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Encapsulation of wheat germ oil: A comprehensive review of composition, properties, encapsulation techniques, and food model applications

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SUMMARY: Wheat germ oil (WGO), which contains significant amounts of tocopherols, vitamin B, phytosterols and policosanols, is extracted from wheat germ using both conventional and non-conventional methods. Accordingly, these compounds are mainly associated with increased athletic performance, reduced platelet aggregation, and lowered plasma cholesterol levels, while also helping to decrease the risk of overweight/obesity and cardiovascular diseases. However, WGO is highly prone to oxidation due to its highly-unsaturated fatty acid profile, resulting in a very short shelf-life. Encapsulation technology has been employed to reduce oil degradation, enhance shelf-life, and mask undesirable sensory attributes. This review summarizes findings from the literature, covering the chemical composition, biological characteristics, and health benefits of WGO, as well as the role of encapsulation technology in preserving its functional components and enhancing its stability for applications in the food and pharmaceutical industries.

KEY-WORDS: *Application; Encapsulation; Food formulations; Oxidative stability; Wheat germ oil.*

RESUMEN*: Encapsulación de aceite de germen de trigo: Una revisión exhaustiva sobre la composición, propiedades, técnicas de encapsulación y aplicaciones en modelos alimentarios.* El aceite de germen de trigo (AGT) se extrae del germen de trigo tanto mediante métodos convencionales como no convencionales y contiene cantidades significativas de tocoferoles, vitamina B, fitoesteroles y policosanoles. Estos compuestos se asocian principalmente con un mayor rendimiento deportivo, una menor agregación plaquetaria y niveles más bajos de colesterol plasmático, además de ayudar a disminuir el riesgo de sobrepeso/obesidad y enfermedades cardiovasculares. Sin embargo, el AGT es muy propenso a la oxidación debido a su alto perfil de ácidos grasos insaturados, lo que resulta en una vida útil muy corta. La tecnología de encapsulación se ha empleado para reducir la degradación del aceite, prolongar su vida útil y enmascarar atributos sensoriales indeseables. Esta revisión resume lo encontrado en la bibliografía, abarcando la composición química, las características biológicas y los beneficios para la salud del AGT, así como el papel de las tecnologías de encapsulación en la preservación de sus componentes funcionales y la mejora de su estabilidad para aplicaciones en las industrias alimentaria y farmacéutica.

PALABRAS CLAVE: *Aceite de germen de trigo; Aplicación; Encapsulación; Estabilidad oxidativa; Formulaciones alimentarias.*

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1. INTRODUCTION

Wheat (*Triticum* spp.), an annual plant belonging to the Gramineae (Poaceae) family, is often referred to as the "king of cereals" and is grown worldwide (Verma *et al*., 2019). A wheat grain is mainly comprised of three unique parts, namely endosperm (81-84%), bran (14-16%), and germ (2–3%) (Dunford and Zhang, 2003; Siraj, 2022). Wheat germ is a nutrient-dense by-product obtained during industrial wheat milling (Capitani *et al*., 2011). It is separated from the grain during modern wheat flour production due to its abundance of unsaturated fatty acids which are highly susceptible to oxidation, leading to rancidity in the flour (Kutlu *et al*., 2024). Although wheat germ is a good source of nutritional compounds such as proteins, lipids, sugars, minerals, dietary fibers and other phytochemicals such as vitamins and carotenoids, it remains underutilized at an industrial scale (Gelmez *et al.,* 2009). While it is mainly used as animal feed, it has also been incorporated into various food products, including cookies, macaroni, beef patty, biscuit, bread, muffin, tarhana, and dairy desserts to enhance their nutritional properties (Brandolini and Hidalgo, 2011).

Wheat germ, constituting approximately 10–15% of the whole wheat grain, contains wheat germ oil (WGO), which is considered its most nutritionally valuable component. It contains unsaturated fatty acids, phytosterols and vitamins including vitamin E, riboflavin and thiamin (Karadeniz *et al*., 2018). Various methods have been developed to extract WGO, ranging from conventional techniques such as cold pressing to advanced technologies, including supercritical carbon dioxide (SC-CO_2) extraction, microwave-assisted extraction, and ultrasound-assisted extraction (Eisenmenger and Dunford, 2008; Özcan *et al*., 2013; Gelmez *et al*., 2009).

Due to the abundance of unsaturated fatty acids in WGO, it is highly susceptible to oxidative rancidity (Ghafoor *et al.,* 2017), which limits its use as a functional food ingredient. Encapsulation has emerged as an efficient way for increasing the stability of bioactive compounds and protecting them from adverse environmental conditions during food processing and storage (Kutlu *et al*., 2024). Overall, this review aims to highlight the nutritional potential of WGO and provide a comprehensive overview of encapsulation techniques and their impacts on its stability. Additionally, it explores the potential applications of encapsulated WGO in various food formulations, emphasizing its integration as a functional ingredient to improve the nutritional profile and stability of food products.

