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Review Article

Acorn Oil: Chemistry and Functionality

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Acorn oil has been receiving increasing attention due to its nutritional potentials. However, its application as a novel food ingredient has not yet been fully explored. This paper summarizes chemical composition, extraction methods, potential health benefits, and current applications of acorn oil, with the aim of providing suggestions for its exploitation. Acorn oil is an excellent source of essential fatty acids (oleic, linoleic, α-linolenic, and palmitic acids). Acorns are a rich source of tocopherols, with γ-tocopherol being the most abundant. It also contains various bioactive compounds such as polyphenols and sterols (mainly β-sitosterol). Diets enriched with acorn oil can be beneficial in preventing cardiovascular disease (CVD), cancer, and type 2 diabetes as well as offer antioxidant activity. Further studies should focus on producing better quality acorn oil such as the application of more innovative and optimized techniques that can increase its health benefits and hence utilization.

1. Introduction

Quercus spp. represent an important genus of the Fagaceae family which consists of 300 species worldwide, including deciduous and evergreen trees. These species produce a widely known fruit, commonly identified as acorns, which are of vital importance for both humans and animals. Usage of acorns in nutrition has a long history. In Algeria, Morocco, and the eastern USA, acorn oil has been used for cooking and as a salve for burns and injuries [1]. In Jordan, acorns have been traditionally used either as food directly or as an ingredient in products such as bread production [2]. In Europe, acorns are usually used as a feed source for free-ranging wild animals, especially the Iberian pigs [3], and extensively under exploitation as fodder for cattle [2]. Acorns are considered as nutritionally rich products, containing about 55% starch, 2.75–8.44% proteins, and fat 0.7–7.4%, presenting a higher nutritional value than cereals [2, 4–6], besides being an excellent source of minerals (such as P, K, Ca, and Mg) [7, 8]. Furthermore, acorns are rich in unsaturated fatty acids, especially oleic acid, and also essential fatty acids such as linoleic ($n-6$) and linolenic ($n-3$) fatty acids, which are important in eicosanoid synthesis and have beneficial effects like regulating blood lipid profile [9]. In addition, acorns contain various biologically active compounds such as tannins, phenolic acids, and flavonoids [3, 10], which are important in the human diet to maintain an adequate level of antioxidants.

The fatty acid composition and physicochemical properties of acorn oil are extremely similar to those of olive oil [2, 11, 12]. Acorn oil is rich in unsaturated fatty acids (75–90%), especially oleic acid (65%), and essential fatty acids such as linoleic (17–37%) and α-linolenic (1–4.58%) acid (Table 1), which is important in eicosanoid synthesis, promoting the decrease of blood serum triglycerides and the increase of HDL-cholesterol levels.

Generally, in acorn oils, the predominant homologs of tocopherol are γ-T and α-T, while β-T and δ-T are present in low amounts or absent [2, 15, 17]. However, [13] reported that β–tocopherol was the main tocopherol in *Q. rubra* acorn oils (93% of the total detected tocopherols), which is a unique phenomenon within not only acorn species but also other plant species. These compounds have shown efficacy as a powerful lipid-soluble antioxidant, protecting muscle and

Table 1: Fatty acid composition of acorn species (% dry weight basis).

