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Utilizing Lentil Proteins and Flours for Sustainable Encapsulation and Techno-Functional Applications in Food Technology

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ABSTRACT

Encapsulation involves forming a thin layer around the core material to separate it from the surrounding environment physically. It is widely used in various industries to provide protection core materials, manipulate release properties, mask undesired sensory properties, immobilize compounds, and to construct a structure to hold the material. The type of wall materials and encapsulation techniques are the main parameters that dictate the success of the operation. Different physical, chemical, or physiochemical methods can be employed depending on the compound to be encapsulated. With their desirable techno-functional properties, legumes are great alternatives to the materials currently used in research and industry. Their high nutritional value, biocompatibility, low cost, and potential health benefits also support their use in encapsulation. Lentils are one of the popular sources of protein after soy and peas. When lentil proteins are used as the only encapsulation agent, modification methods could be employed to enhance its functional properties. Combining them with carbohydrates is another method to improve the characteristics of protein wall materials. This review discusses research on the utilization of lentils to encapsulate different valuable compounds such as probiotics, polyunsaturated fatty acids, phenolic compounds, vitamins, minerals, and coloring agents. The application of lentil flours without purification was also argued. The article highlights the sustainability aspect of employing lentils, considering their renewable nature and potential contribution to reducing environmental impact. Challenges and future prospects are discussed, facilitating further research and development in this area involving legume science and encapsulation technology.

1 | Introduction

The process of confining one material, which is also referred to as the core material, inside another one is defined as encapsulation (Saifullah et al. 2019). Encapsulation can protect the core material from degradation by reducing its reactivity to its outside environment and decreasing or delaying the transfer rate of the core material to the external environment (Wang et al. 2022). The physical characteristics of the original material can also be modified to make it easier to handle (Sonmezler et al. 2023). In addition, the product can be tailored to either release its contents slowly over time or under specific conditions (Khan et al. 2013). In the food industry, encapsulation is explicitly used in the production of functional foods, stabilizing ingredients against deterioration, improving the taste of the product, and enhancing the shelf life (Sasmaz et al. 2023).

Although it is highly dependent on the method being used, particles produced with encapsulation frequently have diameters ranging from a few nanometers to a few millimeters (Saifullah

et al. 2019). Particle size is an essential factor to be considered in food applications; large particles can alter sensory perception, whereas excessively small particles may not provide adequate encapsulation (Djoullah and Saurel 2021). Additionally, the shape of the particles, which can be spherical, irregular, or cylindrical, may also vary depending on the encapsulation method and materials used (Kabakci et al. 2021).

The selection of a suitable method is critical to the success of encapsulation. Different methods can offer distinct advantages, and the best method for encapsulation will depend on a variety of factors, such as the nature of the core material, desired release profile, stability requirements, particle size, and scalability of the process. Some of the extensively used physical methods for capsule formation are spray drying, freeze-drying, and extrusion, while physiochemical methods include coacervation, ionic gelation, and solvent evaporation–extraction. On the other hand, interfacial cross-linking and interfacial polymerization are examples of chemical processes (Mohammadalinejhad and Kurek 2021). The substance to be encapsulated also dictates the encapsulation method. For example, spray drying is the preferred method in the food industry for being more energy-efficient due to reduced energy usage, shorter processing time, and decreased porosity of final dried materials (Wang et al. 2022). Chang and Nickerson (2018) stated that spray drying can be a good choice for encapsulation of oils. Nevertheless, it has several drawbacks when encapsulating materials that are susceptible to heat, such as phenolic compounds. High encapsulation efficiencies can be achieved with coacervation, and it is particularly advantageous in encapsulation and controlled release of the core material in the large intestine. However, this method also presents some limitations, including the high sensitivity of produced particles to pH and ionic strength, challenges with particle agglomeration, and complexity in achieving precise control over particle size (Mohammadalinejhad and Kurek 2021). Extrusion is an uncomplicated method, and capsules produced with extrusion tend to be more uniform in size. However, the applicability of extrusion to industrial methods is low due to the slow and laborious process (Khan et al. 2013). Besides, rapid diffusion and release of the core compound have been reported for hydrophilic or low molecular weight materials (Mohammadalinejhad and Kurek 2021). Therefore, it is important to emphasize that each method possesses its unique advantages and disadvantages and that a multitude of factors must be considered when selecting the optimal method.

The choice of material is another aspect to be considered. A good encapsulation material should first and foremost be able to successfully emulsify or disperse the core material, protecting it against unfavorable environmental conditions and holding it throughout the processing and storage. Other attributes of a suitable coating material include being easy to work with, non-reactive, inexpensive, and releasing the active material at the desired rate when the conditions are favorable (Saifullah et al. 2019). The rheological properties of the materials are also important (Mekala et al. 2022b).

