.3. Product-level quality requirements

After incorporation into the final product, fat analogues can be evaluated using several product-level characteristics. Examples include mechanical behaviour, fluid loss during heating, thermal response, and sensory function (Fu et al., 2025; J. Guo, Huang, Gu, & Meng, 2025; van der Sman & Marangoni, 2026). Table 1 presents a source-based synthesis of these selected considerations and related evaluation approaches.

Table 1. Functional considerations for emulsion-gel fat analogues in plant-based meat.

Functional area	Evidence-based interpretation	Evaluation reported in the cited studies	References
Mechanical properties	Yield stress, strain-dependent behaviour, and recovery after deformation are important textural properties of plant-based adipose mimetics.	Rheological measurements; hardness, springiness, and cohesiveness	Fu et al. (2025) van der Sman and Marangoni (2026)
Fluid loss during heating	Cooking loss and shrinkage are associated with water and fat loss during heating.	Cooking loss; shrinkage; moisture distribution	J. Guo et al. (2025) Wang et al. (2026)
Thermal behaviour	Thermal response includes structural stability during heating and controlled softening.	Thermal processing; temperature-dependent rheology; shrinkage and oil release during cooking	Wang et al. (2026) van der Sman and Marangoni (2026)
Sensory function	Fat contributes to juiciness, mouthfeel, and flavour delivery in plant-based meat analogues.	Juiciness and fluid-release behaviour	van der Sman and Marangoni (2026) J. Guo et al. (2025)

Thermal behaviour is important because fat-like systems should allow controlled softening without structural collapse and support fat release during eating (van der Sman & Marangoni, 2026).

3. Emulsion Gels as Fat Analogues

3.1. Why emulsion gels can mimic fat

Emulsion gels are soft-solid systems in which oil droplets are either held inside a biopolymer gel matrix or connected to each other to form a three-dimensional network (Niu et al., 2025; Wan et al., 2023).

The microstructure and rheological properties of emulsion gels depend on the concentration of gelling agents, the oil volume fraction, and the conditions used for gelation (Wan et al., 2023). In protein-stabilized systems, the structure also depends on how much of the droplet surface is covered by protein at the oil–water interface (Kothuri et al., 2025).

Proteins can help stabilise oil droplets by covering their surface at the oil–water interface (Ren et al., 2022). They can also contribute to gel formation (Ren et al., 2022). Polysaccharides can make the water phase thicker and, under suitable conditions, can also form a gel network around the oil droplets (Niu et al., 2025; Ren et al., 2022).

In emulsion-filled gels, the gelled continuous phase provides structural support and can improve both the mechanical and thermal stability (van der Sman & Marangoni, 2026). In thermoresponsive emulsion-filled gels, changes in temperature can help control how much oil is released during cooking (van der Sman & Marangoni, 2026). Because of these structural features, these systems can be useful as fat mimetics (van der Sman & Marangoni, 2026). In emulsion-filled gels, oil droplets are held within a supporting gel matrix, giving these systems some structural similarities to adipose tissue (van der Sman & Marangoni, 2026).

3.2. From soft gels to realistic adipose-like structures

A realistic fat replacer should do more than simply provide lipid (van der Sman & Marangoni, 2026). In animal meat, fat is organised within a structured tissue, where lipid-containing cells are surrounded by a connective tissue matrix (van der Sman & Marangoni, 2026). This arrangement gives mechanical support during heating and allows fat to be released mainly when the tissue is strongly deformed during eating (van der Sman & Marangoni, 2026). This organisation is important because the behaviour of fat in meat depends on how it is incorporated into the surrounding matrix, not only on the lipid itself (van der Sman & Marangoni, 2026).

Based on these observations, plant-based fat mimetics should keep the fat-rich phase well integrated within the surrounding matrix during processing, while still allowing fat release

during eating (van der Sman & Marangoni, 2026). This idea can be used to create distinct fat-like regions within the surrounding protein matrix. Hu et al. (2025) used emulsion-filled alginate beads to mimic the fatty regions of plant-based salami. These beads were placed within a protein–polysaccharide matrix that represented the lean part of the product (Hu et al., 2025). Their addition also changed the fracture behaviour of the salami analogue, bringing it closer to that of real salami (Hu et al., 2025). Fu et al. (2025) used a different approach by combining a hybrid emulsion-gel fat phase with a fibrous soybean-protein matrix. The hybrid emulsion gel acted as the fat-like phase, while transglutaminase helped improve its integration with the fibrous matrix (Fu et al., 2025). When the hybrid emulsion content was about 20–30%, the product showed textural properties similar to pork belly. However, increasing the amount further did not improve the texture, and the textural properties started to decline at higher levels (Fu et al., 2025).