Acorn species	Source	Saturated				Monounsaturated		Polyunsaturated		SFA	USFA	References
		C14 : 0	C16 : 0	C18 : 0	C20 : 0	C16 : 1	C18 : 1	C18 : 2	C18 : 3	(%)	(%)	
Q. ilex	Algeria	—	16.5	—	—	—	65.0	17.6	0.9	16.5	83.5	[12]
Q. suber		—	17.0	—	—	—	63.8	17.8	0.9	17.0	83.0	
Q. aegilops	Jordan	0.17	18.7	1.02	0.18	0.19	55.6	21.7	1.6	20.52	79.54	[2]
Q. infectoria		0.12	17.8	1.5	0.22	0.25	56.1	21.3	1.6	20.44	79.4	
Q. calliprinos		0.13	18.4	1.6	0.22	0.26	53.3	23.4	1.5	21.01	78.95	
Q. pontica	Turkey	0.5	18.2	2.1	0.4	0.8	32.6	35.9	—	23.1	75.6	[5]
Q. robur		0.2	18.9	2.0	0.7	0.8	22.6	41.9	—	23.9	70.7	
Q. hartwissiana		0.2	17.1	1.8	0.6	0.5	21.4	49.1	—	21.3	76.8	
Q. frainetto		0.4	20.9	3.2	0.8	0.6	25.7	38.7	—	27.7	70.2	
Q. petraea		0.2	19.6	1.8	0.5	0.4	41.4	31.1	—	23.1	75.9	
Q. vulcanica		0.6	13.8	4.0	0.5	0.5	50.2	25.1	—	20.4	79.3	
Q. ithaburensis		0.7	22.8	3.1	0.8	1.8	16.9	38.7	—	29.9	64.4	
Q. brantii		0.2	19.0	2.5	0.5	0.2	46.8	26.1	—	23.1	28.6	
Q. libani		0	13.5	1.9	0.4	0.2	54.3	24.2	—	17.0	26.1	
Q. trojana		0.3	15.7	1.5	0.3	0.4	49.7	26.0	—	18.6	29.0	
		0.2	17.0	1.8	0.3	0.2	51.4	24.7		20.2	27.0	
Q. rubra	Latvia	—	8	1.3	0.3	0.1	62.3	27.1	0.3	9.8	90.2	[13]
Q. robur		—	14.5	1.3	0.4	0.1	41.3	39.9	1.7	16.6	83.4	
—	Turkey	0.12	13.80	1.54	0.25	0.31	57.80	24.16	1.29	15.99	84.01	[14]
Q. faginea	Spain	0.19	11.69	3.50	0.58	0.36	62.44	16.42	0.74	16.96	83.04	[15]
Q. suber		0.31	14.27	2.74	0.26	0.26	56.25	20.73	1.34	18.64	81.73	
Q. pyrenaica		0.18	12.17	3.23	0.54	0.38	57.46	21.30	0.80	17.15	82.85	
Q. coccifera		0.30	16.22	3.31	0.29	0.37	48.02	25.38	1.57	21.01	79	
Q. ilex		0.18	12.28	4.03	0.36	0.17	65.83	14.17	0.54	17.44	82.65	
Q. faginea	Portugal	—	18	2	0.5	0.3	51	20	—	22	78	[6]
Q. ilex		—	14	1	0.4	0.3	64	14	—	16	84	
Q. nigra		—	17	2	0.4	0.5	48	26	—	18	80	
Q. suber		—	14	2	0.1	1	55	21	—	20	81	
Q. robur	Serbia	—	14.8	1.1	0.2	0.4	44.3	37.2	1.8	16.1	83.7	[16]
Q. cerris		—	16.9	1.2	0.2	<0.1	43	32.6	3.7	20.7	79.3	

SFA, saturated fatty acid; USFA, unsaturated fatty acid; —, not known.

other tissues against oxidative stress [18]. Phytosterols (mainly β-sitosterol) are also present in acorn oil between 4632.71 and 11576.09 mg/kg, which are inclusively higher than those reported for almond (1430 mg/kg), soybean (1600 mg/kg), olive (2210 mg/kg), pistachio (2790 mg/kg), and pine oils (4298 mg/kg) [17]. These compounds with various biological activities are useful for promoting the decrease of blood serum triglycerides and cholesterol levels [19]. This review provides a detailed summary of physicochemical, extraction, methods, health benefits, and current applications of acorn oil, with the aim of promoting better utilization in the formation of different value-added products and stimulating future research.