Regarding these characteristics, a variety of synthetic and natural materials can be used to encapsulate valuable core materials. Due to the concerns of the consumers and legislation, researchers are in search of new biological materials to be used in encapsulation (Mekala et al. 2022b). Because natural ingredients are abundant in nature, they provide a cheap and good source of food-grade and environmentally safe shell materials (Wang et al. 2022). Owing to their small size, capability of targeted delivery, slow degradation, and sustained release profile, wall materials of biopolymers have several benefits over other types of delivery agents (Sridhar et al. 2022). The biocompatibility and biodegradability of biopolymer carriers as vehicles are the other advantages. They are GRAS (generally regarded as safe) in food applications and do not induce toxicity or adverse effects (Saifullah et al. 2019). Carbohydrates such as maltodextrin and gum arabic, lipids as liposomes, and proteins derived from animal and plant sources are also utilized in encapsulation. Moreover, combining different types of materials makes it possible to produce capsules with superior properties in terms of protection and controlled release.

Lentil-based materials are increasingly used in encapsulation applications. Their high nutritional value, functional properties such as emulsifying and gelling, and sustainability make lentils a promising choice for various food products and encapsulation applications. Our main objective in conducting this review was to summarize the current findings, identify gaps in existing research, and highlight the advantages of lentil-derived biopolymers in encapsulation applications. By examining the current methods and their effectiveness, we aimed to facilitate future studies, promote the real-world use of lentil biopolymers, and aid to in the advancement of more sustainable encapsulation technologies.

2 | Application of Lentil-Derived Materials for Encapsulation

Proteins and polysaccharides obtained from plants are alternatives to materials currently used in encapsulation processes. Due to considerable growth towards the specialized markets, such as those that prohibit animal-derived proteins based on religious values or dietary choices, the utilization of such proteins could provide a competitive edge to ingredient suppliers and food manufacturers (Avramenko et al. 2016). For example, as they are gluten-free, they can provide an alternative to people with gluten sensitivity. The sustainability of these proteins is another reason affecting consumer preferences. Moreover, legumes provide elevated nutritional value because they are great sources of proteins, minerals, vitamins, fibers, and bioactive substances (Gumus et al. 2017a; Mekala et al. 2022b). The nutritional properties of lentil proteins have promoted its use as a core material in encapsulation, as demonstrated by İşçimen and Hayta (2021).

Functional properties of legume biopolymers such as water and fat binding, emulsifying, gelling, and foaming make legumes attractive to be used in encapsulation as well, specifically for the microencapsulation methods that require preparation of preliminary emulsions. Polysaccharides, in general, contribute to the stability of emulsions by thickening and steric stabilizing abilities, while proteins are widely used to stabilize the oil/water interface of food-grade emulsions

because of their amphiphilic nature (Avramenko et al. 2016). Proteins can adsorb at the oil–water and air–water interfaces. Once adsorbed, proteins exhibit structural changes, attach to droplet surfaces, and create a protective layer over the interface, reducing the interfacial tension (Bernaschina et al. 2024; Mekala et al. 2022a). Polysaccharides may also interact with protein adsorption at the interface, enhancing emulsion stability (Tian et al. 2024). As a result, legume flours, with their rich carbohydrate and protein content, are promising for the stabilization of colloidal systems. Biopolymers extracted and separated from legume flours can be used as functional ingredients in preparing novel food products such as milk substitutes, curd-like products, meat products, and baked goods (Sridhar et al. 2022).

Some of the well-known legumes are beans (*Phaseolus vulgaris*), lentils (*Lens culinaris*), peas (*Pisum sativum*), chickpeas (*Cicer arietinum*), and faba beans (*Vicia faba*) (Sridhar et al. 2022). Among them, lentils are preferred as they are less allergenic than soy proteins and have higher fiber and less fat content compared with peas and chickpeas. They are cultivated globally, readily available from local sources, and demonstrate significant resistance to drought (Bernaschina et al. 2024). Besides, lentil flours displayed higher phenolic content and antioxidant activity. The protein content of the lentil flour was also found to be higher (Ladjal Ettoumi and Chibane 2015).

2.1 | Usage of Lentil Proteins for Encapsulation

Lentil proteins are composed of approximately 70% globulins, 16% albumin, 11% glutelins, and 3% prolamins (Galvão et al. 2023). Based on their sedimentation coefficients, globulins are categorized as either 7S (vicilins) or 11S (legumins; S—Svedberg unit). Vicilin is a trimeric protein with a molecular weight between 150 and 180 kDa while legumin is a hexameric protein with an overall molecular weight of around 300 to 400 kDa. Legume seed albumins, on the other hand, range in molecular weight from 16 to 483 kDa (Can Karaca, Low, et al. 2013). Including globular proteins such as globulin and albumin in the system was hypothesized to fill gaps within the porous matrix, increasing capsule wall density, reducing diffusion out of the capsule, and improving protection in encapsulation operations (Khan et al. 2013).