2. COMPOSITION, NUTRITIONAL AND HEALTH PROMOTING PROPERTIES OF WGO

WGO is widely recognized for its high nutritional value, serving as a rich natural source of lipids and lipid-soluble components such as tocopherols (vitamin E), phytosterols, and policosanols (Eisenmenger and Dunford, 2008; Ghafoor *et al*., 2017; Karadeniz *et al.,* 2018). Notably, WGO possesses a greater concentration of phytosterols compared to many commonly used commercial oils, with sitosterol (60–70%) and campesterol (20–30%) being the predominant types (Eisenmenger and Dunford, 2008). Studies on the fatty acid composition of WGO have consistently highlighted its richness in polyunsaturated fatty acids (PUFAs), particularly linoleic acid (LA, 18:2, n-6 (omega-6)) (49-60%), followed by oleic acid (OA, 18:1, n-9 (omega-9)) (14-25%), linolenic acid (LNA, 18:3, n-3 (omega-3)) (4-10%), palmitic acid (16:0) (11-19%), and stearic acid (18:0) (1%) (Siraj, 2022) (Figure 1). Similarly, Dunford and Zhang (2003) also reported that linoleic acid was the major unsaturated fatty acid in WGO, followed by oleic acid, while palmitic acid was the most abundant saturated fatty acid. Epidemiological studies examining the relationship between dietary fatty acids and their health outcomes have demonstrated that the consumption of PUFAs, especially linoleic acid, was associated with cholesterol lowering effects and reduced risk of cardiovascular diseases (Siraj, 2022). Moreover, linoleic and linolenic acids are essential fatty acids that the human body cannot synthesize, making dietary intake crucial. Additionally, these fatty acids contribute to the production of prostaglandins, which play a vital role in muscle contraction and possess anti-inflammatory responses (Özcan *et al.,* 2013; Ghafoor *et al.,* 2017). Given the unique nutritional profile and health benefits of WGO, especially as a functional ingredient, WGO has garnered increasing scientific interest in recent years. As shown in Figure 2, research on WGO has expanded significantly, reflecting a growing recognition of its potential applications and health-promoting effects.

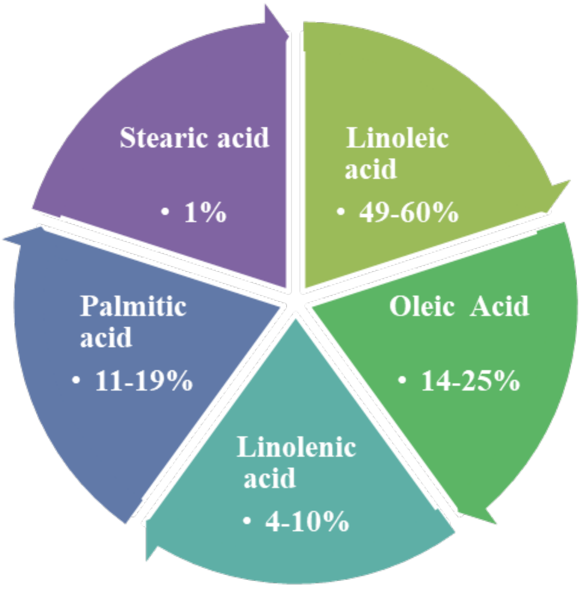

FIGURE 1. Fatty acid composition of WGO.

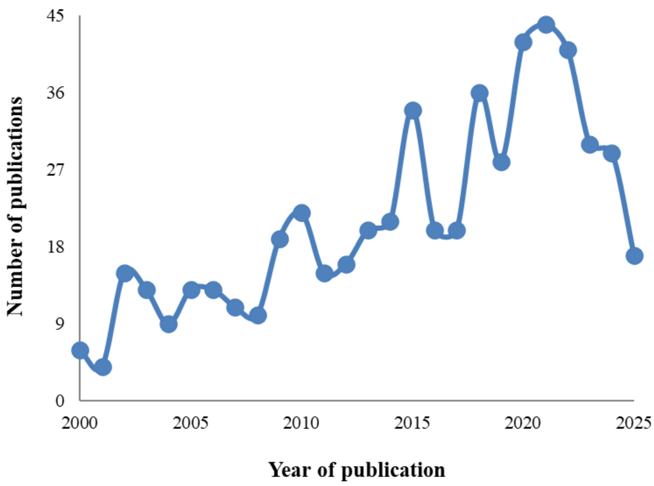

FIGURE 2. Number of research publications on WGO from 2000 to 2025. (The database source: Web of Science; Accessed: 30 September 2025)

WGO is a rich source of total tocopherols (2188 µg), with α-tocopherol (53.9%), β-tocopherol (18.2%), γ-tocopherol (22.5%) and δ-tocopherol (5.4%) (Capitani *et al.,* 2011; Magarino *et al.,* 2015). In addition to tocopherols, WGO contains policosanols, particularly octacosanol, which have been associated with various health benefits, including enhanced athletic performance, improved platelet aggregation and regulation of plasma cholesterol. These compounds also contribute to reducing the risk of obesity and cardiovascular diseases (Lai *et al.,* 2021). However, previous studies have reported that environmental factors, especially heat treatment, even at low temperatures, could lead to a decrease in antioxidant activity and the degradation of tocopherols in WGO (Magarino *et al.,* 2015).

Beyond its lipid-soluble components, WGO serves as a good source of essential micro- and macro-elements, such as potassium, zinc, calcium, phosphorus, selenium, and iron, which have several important roles in maintaining human health (Brandolini and Hidalgo, 2011). It also contains various biologically active compounds, including unsaponifiable matter, which are rich in sterols (phytosterols), pigments, and ceramides (Lai *et al.,* 2021).

WGO has attracted considerable interest in recent years and is widely used not only for food, cosmetic, pharmaceuticals, agricultural purposes but also for biological insect control agents (Gelmez *et al.,* 2019). Moreover, WGO has been traditionally used for a variety of medicinal purposes, including anti-aging effects, cholesterol-lowering activity, cardiovascular protection, anti-cancer, anti-inflammatory, and anti-ulcer benefits (Figure 3) (Aslan *et al.,* 2021; Feltre *et al.,* 2020; Siraj, 2022). Given these wide-ranging health-promoting effects, WGO stands out as an excellent functional component for modern medicine and nutraceutical supplements (Kutlu *et al.,* 2024; Lai *et al.,* 2021).