2. Methods of Extraction

Acorn oil can be extracted through several methods. Traditionally, cold pressing is one of the most methods used to produce acorn oil. This operation can be performed in low pressure at about 0.5 MPa [1, 14]. Generally, cold pressing is more preferable as it required less energy than other oil extraction techniques, is environmentally friendly, and also leads to the short duration of the process [20]. Soxhlet extraction (SE) uses an organic solvent such as hexane and petroleum ether which are widely applied to extract oil from acorn [2, 12, 17, 21]. This method is considered an efficient technique for over a century; the most outstanding advantage of SE includes simplicity (no filtration is required after the leaching step) and low energy consumption [22]. Nevertheless, using a solvent is toxic and hard to be totally eliminated, and this could result in severe contamination for the final products.

Focused microwave-assisted Soxhlet extraction (FMASE) has already been successfully used to extract oil from acorns. This method is based on the same principles as a conventional Soxhlet extractor but is modified to facilitate accommodation of the sample cartridge compartment in the irradiation zone of a microwave oven [23]. Pérez-Serradilla et al. [24] mentioned that FMASE provides an advantage over conventional methods because it enables total extraction of the fatty acids in 30 min, which is much less than the time required by the Folch (4.5 h), Soxhlet (16 h), ISO (8 h) reference methods, and the stirring–extraction method (56 h). Also, it was found that the degree of unsaturation of the oil extracted by FMASE is significantly dependent on the extraction conditions. Therefore, as an alternative to those traditional extraction methods, a series of modern techniques have been applied for acorn oil extraction, such as ultrasonic-assisted extraction (UAE) [13] supercritical CO_2 extraction [25, 26].

Lopes et al. [25] compared the fatty acid composition of acorn oil of two extraction methods: n-hexane in Soxhlet and supercritical fluid extraction (SFE) with CO_2 at 18 MPa and 313 7C. These authors concluded that no significant differences were found by different procedures. In comparison to Soxhlet extraction, SFE using carbon dioxide (CO_2) is considered to be a green processing technique, avoiding the problem of contamination of the oil by a residual solvent. Moreover, carbon dioxide is safe, nonflammable, and available at high purity [27]. In this line, Bernardo-Gil et al. [26] used supercritical CO_2 (SC-CO_2) to extract acorn oil by changing parameters such as particle size, CO_2 density, solvent flow rate, and extractor geometry. It was found that the extraction yield and the initial extraction rate depend on the carbon dioxide density and superficial velocity.

3. Chemical Characteristics of Oil

3.1. Quality Indices. The physical and chemical characteristics of the acorn oil in terms of refractive index, acidity values, peroxide value, iodine value, and saponification value are presented in Table 2. The oil content of acorn species ranged from 5% to 20% depending on the variety and localization of the collected sample. However, Ofcarcik et al. [28] reported higher oil yield (about 30%) in black and red acorn species. Acorn oil presents good nutritional quality, and its flavor is comparable to that of olive oil [11]. The saponification values of acorn oils range from 160.3 to 220 mg KOH/g. The saponification value of acorn oils is comparable to that of olive oil (184–196 mg KOH/g) [2]. This relatively high saponification value indicates that oils hold fatty acids with a high number of carbon atoms. The iodine value represents the degree of unsaturation of the oils and the fat, and the more unsaturation leads to a higher iodine value [29]. The iodine value for acorn oil reported by [2] was 75–88 g/100 g, which is comparable to the value of olive oil 75–94 g/100 g. The highest iodine value of acorn oil was reported to be 129.6 g/100 g [21].

The free fatty acid (FFA) content is an important parameter to evaluate the quality of an oil. The oil is more suitable for human consumption when it possesses low FFA content [29]. The percentage of free fatty acids reported for acorn oils ranges from 0.92% to 5.8%. High values of FFA observed in acorn oils may be caused by the bad conservation of the fruits before extraction and analysis or the incomplete ripeness of the seeds [12]. The specific gravity of the oil extracted from acorn ranges from 0.912 to 0.922 [2, 30], similar to the specific gravity of diesel oil (1.0) [29]. This finding revealed that acorn oils are suitable for diesel production. As regards the physical properties, acorn oils showed a refractive index ranging from 1.449 to 1.453 [21]. These values are similar to those reported previously by [2] for acorn oils from other species and comparable to other vegetable oils such as olive oil 1.4677–1.4705.