Preparation of emulsions was demonstrated to be an effective way to encapsulate sensitive compounds to increase their stability. Emulsions must be durable in a variety of pH conditions and temperatures encountered during manufacturing, transit, and storage to be successfully used in food products, which necessitates the use of emulsifiers (Mekala et al. 2022a). As previously mentioned, lentil proteins consist mostly of globulins. Globular proteins, due to their shape, can form thick, viscoelastic films surrounding oil droplets in emulsion systems that can aid in the stabilization of droplets (Can Karaca et al. 2015). Creating stable emulsions is essential to achieve effective surface coating of droplets and improved entrapment efficiencies (Avramenko et al. 2016). Legume biopolymers have numerous functional properties that can assist emulsion formation. It has been previously demonstrated that lentil proteins are highly effective natural emulsifiers for oil-in-water emulsion systems as they are highly resistant to compositional and environmental stresses, which include heat, pH, and the addition of salts (Alonso-Miravalles et al. 2020).

PUFA-rich oils, such as flaxseed oil and fish oil, find limited use in the food industry due to their immiscibility, low oxidative stability, and disposition to lipid rancidity (Avramenko et al. 2016). Lipid oxidation can cause a reduction in food quality and loss of nutrients within the food. It can also lead to changes in flavor and the formation of toxic by-products (Gumus et al. 2017b). A well-designed encapsulating shell can aid in the delivery and release of these oils while concurrently increasing their bioavailability (Gumus et al. 2017a).

Accordingly, fish oil emulsions were stabilized with lentil, pea, and faba bean proteins. Legume proteins behaved similarly inside the digestive system and showed similar oxidative stability compared with whey protein (Gumus et al. 2017a). Capsules were fully digested in the intestine, which showed that the use of plant proteins did not hinder digestion or release of lipids. The droplet size was smaller than 500 μm, which facilitates the use of these emulsion systems for the delivery of fish oil (Gumus et al. 2017a). Moreover, emulsions increased the oxidative stability of the core material. The presence of non-adsorbed proteins in the system was presumed to be the factor for the enhanced stability (Gumus et al. 2017b).

In another recent study, freeze-dried capsules of blackberry juice were fabricated to fortify kefir using lentil proteins as the carrier. The aim was to improve both the sensory qualities and the health benefits of the product by the addition of the antioxidant-rich extract. Results demonstrated that fortification of kefir in concentrations of 1%, 2.5%, 5%, and 7.5% enhanced the overall acceptability of kefir without causing any changes in the inherent qualities. The stability or microbial safety of the products was also not affected during a storage period of 28 days (Travičić et al. 2023).

The presence of phenolics in the system can affect the functional properties of proteins. Günal-Köroğlu et al. (2022) investigated the interaction of lentil protein with gallic acid and onion skin phenolics. The addition of phenolics to the system significantly affected the functional properties of lentil proteins, such as foaming and emulsion stability. However, interactions may improve the bioavailability and antioxidant effectiveness of phenolic compounds during the digestive process.

Research indicates that in some cases, phytic acid found in legume flours may act as chelators for minerals (Amat et al. 2023). On the contrary, Evcan and Gulec (2020) hypothesized that plant-based proteins can bind to iron, potentially reducing its free form before adsorption and enhancing its bioavailability. Therefore, for iron fortification, complexes of protein and iron were derived from lentil proteins. The functional properties of the hydrolyzed protein–iron complexes were then evaluated on a cell line, which showed promise against iron deficiency anemia in vitro (Evcan and Gulec 2020). In addition, complexation of cyanidin-3-O-glucoside with lentil proteins increased the thermal and oxidative stability by 90.23% and 54.20%, respectively. The complexes were stable as they did not show any precipitation for a storage duration of 24 h. On the contrary, the

antioxidant properties of the anthocyanins were significantly degraded upon mixing with the wall material (Qian et al. 2022).

Moreover, hydrogels are three-dimensional cross-linked structures programmed to release the core compound in specific conditions. Due to their ability to hold water, hydrogels are ideal for entrapping hydrophilic substances (Djoullah and Saurel 2021). They were also used to encapsulate phenolic compounds, bacteria, and oils in various research (Saifullah et al. 2019). Quiroz et al. (2020) demonstrated that for encapsulation of annatto extract using ionic gelation, encapsulation efficiency values for sodium caseinate (79.36%), soy protein (71.88%), lentil proteins (68.61%), and quinoa proteins (58.38%) complied with the content of reactive groups. Even during high temperature storage (65°C), hydrogels offered protection to the extract for 12 days (Quiroz et al. 2020).

In a study conducted by Ladjal Ettoumi and Chibane (2015), the emulsifying properties of lentil flours were found to be inferior compared with pea and chickpea-derived flours. In addition, the solubility of globulins is especially low around their isoelectric point, which occurs at a pH of 4–5, potentially affecting the stability of prepared capsules (Funke et al. 2022). Modifying lentil proteins can enhance their stability and solubility, addressing these challenges (Liu et al. 2014). Structural modifications can change the functional characteristics of materials by forming new electrostatic and hydrophobic interactions, hydrogen bonding, and disulfide bonds between the denatured protein subunits (Quiroz et al. 2020). Hence, modified coating materials may have improved physical and mechanical characteristics compared with individual coating materials (Avramenko et al. 2016).