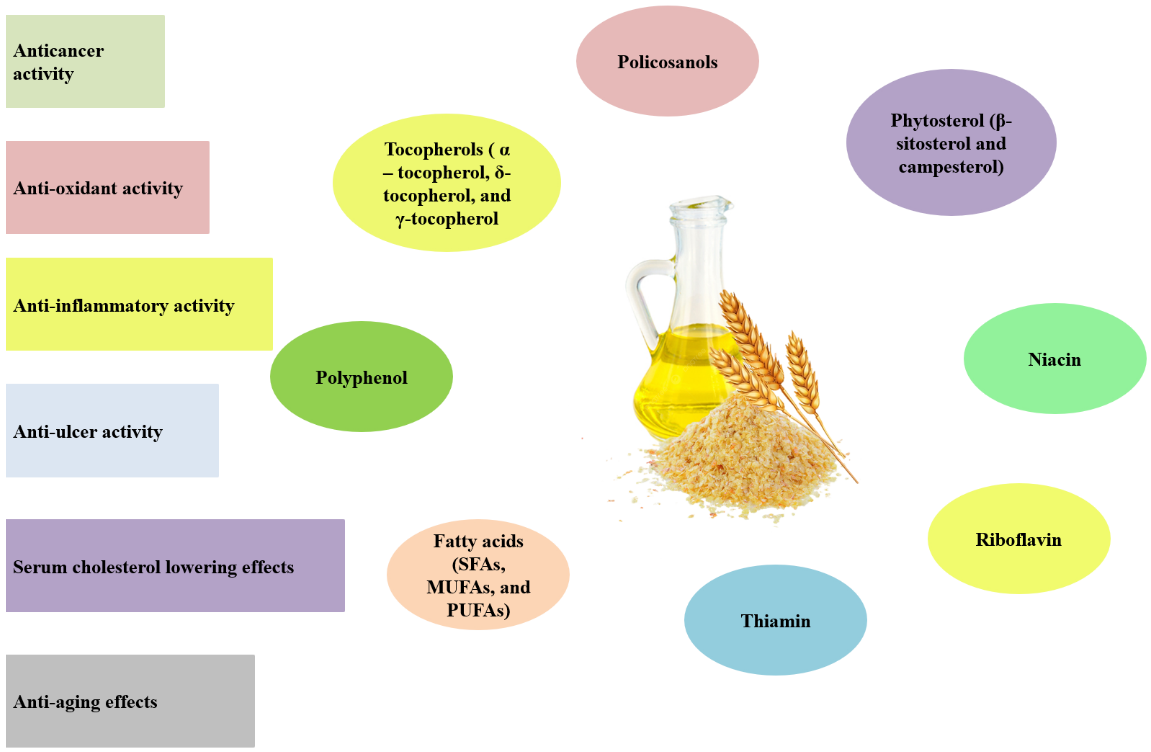

FIGURE 3. Nutritional composition and health benefits of WGO.

Carotenoids, the natural pigments found in plants, exhibit strong antioxidant properties and effectively neutralize singlet molecular oxygen and peroxyl radicals. These compounds play a crucial role in the body's antioxidant defense system, often working synergistically with other antioxidants (Ghafoor *et al.,* 2017; Siraj, 2022). In WGO, lutein is the predominant carotenoid, followed by zeaxanthin and β-carotene. While carotenoids are primarily responsible for the coloration of WGO, flavonoid glycosides contribute only minimally (Ghafoor *et al.,* 2017).

3. ENCAPSULATION OF WGO

The acceptability and market value of oils are primarily determined by their quality and stability, making these parameters essential for quality control. However, when oils are incorporated into formulations without encapsulation, they can negatively impact the flavor, aroma, color and nutritional characteristics of food products. This is mainly due to their instability against oxidation and degradation, particularly in the case of unsaturated fatty acids (*e.g.* linoleic, oleic and linolenic acids) (Feltre *et al.,* 2020; Siraj, 2022). To overcome these challenges, encapsulation techniques have emerged as an effective way to enhance oil stability by providing resistance against external factors.

Encapsulation is a promising strategy that involves the entrapment of the bioactive component(s) within core/coating material(s) to fabricate small protective capsules. This technique offers multiple benefits including protecting the sensitive food ingredients from environmental stresses (*e.g.* light, oxygen, heat and moisture), masking undesirable flavors and improving the delivery of active nutrients (Kutlu *et al.,* 2024). A wide variety of natural or synthetic polymers can serve as wall materials, depending on the desired characteristics of the encapsulated system (Kutlu *et al*., 2024). The choice of the most convenient wall material and encapsulation method is guided by three main criteria: feasibility, cost-effectiveness and safety (Kutlu, 2021). In particular, an ideal wall material for oil encapsulation should exhibit good emulsion and film-forming abilities, low viscosity at high dry matter content, low higroscopicity, a neutral taste and aroma (Jafari *et al.,* 2008).