3.2. Fatty Acid Composition. The fatty acid profiles of oils obtained from different acorn species showed a high variation in the percentage of monounsaturated, polyunsaturated, and saturated fatty acids. The fatty acid composition of acorn oils varies with genetic factors, plant species, abiotic factors (such as the maturation degree), and climate and geographic origin [13]. Oleic and linoleic acids are the major unsaturated fatty acids described in acorns species, ranging from 65.83% to 48.02% and 25.38% to 14.17% of total fatty acids, respectively, while the major saturated fatty acid is palmitic acid ranging from 11.69% to 16.22% [15]. These

Table 2: Chemical characteristics of oil extracted from acorn species.

Acorn species	Origin	Oil (%)	SV (mg KOH/g)	IV (g/100 g)	FFA (%)	PV (meq O_2 kg^{-1})	AV (mg/g)	Specific gravity	RI	References
Q. ilex	Algeria	—	—	103.68	0.97	1.50	—	—	1.453	[21]
Q. suber		—	—	125.28	1.13	0.83	—	—	1.453	
Q. coccifera		—	—	129.60	0.92	1.00	—	—	1.449	
Q. ilex	Algeria	9.0	166.7	85.8	—	—	5.3	—	—	[12]
Q. suber		9.0	160.3	78.6	—	—	5.1	—	—	
Q. aegilops	Jordan	7.51	204.2	87.6	—	—	—	0.912	1.4645	[2]
Q. infectoria		6.57	219.4	76.7	—	—	—	0.922	1.4595	
Q. calliprinos		3.40	192.6	75.2	—	—	—	0.918	1.4529	
Q. castaneifolia			193	112.7				0.9182	1.4738	
—	Turkey	—	—	99.63	—	0.20	1.83	0.83	1.470	[14]
Q. rotundifolia	Portugal	—		81		5	1.1	0.895	1.4629	[25]
Q. suber		—		81		6	1.3	0.888	1.4669	
Q. robur[a]	Serbia	5.6	158.6	89.3	—	—	—	0.9024	1.4669	[16]
Q. cerris[a]		4.8	186.5	91.2	—	—	—	0.9018	1.4605	

SV, saponification value; IV, iodine value; FFA, free fatty acid; AV, acid value; PV, peroxide; RI, refractive index; not detected. [a]Max value.

results are in accordance with values reported by [3, 17, 31, 32], where oleic, linoleic, and palmitic acid are the most predominant fatty acids (oleic acid 63%), followed by palmitic and linoleic acids at similar concentrations (12–20%) of total fatty acids. Table 1 shows the fatty acid composition of acorn oil reported in different studies. The percentage of oleic acid in acorns is significantly higher than in other fruits generally considered a natural source of oleic acids such as walnut (21%), peanut (38.41%), and mustard oil (36.7%) [33] with the concentration of this acid being only exceeded by olive oil (56%–84%) [34]. Indeed, it was found that the fatty acid composition of acorn oil is similar to that of *Pistacia lentiscus* oil and other vegetable oils such as those obtained from peanut, sunflower, cotton, avocado, and olive, suggesting its potential to be used as edible properties of oil [12]. As described previously, oleic acid (OA) is the main monounsaturated fatty acid (MUFA) present in acorn oil. Several studies have revealed the beneficial propriety, particularly in preventing diabetes mellitus T2DM and decreasing cardiovascular disease risk, besides contributing to improving hemostasis, platelet aggregation, and fibrinolysis [34]. Linoleic acid is an important polyunsaturated fatty acid in the human diet. Acorn oils contain high amounts of linoleic acid (37.2%–32.6%) and γ-linolenic acid (1.8% to 3.7%) [16]). Numerous studies showed that these fatty acids, especially α-linolenic acid, can have a role in promoting blood lipid profile and treating the symptoms of dermatitis. Stearic acid (1%–4%), eicosenoic acid (0.37%), arachidic acid (0.38%), behenic acid (0.12%), and behenic acid (0.20%) are shown in minor composition in the acorn oil. Stearic acid is a long-chain saturated fatty acid which is known to be neutral in its effect in the cholesterol concentrations in human.