Partial enzymatic hydrolysis is one of the methods to potentially increase the functional properties of proteins. However, the effect of the treatment largely depends on the source of protein and processing conditions (Ahmed et al. 2019) and can also have a detrimental effect on functionality. For instance, enzymatic hydrolysis of proteins using trypsin was found to form emulsions with higher particle size (Avramenko et al. 2016). Researchers have suggested that the absence of higher molecular weight proteins in samples prepared using hydrolyzed proteins may account for the observed phenomena (Avramenko et al. 2016). In a similar study, high pressure was employed as a pre-treatment to enzyme treatment with alcalase. Although both treatments can enhance the antioxidant activity and degree of hydrolysis of lentil proteins, they negatively impact the emulsion-forming and stabilizing ability due to changes in the protein structure (Ahmed et al. 2019).

Heating is another technique to modify the structure of proteins. High internal phase emulsions are emulsion systems where the internal phase's volumetric fraction exceeds 74%. They exhibit gel-like rheological characteristics and strong resistance to droplet coalescence; therefore, they can be used for fat substitution (Galvão et al. 2023). Galvão et al. (2023) observed that high internal stability emulsions with higher viscosity, smaller droplet size, and therefore increased stability can be fabricated by the application of heat treatment. Heating of lentil proteins facilitated better interaction at the oil–water interface. In another study, Jo et al. (2023) prepared lentil protein-based fibrillar gel particles through heat treatment and sonication. Emulsions stabilized with the fibrillar particles remained stable for 30 days due to the dense network formed around the droplets. Moderately heated lentil proteins were found to perform the best when all properties investigated were concerned. Alonso-Miravalles et al. (2020) investigated the effect of thermal processing and calcium fortification on the stability of model emulsion systems prepared with lentil proteins. Emulsions without fortification were stable after the application of the heat treatment. However, adding calcium, particularly at doses larger than 4 mM, leads to lower heat stability, as seen by the increased particle size and viscosity. Consequently, coalescence and separation were observed in the samples.

Saricaoglu (2020) studied the impact of high-pressure homogenization ranging from 25 to 150 MPa on the functional, structural, and rheological attributes of lentil protein isolate suspensions. The emulsifying activity and emulsion stability index of the suspensions improved with increasing pressure up to 100 MPa. However, a significant decline was observed at 150 MPa due to protein unfolding, which had a detrimental effect. On the contrary, Tabilo-Munizaga et al. (2019) found that stable lentil emulsions could be achieved with homogenization pressures over 200 MPa, noting that exceeding 100 MPa shifted the particle size distribution from multimodal to bimodal and that two passes in the homogenizer significantly reduced droplet size and polydispersity. A related study investigated the effect of high-pressure processing and heat treatment on the structure and functionality of lentil, pea, and faba bean proteins. Both treatments caused significant denaturation, which led to increased surface hydrophobicity, decreased solubility, and lower emulsifying activity. Although emulsion stability did not improve under high pressure, heat-treated samples showed minimal separation after 24 h of storage (Hall and Moraru 2021). In addition to chemical and thermal modifications, ultrasound can be an alternative to enhance the functional properties of plant proteins and their ability to perform as capsule materials, as demonstrated by Tian et al. (2024).

2.2 | Usage of Lentil Starch for Encapsulation

The starch portion of the lentil flour can also be used in encapsulation. Lentil starch was used as an alternative to potato starch to prepare biodegradable and edible packaging films. Higher water vapor permeability and lower flexibility of films prepared using lentil starch were commented to require further research to improve the properties of the films (Pająk et al. 2019).

Moreover, Ren et al. (2021) employed treatments such as autoclaving, pullulanase treatment, and ultrasound for debranching of lentil starch. Debranched starches were then successfully used to encapsulate rutin, a flavonoid compound. The highest encapsulation efficiency (67.95%) was obtained for samples in which all treatments were applied. A second autoclave treatment, contrarily, led to a decrease in efficiency. Additionally, the release rate data suggested that carriers with lower molecular weight and degree of polymerization, along with higher molecular order, facilitated a slower release of the core material. A higher molecular order refers to the more organized and structurally uniform arrangement of molecules within the

starch matrix. The molecular orderliness was measured through solid-state cross-polarization magic angle spinning carbon-13 nuclear magnetic resonance (^{13}C CP/MAS NMR) spectroscopy, X-ray diffraction (XRD), and differential scanning calorimetry (DSC). High-pressure treatment can also be used to modify the properties of lentil starches. A pressure of 600 MPa for 10 min resulted in complete gelatinization of starch present in the solution. Increasing the pressure also had an increasing effect on damaged starch and resistant starch (Ahmed et al. 2016).