Oils are encapsulated for various purposes, including conversion of liquid oils to solid forms to facilitate handling and transportation, protecting them from volatilization or oxidation, masking undesirable tastes and odors, and enabling controlled release applications (Kutlu, 2021). Encapsulation techniques are generally categorized into three main groups based on the average particle size in the resulting capsule: (i) micro-encapsulation, (ii) nano-encapsulation and (iii) macro-encapsulation (Suresh *et al.,* 2022). Micro-encapsulation involves entrapping small particles or droplets of an active core material, whether solid, liquid or gas, within a wall material to form microcapsules or microspheres (Calvo *et al.,* 2011). These microcapsules typically range from 1 to 1000 µm in size, and microencapsulation methods usually include spray-drying, spray-chilling, fluidized bed coating, extrusion, coacervation, and interfacial polymerization. Among the methods given, the spray-drying and extrusion methods require emulsion preparation as a critical step for effective encapsulation (Bratovcic and Suljagic, 2019). In contrast, nano-encapsulation involves the formation of particles in the nanometer range (1-100 nm), providing improved bioavailability and stability of the encapsulated compounds (Tarafdar, 2013).

Biopolymers which can be used in food formulations (e.g. foams, emulsions, and dispersions) are considered amphiphilic macromolecules which play an important role in stabilizing active agents. Under certain conditions, including protein-polysaccharide ratio, pH, ionic strength, temperature, and mixing process, protein and polysaccharide complexes exhibit superior functional properties compared to the individual use of proteins or polysaccharides. Moreover, the electrostatic interactions between oppositely charged proteins and polysaccharides can enhance the adhesion of the oil-water interfaces, thereby improving overall stability (Kutlu *et al.,* 2024).

Given its high PUFA content, WGO is particularly prone to oxidation, leading to extensive research efforts aimed at its oxidative stability. Table 1 presents a comprehensive summary of recent studies on WGO encapsulation, highlighting various nano/micro-emulsion formulation techniques, coating materials, emulsifiers, research objectives, and key findings. For instance, Lai *et al*. (2022) investigated the effects of high-pressure homogenization on a WGO-water system by varying the homogenization pressure (100–300 bar), oil fraction (10–20%, v/v), and lecithin concentration (0–0.2%, w/v). The authors reported that a rise in homogenization pressure and lecithin concentration led to smaller particles and enhanced emulsion stability. However, a higher fat fraction had the opposite effect. Similarly, Feltre *et al.* (2020) encapsulated WGO within sodium alginate-gelatinized corn starch beads at different ratios (2:0, 1:1, 1:2, and 1:4) and found that the 1:1 alginate-starch ratio provided the best physicochemical stability during the storage of the WGO capsules. Additionally, the beads exhibited higher tocopherol content and lower oxidation level at the end of the six-days accelerated stability test conducted at 65 °C. Subsequently, Mirtalebi *et al*. (2020) encapsulated WGO within nanostructured lipid carriers. The emulsions allowed for the preservation of WGO and provided greater oxidative stability when the matrix was prepared at a suitable pH, surfactant type and ratio.

TABLE 1. Encapsulation techniques applied in the fabrication of nano/microemulsions loaded with WGO based on the scientific database from 2015 to 2025.

Emulsion preparation method(s)	Coating material(s)	Emulsifying agent(s)	Main goal of the study	Results	References
High-pressure homogenization	-	Lecithin	To research the effects of various parameters such as homogenization pressures, oil fractions and lecithin concentrations on the distribution of particle diameters and homogenization efficiency.	Particle size and emulsion system stability were significantly affected by operating conditions. The highest emulsion stability (98.61%) with a mean particle size of 3.32 μm was observed under the following conditions: operating pressure of 300 bar, oil fraction of 10% (v/v), and lecithin concentration of 2% (w/v).	Lai *et al.* (2022)
Ultrasonication process and ionic gelation	Combination of sodium alginate and gelatinized corn starch	-	To generate a closed microstructure matrix, enhance oxidative stability and decrease the degradation of WGO compounds.	The combination of sodium alginate and gelatinized corn starch resulted in a higher encapsulation yield and more dispersed emulsions compared to sodium alginate alone. Additionally, all of the prepared emulsions showed pseudoplastic behavior with shear-thinning properties.	Feltre *et al.* (2020)
Ultrasonication process	Nanostructured lipid carriers	Tween 80, lecithin, span 40, sodium dodecyl sulfate, poloxamer 407 and percirol ATO5	To investigate the influences of surfactant type, surfactant composition, and pH on the oxidative stability of nanostructured lipid carriers including WGO.	The type of surfactant affected the particle size, showing that the nonionic emulsifier outperformed the ionic emulsifier. Also, pH was an important factor affecting oxidative stability, with nanostructured lipid carriers displaying the highest oxidative stability at pH 8. WGO can be protected from oxidation better in the nanostructured lipid carriers than in O/W emulsions.	Mirtalebi *et al.* (2020)
Ultrasonication process	Maltodextrin, whey protein concentrate and gum Arabic	-	To enhance the efficiency and stability of WGO by applying two encapsulation techniques, micro and nanoencapsulation, and to study their effects on the characteristics of micro and nano emulsions.	Lower peroxide value, thiobarbituric acid-reactive substance, acid value, emulsion stability index, particle size, viscosity as well as higher pH, were determined in nano WGO emulsions compared to micro WGO emulsions during the storage period.	Salem and Khalifa (2018)
Ultrasonication process	-	Lecithin and Tween 80	To prepare and characterize the phyto-nanoemulsions and determine their cytotoxicity, wound healing, and antioxidant properties.	Phyto-nanoemulsions of WGO and black cumin oil containing phyto-components of *Calendula* flowers showed greater bioactivity than their plain forms. The developed formulations can be used for various purposes such as dermal cosmetic products or food supplements.	Gumus *et al.* (2015)