Based on these findings, it can be concluded that acorn oil is a healthy source of important fatty acids which can be used for the dietary purpose and cosmetic uses. In addition, the difference in their percentages may be useful as a biochemical fingerprint to differentiate between acorn species.

3.3. Phytosterols and Aliphatic Alcohols. Plant sterols and plant stanols, known commonly as phytosterols, are an important group of natural compounds, biologically active in the prevention of several diseases. Table 3 indicates the phytosterol content of acorn oil found in the previous studies [2, 13, 17]. Phytosterol is present in acorn oil between 4632.71 and 11576.09 mg/kg, [17] which were inclusively higher than those reported for almond (1430 mg/kg), soybean (1600 mg/kg), olive (2210 mg/kg), pistachio (2790 mg/kg), and pine oils (4298 mg/kg), despite being in the same range as those described for sesame and corn oils (8650–9680 mg/kg, respectively) [35–37]. The acorn oils are generally characterized by a high percentage of β-sitosterol (88.3–92.5%) followed by campesterol (1.57–4.28%) and campesterol (1.57–4.28%). However, stigmasterol, clerosterol, 5-avenasterol, 5,24–stigmastadienol, Δ^7-stigmastenol, and Δ^7-avenasterol were present with minor amounts (lower than 2%) [17]. Moreover, [13] investigated the sterol composition of different varieties of acorn and found β-sitosterol as dominant (64.3%–68.1%) followed by cycloartenol (11.4%–15.0%), campesterol, Δ5-stigmasterol, Δ5-avenasterol, and 24 methylenecycloartanol (rang of 3.0–6.7%). The amounts of campestanol, sitostanol, and Δ7-avenasterol were below 3.0%. Phytosterol consumption is important for consumers to decrease cholesterol levels in the blood [19]. In addition, it displayed anticancer properties in vivo on prostate, lung, stomach, ovarian, colon, and breast cancer [38].

Furthermore, acorn oils were reported to contain appreciable amounts of aliphatic alcohol (2190–2240 mg/kg) [17]. Tetracosanol was the predominant compound of this class (43.70%–59.48%), followed by hexacosanol (18.66–26.93%), yet, docosanol and octacosanol were the less abundant aliphatic alcohol in acorn oils, consisting of 13.17–26.24% and 1.52–9.33%, respectively. The presence of high percentages of aliphatic alcohols (polycosanols) is always remarkable. Extensive investigations showed the potential therapeutic of aliphatic alcohols (polycosanols). For example, it was reported that docosanol and tetracosanol

Table 3: Composition (%) of sterols in acorn oils.

Acorn species	Source	Cholesterol	Campesterol	Stigmasterol	Clerosterol	β-Sitosterol	Δ5-Avenasterol	Δ7-Avenasterol	References
Q. aegilops	Jordan	0.052	0.07	3.02	0.35	84.61	5.80	0.24	[2]
Q. infectoria		0.42	0.07	2.60	0.34	77.20	11.40	0.24	
Q. calliprinos		0.44	0.08	3.8	0.34	78.70	9.30	0.25	
Q. rubra[a]	Latvia	—	15.8	8.5	—	184.8	18.1	2.6	[13]
Q. robur[a]		—	11.4	10.4	—	157.5	10	6.9	
Q. rotundifolia[b]	Portugal	0.18	2.12	2.91	1.60	88.21	2.92	0.31	[25]
Q. suber		0.10	10.2	3.61	1.12	83.52	0.36	0.06	
Q. ilex (Zaghouan)	Tunisia	—	4.28	1.95	1.92	88.28	1.27	1.63	[17]
Q. suber (Nabeul)		—	1.82	1.55	0.95	92.11	1.44	1.60	

[a]Phytosterol content (mg/100 g oil); [b]extracted by hexane; —, not known.