2.3 | Usage of Lentil Proteins Combined With Polysaccharides for Encapsulation

Because no substance possesses all the qualities required for a perfect encapsulating agent, researchers are constantly searching for ways to use a variety of biopolymers in combination as wall materials to improve entrapment efficiency (Chang et al. 2016). When polysaccharides were combined with proteins in the preparation of carrier materials, capsules with better protection, stability, and efficiency were produced (Wang et al. 2022). Chang et al. (2016) demonstrated that the type of polysaccharide was also effective on the shape and surface of capsules. The addition of maltodextrin in microcapsule wall compositions resulted in a coarser surface texture and more noticeable indentations, while capsules prepared with sodium alginate had a smooth surface.

Polysaccharides and proteins are utilized together in complex coacervation, which may improve their functional position as components without requiring chemical or enzymatic modifications (Mohammadalinejhad and Kurek 2021; Tian et al. 2024). For this method, gum arabic and pectin are the most extensively employed biopolymers, although alternative sources, some of which are legume-based, are also receiving attention (Wang et al. 2019). To that end, Wang et al. (2019) investigated the complexation of lentil protein isolate and various anionic polysaccharides (alginate, gum arabic, carboxymethyl cellulose, and ι-carrageenan) at a 4:1 protein isolate to polysaccharide mixing ratio. Researchers pointed out that using different pH values (pH 1.5–8) affected the formation of complexes significantly. Complexes prepared with ι-carrageenan possessed higher stability due to their smaller complex sizes and favorable electrostatic characteristics. Sasmaz et al. (2023) worked on the optimization of encapsulation parameters for coating black garlic phenolics using pectin and lentil protein isolate as the coating materials. An increase in the lentil protein/pectin ratio caused the pH at which the maximum amount of complex coacervate is obtained to shift from pH 3.0 to 3.5 and up to pH 4.0 as the ratio increased. Optimization studies revealed that the highest encapsulation efficiency (73.86%) was obtained with the lowest core/coating ratio (1:4), highest coacervate/maltodextrin ratio (6.0), and highest extract concentration (50%) studied. In another study, lentil proteins and gum arabic were conjugated through a wet-heating Maillard reaction, followed by enzymatic cross-linking to form microgel particles. The particles demonstrated good colloidal stability as pickering stabilizers and interacted effectively at the oil–water interface. Emulsions were stable across a range of ionic concentrations (200 mM salt) and temperatures (4°–85°) for 3 h, although instability was observed for low pH values (pH 3–5) (Du et al. 2023). Even though conjugates were successfully used as emulsifiers, more research is needed regarding safety. Another drawback was that conjugation using the Maillard reaction produces darker-colored capsules, which may limit the application.

Ultrasound treatment enhanced the binding affinity between lentil proteins and *Tremella fuciformis* polysaccharides. This facilitated the formation of more stable and effective protein-polysaccharide complexes by increasing the zeta potential and hydrophilicity of the proteins. Higher total biopolymer concentrations pushed the optimal pH for complex formation to higher pH values (pH 4–5.5) (Tian et al. 2024). Ultrasound treatment also has the potential to produce stable emulsions. Lentil and whey proteins were treated with high-intensity ultrasound and compared regarding their ability to stabilize colloidal systems. For lentil protein emulsions, a nominal power of 600 W decreased the particle size of emulsions by half (5.44 to 2.07 μm), whereas increasing the power to 1200 W did not contribute to a further decrease due to the gelatinization of starch. Additionally, pectin hydrogels filled with lentil protein stabilized emulsions were produced using high-intensity ultrasound for homogenization. Both the hydrogels and CO_2-dried aerogels successfully encapsulated oil-soluble vitamins. Researchers also investigated the effect of adding xylooligosaccharides and ascorbic acid on the structure. It was also commented that the ultrasound treatment did not cause any detrimental effect on the core materials, and increasing the power level improved the characteristics of hydrogels by enhancing the interaction between ingredients (Mekala et al. 2022b). Aerogels prepared using the same method were investigated for the interactions between the lentil protein concentrate-pectin. Results demonstrated that combining polysaccharides with proteins induced the formation of electrostatic interactions and hydrogen bonds, leading to stronger gels and a lower zeta potential value. Application of the ultrasonication treatment led to partial unfolding of the proteins and therefore facilitated gelation of samples (Mekala and Saldaña 2023).