WGO: Wheat germ oil

A different study conducted by Salem and Khalifa (2018) prepared micro and nano-WGO emulsions using maltodextrin (10%) and gum Arabic (10%). The authors concluded that nano-WGO emulsions (produced via ultrasonication) led to the formation of lower levels of thiobarbituric acid-reactive substances (0.84-0.91 mg MDA/L) compared to micro-WGO emulsions (0.87-1.01 mg MDA/L). Furthermore, nano-WGO emulsions had lower peroxide value (0.83-59.78 μg Fe/mL), lower acid value (0.90-1.70 mg/g), reduced viscosity (99-130cP), smaller particle size (71.41 μm), and a higher negative charge (-32.87 mV). Also, storage duration caused an increase in the emulsion stability index values, with micro-WGO emulsions showing a more pronounced increase (0.00-57.50%). In an earlier study, Gumus *et al.* (2015) prepared bioactive extracts of Calendula flower infused with black seed oil and WGO for pharmaceutical, food and cosmetic applications. Their results showed that phyto-nanoemulsions enriched with Calendula infusion exhibited superior biological activities, particularly in wound healing and radiation protection, compared to pristine oils.

Table 2 summarizes the key findings from studies investigating the production and characterization of WGO-loaded capsules. For example, Rehman *et al.* (2022) fabricated WGO-loaded microcapsules using sodium alginate partially substituted with starch, pectin, and whey protein. Their findings demonstrated that higher oil levels in the microcapsules led to reduced encapsulation efficiency. Also, microcapsules composed solely of alginate and pectin exhibited lower encapsulation efficiency compared to those formulated with a combination of these biopolymers. It was also observed that increasing the core-to-coating ratios and the substitution of sodium alginate with other polymers resulted in a higher oil release. In another study, Aslan *et al.* (2021) encapsulated WGO in buttermilk using a high-pressure homogenizer followed by freeze-drying. Their study demonstrated that the resulting microcapsules exhibited superior oxidative stability and enhanced protection of tocopherols, phytosterols, and carotenoids compared to bulk WGO, making them a promising functional ingredient in food formulations. Similarly, Cetinkaya *et al*. (2021) encapsulated WGO using *Saccharomyces cerevisiae* cells in three different states: alive, plasmolyzed, and non-plasmolyzed. Plasmolyzed yeast cells were shown to be the most effective encapsulating agent, offering significantly improved oxidative stability of WGO. The authors suggested that yeast cell encapsulation could increase the potential use of WGO in functional food applications. In another study, Güneş and Gülseren (2021) investigated natural body fat emulsions prepared using wheat germ and found that these emulsions exhibited low resistance to acidification and heating due to structural changes in natural body fat proteins and triacyl glycerides. However, they showed high stability under refrigerated storage and lyophilization. The authors suggested that additional hydrocolloids, emulsifiers and homogenization techniques were needed to increase their stability. In another study, Kutlu (2021) and Kutlu *et al.* (2024) noted that nano-encapsulation containing 4% WGO achieved the highest encapsulation efficiency. Encapsulation led to the formation of wrinkled surface structures, but no significant decrease in the viability of L-929 human fibroblast cells was observed. Likewise, Bendala (2020) formulated WGO-loaded solid lipid nanoparticles and evaluated different production techniques. The author demonstrated that both the double emulsification and the hot homogenization methods, utilizing high concentrations of lipids (palmitic acid, 15-20%) and emulsifying agents (lecithin, 3.5- 5.5%; Tween 80, 5-7.5%) were effective for the production of nanoparticles. Feltre *et al.* (2020) applied the ionic gelation method to encapsulate WGO in alginate-gelatinized corn starch (1:1) beads. This approach significantly improved the physicochemical properties and stability of WGO. Karadeniz *et al.* (2018) compared various homogenization methods (silent crusher, microfluidization and ultrasonication) and different coating materials (maltodextrin: whey protein concentrate (1:3, 1:4), maltodextrin-gum Arabic (1:3), maltodextrin-chitosan (10:1), maltodextrin-sodium salt of casein (10:1, 1:3), whey protein concentrate-chitosan (1:1)) to extend the storage life of WGO. The study found that emulsions produced using the silent crusher and microfluidization techniques were more stable than those formed by ultrasonication. The best results were achieved with a core-to-coating ratio of 1:3 and maltodextrin-sodium caseinate as the wall material. In other study, Salem and Khalifa (2018) encapsulated WGO by applying spray-drying with maltodextrin, whey protein concentrate and gum Arabic, and analyzed *in vitro* digestion characteristics. In comparison with nano-WGO capsules, the micro-WGO capsules showed higher free fatty acid release and lower encapsulation efficiency. However, both encapsulation methods successfully extended the shelf life of WGO. Badea *et al.* (2015) designed nano-structured lipid carriers incorporating WGO and other vegetable oils to create formulations with UV protection and antioxidant properties. The combination of pomegranate seed oil and WGO demonstrated the highest functionalities, suggesting potential applications in photoprotective cosmetic products. Furthermore, Yazicioglu *et al.* (2015) applied spray-drying to encapsulate WGO, optimizing the process based on core-to-coating ratios (1:8, 1:4, 1:2, 3:4, 1:1), coating materials ratios (maltodextrin: whey protein concentrate; 3:1, 2:2, 1:3) and ultrasonication time (320 W and 20 kHz for 2, 5, 10 min). The optimum conditions were found as follows: maltodextrin: whey protein ratio of 1:3, a core to coating ratio of 1:8, and an ultrasonication time of 10 min. Finally, Yun *et al.* (2014) reported that the gas-saturated solutions process using SC-CO_2 can be efficiently used to micronize WGO, providing enhanced DPPH radical scavenging activity.