Table 4: Tocopherol homologue content (mg/kg oil) of acorn oils.

Acorn species	Origin	Tocopherols					Reference
		α-Tocopherol	ß-Tocopherol	γ-Tocopherol	&-Tocopherol	Total (mg/kg)	
Q. Aegilops	Jordan	230	—	1210	—	1440	[2]
Q. infectoria		171	—	1612	—	1783	
Q. calliprinos		141	—	1501	—	1642	
Q. faginea	Spain	6.96	—	24.33	0.54	31.83	[15]
Q. suber		9.50	—	21.16	0.94	31.60	
Q. pyrenaica		10.25	—	21.44	0.60	32.29	
Q. coccifera		5.48	—	26.05	1.01	32.54	
Q. ilex		11.63	—	32.19	1.44	45.25	
Q. ilex (Zaghouan)	Tunisia	3.92	—	93.30	—	181.47	[17]
Q. suber (Nabeul)		4.03	—	95.97	—	125.26	
Q. rubra	Latvia	42	725	5	11	784	[13]
Q. robur		55	9	4298	116	4477	
Q. ilex	Algeria	244		403	16.33	664.58	[21]
Q. suber		126		389	13.66	530.16	
Q. coccifera		138		422	19.73	579.84	

Table 5: Polyphenols of acorn oil.

Phenolic compounds (mg GAE kg^{-1} oil)	Species		
	Q. ilex	*Q. suber*	*Q. coccifera*
Digalloyl hexose	1.73	1.26	1.22
Castalagin	2.01	1.45	1.52
Pedunculagin	0.14	1.22	1.12
Digalloyl hexahydroxydiphenoyl glucose	0.26	3	2.36
Casuarictin	0.22	1.93	2.63
Digalloyl hexahydroxydip glucose (785)	Nd	1.32	3.88
Trigalloyl glucose	1.49	3.32	4.87
Tetragalloyl-pentoside	1.98	6.06	6.55
Tetragalloyl- pentoside (787), trigall oyl hexahydrodipenoyl glucose (937)	Nd	17.52	21.26
Tetragalloyl-pentoside (787), trigalloyl hexahydrodiphenoylglucose (937)	20.83	28.13	34.82
Trigalloylhexahydrodiphenoyl glucose	81.89	101.47	129.15
Pentagalloyl glucose (939)	10.75	20.90	20.22

Adapted from [21]. Nd: not detected.

Table 6: Total phenolic content and total flavonoid content of acorn fruit oil and flour.

Species		Phenolic content (mg GAE/kg dry weight)	Flavonoid content (CE/kg dry weigh)
Q. ilex L	AF	1101	279.82
	AO	195.6	131.6
Q. suber L	AF	1464	212.26
	AO	322.06	122.99

AF, acorn flour; AO, acorn oil. Adapted from [21].

induced antiproliferative effects on the growth of CHO-K1 and human melanoma oncogenic cell lines [39]. Additionally, docosanol displayed antiviral activity on the herpes simplex virus (HSV-1) by interfering with early intracellular events surrounding viral entry into target cells [40].