Researchers have also explored the encapsulation of a variety of different oils by using protein and polysaccharides as wall materials. High encapsulation efficiencies were obtained for lentil protein isolate-maltodextrin for encapsulation of flaxseed oil. The capsules were effective in delivering the oil in the gastrointestinal environment and preventing the oxidation of oil throughout a 25-day storage period. Researchers observed that an increase in the core material (10% to 20%) resulted in an increase in the surface oil of the capsules and a decrease in encapsulation efficiency (90.4% to 85.6%), which is consistent with the literature (Can Karaca, Low, et al. 2013). The amount of wall material may be insufficient to encapsulate the material, resulting in lower encapsulation efficiencies. Efficiency was in the range of 85.6%–90.42% for capsules prepared using spray-drying (Can Karaca, Low, et al. 2013), whereas for freeze-dried capsules, it was around 84.4% (Can Karaca, Nickerson, et al. 2013). In addition, both studies highlighted that capsules utilizing lentil protein exhibited a darker color than those using chickpea protein.

Lentil protein–maltodextrin–alginate microcapsules displayed high efficiency and oxidative stability for encapsulation of canola oil, possibly owing to their lower surface oil and larger droplet size. A larger droplet size was proposed to limit the contact between the capsule and the outer environment, decreasing

oxidation. The thicker complex interface achieved by the microcapsules could also have contributed to the stability of the capsules. Researchers encapsulated canola oil with oil concentrations of 20% (using 2%–8% lentil protein isolate and 12%–18% maltodextrin) and 30% (using 2%–8% lentil protein isolate and 9.5%–15.5% maltodextrin). The highest entrapment efficiency (73%) was obtained by employing 20% oil, 2% lentil protein isolate, and 18% maltodextrin in the microencapsulation process (Chang et al. 2016). The same method and capsule materials were used in another research to investigate the effect on encapsulation of canola, fish, and flaxseed oils. It was concluded that the physical properties, efficiency, and fatty acid profiles of the capsules were similar because the identical composition of wall material and conditions for drying. Moreover, encapsulation efficiency was similar (~88%) to the studies in which animal proteins were used to encapsulate the same oil types. Researchers also commented that spray drying did not have a significant effect on the fatty acid profile and, therefore, it was a suitable method for encapsulating oils rich in omega fatty acids (Chang and Nickerson 2018). Avramenko et al. (2016) fabricated lentil protein–maltodextrin capsules by freeze-drying for delivery of flaxseed oil. Lentil proteins were subjected to different treatments to increase their emulsifying properties. Capsules prepared with 4% native lentil protein isolate, 36% maltodextrin, and 10% oil had the lowest surface oil content and the highest encapsulation efficiency. Surface oil refers to the amount of oil present on the outer surface of microcapsules, indicating unentrapped oil, which may affect the stability and shelf life of the encapsulated product. It was measured by dispersing microcapsules in hexane, shaking, filtering, and then evaporating and weighing the remaining oil after heating to remove residual solvent. The lower surface oil of these emulsions demonstrates that lentil protein does not require further heat or partial hydrolysis to function as an encapsulation agent. Researchers argued that stronger chemical treatments might produce different results.

Increasing the amount of core oil to a level of 20% or 30% was aimed by Wang et al. (2022) using lentil protein-κ-Carrageenan and -ι-Carrageenan capsules prepared using spray and freeze drying. Researchers emphasized that the addition of both types of carrageenan ensured the stability of flaxseed oil capsules, while destabilization occurred when only lentil protein isolate was used due to lower viscosity. Even though higher efficiencies were obtained for spray drying, it resulted in very high oxidation for the flaxseed oil. Increasing the ratio of the core material is desirable for industry applications; however, increasing the amount of flaxseed oil in the samples resulted in a lower yield, as demonstrated by Wang et al. (2022). It has been previously emphasized that to increase the encapsulation efficiency and to improve both flow characteristics and the long-term oxidative stability of the powder product, the surface oil of the microcapsules needs to be reduced. Higher oil loads, contrarily, are found to increase the surface oil of the capsules (Avramenko et al. 2016).

Probiotics are used for a variety of health purposes. Still, their effectiveness depends on the viability of the microorganisms throughout the shelf life of the product and the upper digestive system (Khan et al. 2013). Encapsulation can increase the proposed health benefits of such probiotics by forming a barrier against unfavorable environmental conditions and increasing the ability of probiotics to reach the desired part of the body (Wang et al. 2014). Khan et al. (2013) investigated the relative ability of different legume proteins (pea, soy, faba bean, and lentil) to protect the viability of *Bifidobacterium adolescentis* cells under adverse conditions. Legume proteins were used in combination with alginate (0.6% w/w) during extrusion, which can prevent the drawbacks of using alginate alone as the only capsule material, such as the porosity of the alginate beads, which causes degradation in acidic environments, as well as the challenge of scaling up the procedure. The extrusion process involved heating the protein solution to 80°C with controlled stirring, and the microorganisms were added by mixing the harvested *B. adolescentis* cells with the protein-alginate solution before extrusion into a calcium chloride cross-linking bath at room temperature. All the legume proteins provided the microorganisms sufficient protection against synthetic gastric environment, ensuring targeted delivery and release in the intestine lower gastrointestinal tract. Encapsulation of bacteria with the capsules also increased the viability of microorganisms when added to yogurt products during a 30-day storage period (Khan et al. 2013). On the other hand, Wang et al. (2014) observed that lentil and faba bean proteins were less successful in protection of live cells compared with pea and soy proteins against synthetic gastric juice. Due to the poor protection provided by lentil-alginate capsules, most of the *B. adolescentis* cells lost viability after 30 min of incubation. The presence of irregular and large number of pores may have contributed to the lower stability. On the other hand, the capsules released the core material successfully in synthetic intestinal fluids, which is the desired outcome to ensure health benefits from the probiotic microorganisms. The differences in results between these studies may arise from the concentration of biopolymers or the method used in the research.