TABLE 2. Encapsulation techniques applied in the fabrication of nano/microcapsules loaded with WGO based on the scientific database from 2014 to 2025.

Encapsulation technique(s)	Coating materials(s)	Emulsifying agent(s)	Main goal of the study	Results	References
Spray-drying, freeze-drying, spray freeze-drying	The different combinations of whey protein isolate and pectin obtained from citrus sources	Polyglycerol polyricinoleate	To investigate the effects of WGO co-encapsulation and microencaplation on probiotic viability, storage stability, and gastrointestinal digestion tolerance using different drying methods and wall materials.	*L. plantarum* WH021 showed the highest survival rate when encapsulated using W1/O/W2 double emulsion with 9% WPI and 1% PEC as the outer aqueous phase. Spray-drying was the most effective method, ensuring high probiotic viability, superior powder properties, and cost efficiency.	He *et al.* (2025)
Emulsification and freeze- drying	Soluble oat protein fraction and gum Arabic	-	To optimize the microencapsulation of juniper essential oil dissolved in WGO using oat soluble protein and gum Arabic as wall materials through complex coacervation, evaluating the effects of mixing ratios and pH on encapsulation efficiency and physicochemical properties of the resulting powders.	Combining oat protein with gum Arabic effectively stabilized juniper essential oil dissolved in WGO, enhancing its thermal stability and solubility (> 80%). However, the encapsulation efficiency remained low (< 27%), suggesting the need for further optimization of wall material composition and pH conditions.	Napiórkowska *et al*. (2024)
Spray-drying and freeze-drying	Soy protein isolate and gum Arabic	-	To develop stable functional powders by utilizing antioxidants, oil blending, and microencapsulation through different drying methods, focusing on chia oil (CO) blends with virgin sesame and wheat germ oils, and CO with the addition of TBHQ as a positive control.	The hydroperoxide content significantly increased after the emulsification and spray-drying of the CO/WGO 80/20 blend. Despite the antioxidant activity of the α- and β-tocopherol components and their activity against the DPPH radical, it is suggested that these compounds may participate in pro-oxidant mechanisms, potentially enhancing oxidation reactions.	Bordón *et al.* (2022)
The external gelation method	The combination of sodium alginate with corn starch, pectin, and whey protein in different ratios.	Tween 80	To investigate the effects of different wall material combinations on the encapsulation efficiency, size, and angle of repose as well as oil release studies.	Among the wall material combinations, the highest encapsulation efficiency (84.14%), smallest mean size (343.57 µm) medium angle of repose (32.79°), and the lowest release (in hexane (64.33%), simulated gastric fluid (17.89%) and intestinal fluid (63.1%)) were found in sodium alginate-whey protein.	Rehman *et al*. (2022)
High-pressure homogenization and freeze-drying	Buttermilk	-	To assess the efficiency of WGO microencapsulation in buttermilk to prevent oxidative degradation.	Peroxide and p-anisidine values as well as the degradation of tocopherols, phytosterols, and carotenoid contents were found to be lower in microencapsulated WGO compared to the bulk WGO.	Aslan *et al.* (2021)
Freeze-drying	The yeast cell wall	Tween 80	To evaluate the feasibility of *Saccharomyces cerevisiae* cell-based microencapsulation for WGO based on oxidative stability and *in vitro* release properties.	The highest encapsulation efficiency and loading capacity, oxidative stability, smallest release in the esophagus-stomach digestion and the greatest release in the duodenum-ileum were found in the WGO encapsulated with plasmolyzed yeast compared to the WGO-loaded in non-plasmolyzed and alive cells.	Cetinkaya *et al.* (2021)
Freeze-drying	-	-	To extract oil bodies from wheat germ, prepare oil body emulsions, and determine stability limits without further homogenization or additional emulsifiers or organic solvents.	In general, the lyophilization process had the smallest impact on the structural properties of the oil body systems, while changes in both pH values and heat treatment time led to varying degrees of instability in the samples. The mean average size of unprocessed (< 8 µm) and reconstituted samples (< 6 µm) increased to $d_{32} \geq 9$ µm and $d_{32} \geq 8$, respectively, at the end of the storage period. Unprocessed, lyophilized and reconstituted samples exhibited different thermographs according to their location and magnitude.	Güneş and Gülseren (2021)