3.4. Tocopherols and Phenolic Compounds. Tocopherols are lipid-soluble phenolic compounds that naturally exist in oilseeds in four different forms (α-, β-, γ-, and δ-tocopherols). These compounds are valued for their capacity to protect humans from the oxidative damage mediated by active oxygen and nitrogen species and prevent lipids and lipid-containing foodstuffs from oxidation during storage [41]. Furthermore, Tocopherols have been shown to play a pivotal role in preventing hormone-dependent breast cancer progression, colon carcinogenesis, lung tumorigenesis, and prostate cancer cell growth [18]. Acorn oils are also an excellent source of tocopherols, since it was found that tocopherol contents in acorn oils range from 1440 to 1783 mg/kg oil, which were much higher than those reported for other species such as olive (240 mg/kg) and peanut (540 mg/kg) [2]. Indeed, Akcan et al. [15] conducted an experiment to evaluate tocopherol contents of different acorns from the Mediterranean forest in Spain. In this study, tocopherol content ranged from 31.83 to 45.25 mg kg^{-1}, and γ-tocopherol constituted 67–78% of total tocopherols. Rabhi et al. [17] analyzed tocopherol composition from two different varieties of acorn and reported that γ-tocopherol is the most abundant vitamer, accounting for more than 90% of the total tocopherol whereas α and β-tocopherols were not detected. The levels of tocopherols were between 181.47 mg/kg and 205.59 mg/kg for *Q. ilex* acorns and from 125.26 mg/kg to 149.81 mg/kg in *Q. suber acorns*. These oils vary widely in their content of different tocopherols. Recently, Gornas et al. [13] reported that β- and γ-tocopherols are predominated homologues in acorn oils from *Q. rubra* and *Q. robur*. The total concentration of tocopherols in *Q. robur* acorn oil was 447.7 mg/100 g oil, whereas the concentration in *Q. rubra* acorn oil was 78.4 mg/100 g oil. Similarly, it was observed that $\beta + \gamma$-tocopherols are the most abundant, accounting for more than 70% of the total tocopherol content [21]. On the other hand, β-tocopherol and δ-tocopherol were reported as minor tocopherol contents in acorn oils which contributed to the total tocopherol content of ≤0.3 mg/100 g oil [6]. The tocopherol content of acorn oil is higher than those reported for other vegetable oils like refined corn (70.7 mg/100 g oil), soybean (72.5 mg/100 g oil), sunflower (73.7 mg/100 g oil), and walnut oils (63.4 mg/100 g oil) [42]. Table 4 shows the tocopherol content in acorn oil reported in the previous studies.

Attempts have been made by few investigators to determine the phenolic content in acorn oil. Makhalouf et al. [21] had identified twenty phenolic compounds through LC-MS/MS in acorn oils. The predominant compounds were hydrolysable tannin derivatives (gallotannin or ellagitannin) in the form of hexahydroxydiphenoyl esters of glucose and galloyl glucose esters (trigalloyl glucose and pentagalloyl glucose) (the results are shown in Table 5). In addition, Makhloufi et al. [43] assayed both total phenolic and total flavonoid contents of acorn oils and the results are shown in Table 6. The level of phenolic contents (expressed in gallic acid equivalent) ranged between 195.6 and 322.06 mg GAE/kg oil while flavonoid contents (expressed in catechin equivalent) ranged between 122.99 and 131.6 mg CE/kg of oil. The total phenolic compound contents in different varieties of acorn oil ranged between 84 and 109 mg/kg [2]. These compounds contribute to increasing the oxidative stability of the acorn oil.

3.5. Carotenoids. Carotenoids are also found in high contents (66.33 ± 0.90 mg kg^{-1} oil) in the acorn oil extracted from *Q suber* L.; this oil is also rich in chlorophylls (2.03 ± 0.01 mg kg^{-1} oil) [21]. Acorns (*Q. faginea)* are rich in lycopene compound (183 ± 141 g/g dm) and β-carotene (1312 ± 890 (μg/g dm) [6]. β-Carotene is known to be a potent antioxidant that has a crucial role in inhibiting photooxidation by reacting with peroxyl radicals. In addition, it has been reported that a small amount of acorns would guarantee the recommended daily requirements of vitamin A, which is important from the point of view of human health [10].