2.4 | Usage of Lentil Flours for Encapsulation

As mentioned in the previous sections, in most cases, the combined use of carbohydrates and proteins improved the degree of protection of the core material. The efficiency of the operation was also higher, showing that different portions of the same type of legume can also be employed in encapsulation. Furthermore, using only the proteins or polysaccharides of lentil flour requires the separation of the desired fraction. It has been debated that purification processes only use a fraction of the plant's components and often require substantial amounts of water, energy, and solvents due to the complex nature of purification (Sridharan et al. 2020). Li et al. (2020) also stated that the current purification methods led to protein denaturation and aggregation to a high degree, which represented difficulties. The decision to use lentil flour instead of lentil concentrate or isolate may also facilitate the potential industrial applications (Bernaschina et al. 2024).

Most of the work done on lentil flours included the formulation of emulsions. After preparation, emulsions can be incorporated into food materials or dried using several techniques to obtain powders (Avramenko et al. 2016). Vasilean et al. (2018) focused on employing minimally refined flours from red and green lentils as emulsifiers. Flours showed comparable emulsification ability and thus could be an alternative to the more popular soybean flour as the capsule material.

A similar study investigated lentil protein sources with different refinement levels (isolate, concentrate, and flour) concerning their emulsifying ability (Bernaschina et al. 2024). Protein isolates provided smaller droplet sizes and more stability compared with concentrates and flour. On the other hand, emulsions prepared using less purification showed fewer aggregates. Despite the higher droplet sizes and polydispersity, emulsions did not show coalescence during storage (Bernaschina et al. 2024). Funke et al. (2022) also reported that emulsions prepared using highly refined fractions had smaller droplet sizes and were initially more stable. However, they experienced phase separation over time due to the settling of larger insoluble components. Conversely, less refined fractions containing less protein and more starch resulted in emulsions with larger droplet sizes that also separated upon storage. The difference in stability may be a result of the different methods used for refining. Overall, flours can be advantageous for certain uses, like concentrated emulsions, where their high viscosity and hydrodynamic interactions between particles can mitigate the impact of gravitational sedimentation (Funke et al. 2022).

Kabakci et al. (2021) encapsulated magnesium using double emulsions with varying concentrations of lentil flour. Double emulsions are emulsions dispersed in another emulsion. Ensuring the controlled release and transport of bioactive substances, they are promising in many fields as a result of their structures that perform functions such as separation, encapsulation, and protection (Sonmezler et al. 2023). Even though double emulsions are successful carriers of the core material, they are still thermodynamically unstable, resulting in coalescence and flocculation of the particles as well as creaming or breaking of the emulsion (Bernaschina et al. 2024). Therefore, both hydrophilic and lipophilic emulsifiers are employed to stabilize different phases of the emulsion. Their study used lentil flour as the hydrophilic emulsifier needed to stabilize the outer water phase. Encapsulation efficiency exceeded 93% for all the samples. An increasing trend in stability was observed in higher flour concentrations, which was attributed to the higher viscosity and lower particle size. The application of ultrasonication also enhanced the stability of samples. The optical images of double emulsions prepared with high speed homogenization and ultrasonication can be seen in Figure 1. In addition, the baking stability and percent release in after simulated gastric and intestinal juice of magnesium with and without encapsulation can be seen in Table 1. For the baking stability analysis, emulsions were added to the batter and cakes were baked at 175°C for 30 min in a conventional oven. Emulsions were successful agents for carrying magnesium through baking and storage, along with increasing the bioavailability by breaking down in the body and releasing the core material in the intestine. (Kabakci et al. 2021).

It is harder to understand the actual mechanisms that are taking place when flours are directly used in the encapsulation process. Nevertheless, further research on the topic will shed light on how different species interact and how these interactions affect encapsulation efficiency. This will facilitate the use of legume flours in operations without the need for the isolation of separate portions of the flour.