Taken together, these studies show that the performance of a fat-like phase depends not only on its composition, but also on how it is positioned and integrated within the surrounding protein matrix (Fu et al., 2025; Hu et al., 2025). Similar approaches have also been tested in other plant-based meat systems, as discussed in section 3.3.

3.3. Recent application evidence in plant-based meat

Recent studies have used emulsion-gel fat analogues in different plant-based meat products. Some studies mainly used emulsion gels to replace conventional fat (Kothuri et al., 2025; Lei et al., 2025). Others used them to form separate fat-like regions within the product (Fu et al., 2025; Hu et al., 2025). Other studies focused more on how these systems behave during processing and heating (J. Guo et al., 2025; Qiao, Chen, Luo, Zhang, & Liu, 2026; Wang et al., 2026).

Representative examples are summarised in Table 2.

Table 2. Recent applications of emulsion-gel fat analogues in plant-based meat and related systems (2024–2026).

Structured-fat design	Product / application	Main reported finding	References
Olive-oil emulsion gels with chia flour, oat bran, or soy protein isolate	Plant-based patties	Emulsion-gel patties had lower cooking loss and higher water-holding capacity. Chia-containing patties also showed stronger texture values than the control.	Kothuri, Keum, Lee, Han, and Han (2024)
Soy-protein/polysaccharide hybrid emulsion gel	Two-phase plant-based meat	Around 30% hybrid emulsion gel gave a texture close to pork belly. Transglutaminase helped the gel phase integrate with the fibrous protein matrix.	Fu et al. (2025)
Spirulina-protein-based emulsion-gel fat analogues	Meat analogues	These systems improved juiciness. Their cooking loss and shrinkage were comparable to conventional fat systems.	J. Guo et al. (2025)
Vegetable-oil emulsion gels	Soy-protein-based plant-based meat	Emulsion gels lowered cooking and thawing losses. Replacement levels of 75% or more also gave higher sensory scores than direct oil addition.	Lei et al. (2025)
Emulsion-filled alginate beads	Marbled plant-based salami	Adding the beads made the fracture behaviour of the plant-based salami closer to that of real salami.	Hu et al. (2025)
Pea-protein-stabilised emulsion gel with a curdlan/KGM double network	Animal-fat analogue	Some formulations showed cooking-induced shrinkage close to pork fat. However, the gels did not reproduce all changes seen in animal fat.	Wang et al. (2026)
Thermoresponsive soy-protein/carrageenan soft emulsion gel	Plant-based patties and 3D-printable fat analogue	The gels reduced cooking loss to about 10%. Printing accuracy and stability were above 90%.	Qiao et al. (2026)

Overall, these studies show that emulsion gels can have different roles in plant-based meat systems. They can improve fluid retention, juiciness, and texture. They can also be used to create separate fat-like regions and systems that respond to heating or 3D printing (Fu et al., 2025; J. Guo et al., 2025; Hu et al., 2025; Kothuri et al., 2024; Lei et al., 2025; Qiao et al., 2026; Wang et al., 2026).

The main steps discussed in this chapter are summarised in Figure 2. The figure links the need for fat structuring with emulsion-gel design, fat-like organisation, and final product performance.