Freeze-drying, ionic gelation, and ultrasonication	Combination of chitosan, nettle seed gum and ovalbumin	-	To optimize the wall material fabrication conditions by measuring the zeta potential and average particle size using the Box-Behnken design and perform the characterization studies of neat nanoparticles and WGO-loaded nanoparticles.	Encapsulation efficiency of the nanoparticles was found to be between 48.66-71.91% depending on the loaded WGO concentration. Moreover, fabricated nanoparticles showed both endothermic and exothermic peaks. Regarding the FT-IR and SEM measurements, encapsulation of WGO led to wavelength changes on the amino and carboxyl groups and formation of a wrinkled surface, respectively. An increase in the concentration of neat nanoparticles and WG- loaded nanoparticles resulted in a decrease in the viability of fibroblast cells in the concentration range of 0-10 mg/mL.	Kutlu (2021); Kutlu et al. (2024)
W/O/W double emulsification method, hot homogenization method, and cold homogenization method.	Polyvinyl alcohol (for the W/O/W double emulsification method)	Tween 80 and lecithin	To fabricate WGO-loaded solid nanoparticles using different preparation methods and concentrations of lipid and surfactant in formulations and determine their particle sizes, surface morphologies and visual stability.	Among the homogenization methods, the most stable and solvent-free preparation was achieved using the hot homogenization method. The following formula was determined as having the best conditions: 20% lipid, 5.5% lecithin, and 7.5% Tween 80.	Bendala (2020)
Extrusion method	Combination of sodium alginate and gelatinized corn starch	-	To generate a closed microstructure matrix, enhance oxidative stability and decrease compound degradation in WGO.	Different combinations of sodium alginate and gelatinized corn starch had no significant effect on encapsulation efficiency or FT-IR analysis results. On the other hand, the microstructure and stability of beads, corresponding to their PVs and the content of tocopherols, were affected by the proportion of gelatinized starch used in the fabrication of the beads.	Feltre *et al*. (2020)
Freeze-drying	*Maltodextrin: whey protein concentrate *Maltodextrin-gum Arabic *Maltodextrin-chitosan *Maltodextrin-sodium salt of casein *Whey protein concentrate- chitosan	-	To investigate the effects of different homogenization methods and wall material combinations on the physicochemical properties and storage stability of encapsulated WGO.	Among the wall material combinations, the highest encapsulation efficiency was found for maltodextrin-sodium salt of casein (1:3) using microfluidization. Lower totox values and the percentage loss of α-tocopherol were tested in the microcapsules fabricated using maltodextrin-sodium salt of casein (1:3) compared to fresh WGO.	Karadeniz *et al*. (2018)
Ultrasonication and spray-drying	Maltodextrin, whey protein concentrate and gum Arabic	-	To enhance the efficiency and stability of WGO by applying two different encapsulation techniques, namely, micro and nano-encapsulation, and study the effect of these techniques on the characteristics of micro and nanocapsules.	Corresponding to the *in vitro* digestion, the percentage free fatty acid release of nano WGO capsules was lower than micro WGO capsules, which had lower encapsulation efficiency.	Salem and Khalifa (2018)
Freeze-drying	-	Sodium cholate, Tween 20, and poloxamer	To prepare nanostructured lipid carriers loaded with different vegetable oils (blackcurrant seed oil, carrot root oil, pomegranate raspberry seed oil, rice bran oil, seed oil, sesame seed oil, and WGO) and their combinations to determine the best formulation conditions with high UV protection performance and antioxidant capacity.	Due to the inclusion of the oils at a nanoscale size into nanostructured lipid carriers, all nanostructured lipid carriers, but especially those made with pomegranate seed oil and its mixtures, demonstrated good antioxidant activity, which was improved when compared to the nonencapsulated vegetable oils. Also, the production of NLCs with the proper particle size and excellent physical stability was made possible by all the vegetable oils and their combinations.	Badea *et al.* (2015)
Ultrasonication and freeze-drying	Maltodextrin and whey protein concentrate at different ratios	-	To reveal the influences of some factors such as core to coating ratio, coating materials ratio and ultrasonication time on particle size distribution of emulsions, encapsulation efficiency and surface morphology of capsules loaded with WGO.	An increase in the whey protein concentrate and sonication duration led to an increase in encapsulation efficiency and a decrease in the average particle size. The encapsulation efficiency was positively affected by the increase in ultrasonication time.	Yazicioglu *et al*. (2015)
Gas-saturated solutions process	Polyethylene glycol	-	To investigate the different process parameters (*e.g.* temperature, pressure and WGO ratio) on the average particle size and the particle characteristics.	The fabricated nanoparticles had an average particle size with a uniform size distribution. Also, particle size distribution was moderately affected by the pressure and temperature applied during the particle fabrication. The main fatty acid found in the micronized oil was linoleic acid. After the micronization procedure, the highest DPPH activity and total phenolic content were observed in the mixing ratio of 5:1 compared to the 10:1 of WGO.	Yun *et al.* (2014)

WGO: Wheat germ oil

Overall, the findings summarized that nanoencapsulation provided superior lipid oxidation resistance and improved storage stability to WGO. These advancements have strengthened WGO's potential in food applications by improving its functional and technological properties. The findings from these studies provide valuable insights into the development of functional encapsulated WGO-based formulations with enhanced bioactive retention and prolonged shelf life.

4. FOOD APPLICATIONS FOR ENCAPSULATED WGO

Recent studies conducted between 2019 and 2025 (Table 3) have shown that the application of WGO capsules in functional food product formulations still remains limited. However, the existing research highlights promising outcomes regarding its potential for enhancing food quality, stability, and nutritional value. In this sense, Yan *et al*. (2021) studied the impacts of A-starch-WGO and B-starch-WGO complexes on the textural alterations of cooked noodles within the first 2 h of storage. Texture studies showed that these complexes exhibited similar effects on hardness and chewiness, although the A-starch-WGO complex generally supplied higher firmness, springiness and chewiness values during the storage period. In another study, Ceylan *et al.* (2020) examined the impact of WGO-loaded nanoemulsions on cooked fish fillets stored under refrigeration. Their findings demonstrated that these emulsions effectively preserved the oil in the fillets prior to cooking, thereby contributing to better oxidative stability.

Further expanding on WGO's potential in functional foods, Kaur *et al.* (2020) applied an air-atomization technique with sodium alginate and pectin (1.5:2) as wall materials to micro-encapsulate WGO and α-tocopherol. They then evaluated the physical, sensory and storage properties of cookies with different formulations (control, liquid WGO, encapsulated WGO, encapsulated α-tocopherol). Enriched cookies showed promising results in terms of improved shelf life and nutritional value compared to the reference cookies. Interestingly, no vitamin E retention was detected in the cookies incorporated with liquid WGO after 90 days of storage, although the highest retention was observed in biscuits enriched with encapsulated α-tocopherol at the end of four months. Previously, Soliman *et al*. (2019) nano-encapsulated WGO into the casein micelles and the applied the fabricated nanocapsules in the preparation of functional Labneh cheese. Their results showed that 50% substitution of skim milk with WGO-loaded nanocapsules not only provided sensory qualities but also significantly enhanced the antioxidant activity of the final product. Overall, although research on WGO encapsulation in functional foods is still emerging, these studies demonstrated its potential for improving the stability, functional properties, and sensory quality of various food products.