2.5 | Usage of Lentil Proteins and Flours for Nanofiber Production

Production of nanofibers using electrospinning has gained popularity in various sectors such as textiles, biomedical, cosmetics, and pharmaceuticals recently because it allows for the

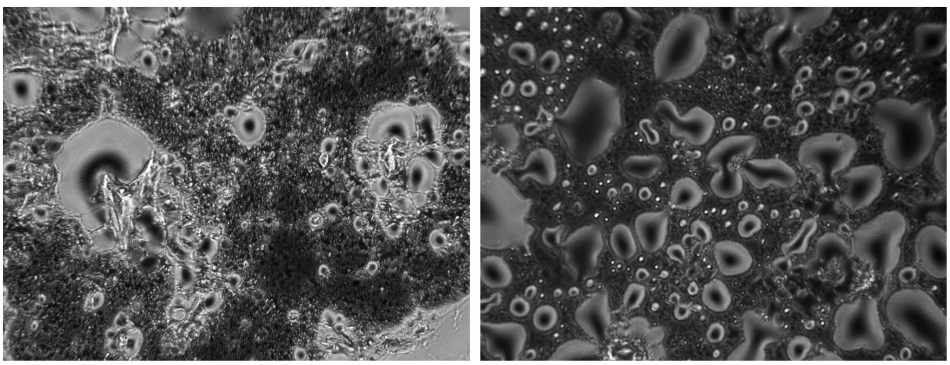

FIGURE 1 | Optical images of double emulsions prepared using lentil flour (left: high-speed homogenization; right: ultrasonication) *Source:* (copied with permission Kabakci et al. 2021, Copyright 2021, Springer).

TABLE 1 | Baking stability and percent release in after simulated gastric and intestinal juice of double emulsions prepared using lentil flour for encapsulation of magnesium.

	Baking stability	Percent release in gastric juice (%)	Percent release in intestinal juice (%)
Control (magnesium)	0.82 ± 0.03^{c}	69.57 ± 0.31^{a}	85.05 ± 0.67^{ab}
Primary emulsion	71.67 ± 0.94^{b}	63.85 ± 1.70^{a}	85.46 ± 2.06^{a}
Double emulsion	82.86 ± 1.20^{a}	59.22 ± 2.87^{a}	74.50 ± 2.77^{b}

Note: Different letters in the same column represents a significant difference ($p \leq 0.05$).
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continuous production of fibers and operates under milder operational conditions (Işçimen and Hayta 2024). However, their application in the food industry is limited, primarily due to the limited number of solvents available for non-toxic electrospinning applications (Tam et al. 2017). Therefore, materials with spinnability in solvents that are safe for food applications need to be investigated. This method can be employed in packaging applications, and fibers can serve as carriers for functional compounds.

Işçimen and Hayta (2024) used lentil proteins in combination with polyvinyl alcohol to encapsulate ferulic acid. Carrier polymers are used because the spherical structure of lentil proteins does not provide sufficient chain structure necessary for fiber formation, which causes limited electro-spinnability when lentil proteins are used alone. Fibers with lower diameter were obtained when the protein content of the mixture was increased. Also, antioxidant material was homogenously distributed within the fibers. Encapsulation efficiencies around 78% was obtained for 50:50 polyvinyl alcohol–lentil protein isolate mixture.

Similarly, fibers prepared from lentil flour/polyethylene oxide to act as an active packaging material. This study succeeded in reducing the oxidative degradation of walnuts by encapsulating gallic acid in the fibers. pH of the solutions was highly effective in determining the properties of resulting fibers with an acidic pH (pH 3), leading to a higher loading efficiency, total phenolic content, and antioxidant activity due to lower viscosity and higher electrical conductivity. On the other hand, alkaline conditions (pH 10) were adopted for the storage studies because the fibers were found to be more homogenous in structure (Aydogdu et al. 2019). On the other hand, a neutral pH (pH 7) can cause bead formation in fibers, as demonstrated by Tam et al. (2017). Researchers successfully prepared fibers by combining lentil flours with hydroxypropyl cellulose. This also demonstrates that advanced microstructures may be fabricated sustainably from raw materials and that resource-intensive purification of plant biopolymers is not required (Li et al. 2020).

3 | Conclusions

The findings of this review suggest that lentil protein, starch, and flours can be used to encapsulate valuable compounds. Lentils are cheap, abundant, and renewable, making them a good source of wall materials. They also possess functional properties that can be modified physically, chemically, or by enzymes that can further increase their applicability. Novel processes can also be employed in the modification of proteins. However, research is needed regarding the safety implications.

Moreover, encapsulated materials can be employed explicitly in the fortification of foodstuffs and the production of functional foods. However, the variation of food materials used in the present studies is relatively limited. Micro- and nano-capsules could be utilized in different products, expanding the research scope. The industrial applicability of encapsulation operations also needs to be discussed. As previously mentioned, some of these encapsulation techniques are hard to adapt to the industry due to concerns about cost and the intricate or slow nature of the operation. It was also debated that flours, even when used without purification, are able to stabilize emulsions successfully. However, more studies are needed to study the interactions between molecules during encapsulation and long-term storage.

Author Contributions

Demet Sonmezler: conceptualization, investigation, writing – original draft. **Gulum Sumnu:** conceptualization, supervision, writing – review and editing. **Serpil Sahin:** conceptualization, writing – review and editing.

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The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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