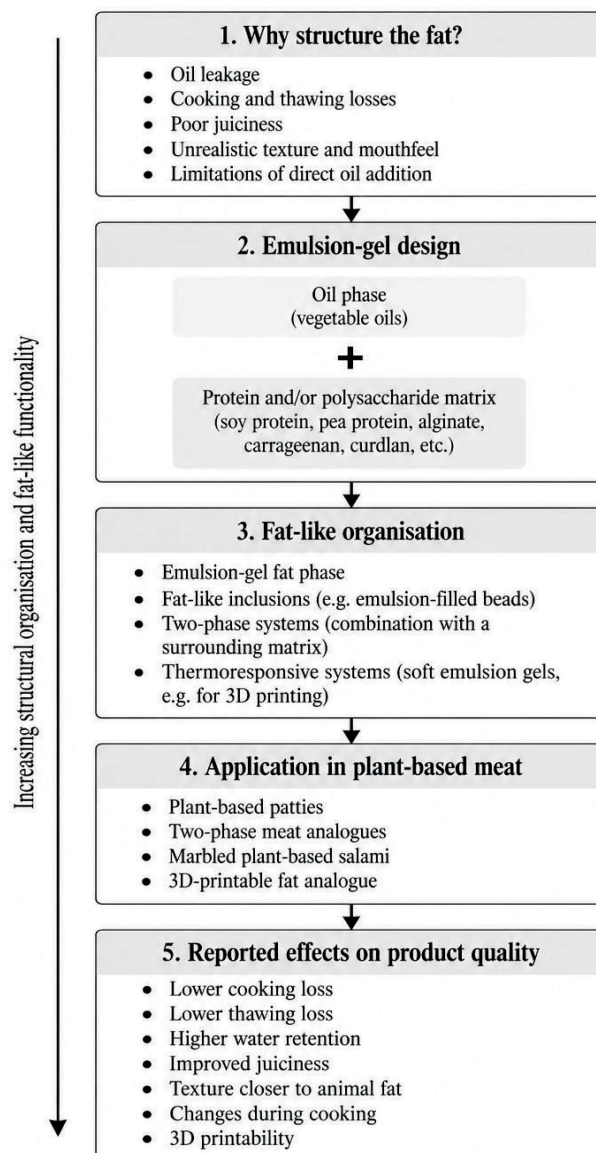


Figure 2. Main steps in emulsion-gel fat structuring for plant-based meat. Developed by the author based on findings reported by Fu et al. (2025), J. Guo et al. (2025), Hu et al. (2025), Kothuri et al. (2024), Lei et al. (2025), Qiao et al. (2026), and Wang et al. (2026).

Overall, Figure 2 suggests that both the type of oil and how it is structured within the product may be important when designing fat analogues for plant-based meat (van der Sman & Marangoni, 2026).

4. Challenges and Future Perspectives

Fat analogues need to be tested in the final product and during processing, cooking, and eating. Their performance cannot be understood from isolated material properties alone (van der Sman & Marangoni, 2026).

Thermal behaviour remains a challenge (van der Sman & Marangoni, 2026). The fat-like phase needs enough stability during processing (van der Sman & Marangoni, 2026). It should also soften in a controlled way and allow lipid release during cooking or eating (van der Sman & Marangoni, 2026). Thermoresponsive emulsion gels may offer a solution (Qiao et al., 2026). Qiao et al. (2026) developed such gels for use in plant-based meat patties.

Oxidative stability is also important when unsaturated plant oils are used (Ali et al., 2026). These oils are more prone to oxidation, which may lead to off-flavours (Ali et al., 2026).

Scale-up is also a challenge (Zhang & Zhang, 2026). Emulsion-gel-based meat products may have high production costs and limited scalability (Zhang & Zhang, 2026). Some structured lipid systems also require specialised ingredients or additional processing steps (Ali et al., 2026). This can increase production complexity and cost (Ali et al., 2026).

Moreover, sensory properties are also a challenge in plant-based meat analogues (van der Sman & Marangoni, 2026). The structured fat should give the product a suitable texture and mouthfeel while keeping oil loss under control (van der Sman & Marangoni, 2026).

Future studies should consider thermal stability, oxidative stability, sensory performance, and practical production requirements together (Ali et al., 2026; van der Sman & Marangoni, 2026).

5. Conclusions

In plant-based meat analogues, fat plays an important role in texture, juiciness, and flavour release (van der Sman & Marangoni, 2026). Adding plant oil alone is not enough (van der Sman & Marangoni, 2026). The oil needs to be structured and incorporated into the surrounding protein matrix (Fu et al., 2025; van der Sman & Marangoni, 2026). Emulsion gels can turn liquid plant oils into semi-solid fat replacers (Niu et al., 2025).

How well these systems work depends on the type of oil used and how the fat-like phase is arranged within the surrounding matrix (van der Sman & Marangoni, 2026). A good fat analogue should remain stable during processing and cooking but still release oil in a controlled way during eating (van der Sman & Marangoni, 2026).

Recent studies have explored the use of emulsion-gel fat analogues in a range of plant-based meat products (Fu et al., 2025; Hu et al., 2025; Kothuri et al., 2024; Lei et al., 2025; Qiao et al., 2026). Examples include plant-based patties (Kothuri et al., 2024), two-phase meat analogues (Fu et al., 2025), and marbled salami (Hu et al., 2025). Qiao et al. (2026) also developed thermoresponsive emulsion gels for plant-based meat and 3D printing applications.

Future studies should consider thermal stability, oxidative stability, sensory properties, and practical production requirements together (Ali et al., 2026; van der Sman & Marangoni, 2026). Production costs and the challenges of large-scale production also need attention (Ali et al., 2026; Zhang & Zhang, 2026).

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