TABLE 3. Encapsulation techniques applied in the fabrication of nano/microcapsules loaded with WGO based on the scientific database from 2014 to 2025.

Material	Encapsulation technique(s)	Coating material(s)	Emulsifying agent(s)	Main goal of the study	Results	References
Yogurt	Ultrasonication and gelification method	Whey protein isolate, agar and gellan gum	-	Explore the formation of different emulsions and composite emulsion gels using WGO and probiotics, and to assess their oxidative stability, probiotic survival rate, and potential application in yoghurt as a food model.	This study successfully developed composite emulsion gels enriched with WGO and probiotics, demonstrating improved oxidative stability, probiotic viability, and texture properties. The formulations were applied to yogurt as a food model, showcasing their potential in the food industry.	Abu-El Khair *et al.* (2023)
Noodle	Dripping	A- and B-type wheat starches	-	Investigate the properties of A-starch-WGO complex and B-starch-WGO complex and their influences on noodle texture	Higher reactivity in terms of encapsulation of WGO was observed in A-type wheat starch. Both A and B-starch-WGO complex exhibited similar crystallinities and short-range ordered structures; however, a higher swelling power was determined in the A-starch-WGO complex. These complexes did not always have the same effect on the noodle texture.	Yan *et al.* (2021)

Fish fillets (*Scomber scombrus*)	Ultrasonication process	Maltodextrin	Tween 20	Reveal the effects of WGO-loaded nano emulsions on cooked fish fillets stored under cold storage conditions.	The rapid oxidation in the cooked mackerel fillets was delayed by the nano-application of WGO. A lower increase in the thiobarbituric acid, free fatty acid, peroxide value, conjugated diene and conjugated triene values were observed in the fish fillets treated with nano emulsions compared to the untreated samples. Also, some nutritional quality indexes such as hypocholesterolemic/hypercholesterolaemic index, atherogenic index, thrombogenicity index and polyene index values as well as EPA/DHA, PUFA/SFA, n3/n6 ratios of the fish fillets treated with nano emulsions were within the prescribed limits; however, untreated samples were not within quality assurance limits.	Ceylan *et al.* (2020)
Cookie	Air atomization technique	Pectin, sodium alginate	Tween 80, glycerol	Research the influences of fortification with WGO and α-tocopherol-loaded microcapsules on the shelf life and vitamin E retention parameters in cookies.	Fortified cookies exhibited greater storage stability, improved storage characteristics, higher antioxidant activity and lower free fatty acid formation compared to the control cookies.	Kaur *et al*. (2020)
Labneh cheese	Ultrasonication	Casein micelles	-	Develop functional Labneh cheese incorporated with nano-encapsulated WGO.	The encapsulation efficiency of particles loaded with WGO (0.3 to 1.2%) exceeded 95%. The findings displayed that the fabricated nano-particles had a spherical-shape and exhibited high oxidative stability and DPPH scavenging activity. The composition and quality of the prepared functional Labneh cheese were comparable to the reference sample.	Soliman *et al.* (2019)

WGO: Wheat germ oil

5. CONCLUSIONS

This review highlights the chemical composition, biological and health-promoting properties of WGO, with a particular focus on encapsulation technologies aiming to protect its functional components and enhance its stability for food and pharmaceutical applications. WGO, rich in tocopherols, phytosterols, and policosanols, offers significant bioactive potential but is highly prone to oxidation due to its highly-unsaturated fatty acid content. Encapsulation has emerged as an effective strategy to overcome these challenges by improving oxidative stability, extending shelf life, and enhancing bioavailability. Various techniques, including spray-drying, freeze-drying, extrusion, and ionic gelation, have been explored to optimize its functional properties. The choice of encapsulation materials plays a vital role in stabilizing WGO. Polysaccharides (e.g., sodium alginate, gum Arabic, pectin), proteins (e.g., whey protein isolate, soy protein isolate, ovalbumin, buttermilk), and lipids (e.g., nanostructured lipid carriers) have been successfully employed to enhance emulsion stability, reduce pro-oxidant activity, and protect bioactive components. Additionally, emulsifiers such as lecithin, Tween 20, and polyglycerol polyricinoleate have further improved dispersion and oxidative resistance. Encapsulation has been shown to reduce peroxide and p-anisidine values, to protect tocopherols and phytosterols, and to delay lipid oxidation, thereby extending WGO's shelf life. In food applications, encapsulated WGO has shown improved structural integrity, sensory quality, and antioxidant activity in products like yogurt, cookies, and fish fillets. Furthermore, it has contributed to maintaining probiotic viability and enhancing the textural properties of starch-based complexes. Despite these promising outcomes, research involving real food model trials remains limited. Further studies are needed to refine encapsulation techniques, optimize material selection, and expand the functional applications of WGO in diverse food and pharmaceutical formulations.

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AUTHORSHIP CONTRIBUTION STATEMENT

G. KUTLU: Conceptualization, Investigation, Writing original draft, Review & Editing, Visualisation; F. TORNUK: Writing original draft, Review & Editing, Project administration.

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DATA AVAILABILITY

The data supporting this article is available upon reasonable request.

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