4. Animal In Vivo Studies on Acorn

Acorns from oak (*Quercus* spp.) are commonly used as a feed source for animals. The results of large observational studies suggest that the inclusion of acorns in animal feeding affects positively the nutritional value of meat and meat products. Recently, the effect of consumption of acorn during suckling and fattening of lambs on growth, meat quality, and fatty acid profile was conducted by Mekki et al. [44]. The findings indicated that acorn may be replaced barely without any impact on growth performance. Lambs fed on acorns have also an increased α-linolenic acid concentration, which may result in lowering $n-6:n-3$ ratio. In addition, it was reported that meat products from Iberian pigs fed extensively on acorns during the fattening phase have greater quality compared to those fed with mixed diets. [3]. Posteriorly, Rey et al. [45] observed that diets based on acorns provide a source of γ-tocopherol for pigs raised extensively. In a recent study, Alipanahi et al. [46] reported that the inclusion of acorn (100 g/kg DM) in diets containing extruded soybean seed did not affect performance, ruminal fermentation, and plasma metabolites in lactating goats. Besides, it contributes to improving the nutritional value of milk fat for human consumption. The influence of acorn intake on blood profile and longissimus muscle (MLD) composition of the Slavonian pig was also investigated by Salajpal et al. [9]. The results indicated that triglyceride and total cholesterol levels were lower in the blood compared with the intake of a corn-based diet. The intake of acorn resulted in 11% (0.22 mmol/l) lower total cholesterol concentration and 48% lower (0.20 mmol/l) triglycerides concentration. Tejerana et al. [32] showed that acorns and grass are natural sources of antioxidants and fatty acids in the "montanera" feeding of Iberian pig, which are important from the point of view of consumer health. There was also a study showing the protective effect of acorns with oleic acid in preventing ulcerative colitis in an animal study [47].

5. Health Benefits

Accumulation of atherosclerotic plaques on the blood vessel walls is the primary cause of cardiovascular disease. The formation of these plaques is dependent on several factors; one among them is the dysregulation of the balance between low-density lipoprotein (LDL) and high-density lipoproteins (HDL) in circulation [48]. The increased circulation of oxidized LDL in the blood circulation is associated with clinical atherosclerotic cardiovascular diseases (ASCVD) [49]. Previously, a diet with a high content of MUFA has been proved to decrease cardiovascular morbidity and mortality [50]. In addition, plant oils rich in PUFA (especially linolenic acid and γ-linolenic acid) may help to regulate the blood plasma triglyceride levels in patients with dyslipidemia, lower the blood pressure, and protect against coronary heart disease [51].

As previously stated, oleic acid forms a significant fraction of the MUFAs from acorn as well as α-linolenic acid, which is important in eicosanoid synthesis, promoting the decrease of blood serum triglycerides and the increase of

HDL-cholesterol levels. This is also consistent with a study carried out by [9] on the influence of acorn intake on the blood lipid profile of black Slavonian pig. In this study, the intake of acorn resulted in 11% (0.22 mmol/l) lower total cholesterol concentration and 48% lower (0.20 mmol/l) triglyceride concentration. A beneficiary effect of acorns on blood lipid level could be related to the presence of high amounts of unsaturated fatty acids (more than 80%) such as linoleic (43.38%), oleic (30.52%), and alpha-linolenic (4.58%) acid. Moreover, intake of acorn effectively reduced the level of total cholesterol and LDL cholesterol in mice fed a high-fat diet [52]. Besides that, acorns contain various biologically active phenolic compounds such as tannins, gallic and ellagic acid, and different galloyl and hexahydroxydiphenoyl derivatives [3, 9], which are known for their role in the regulation of blood lipid level.

Unsaturated fatty acids like linoleic acid (PUFA) and oleic acid (MUFA) have been shown to exhibit a beneficial effect in the prevention of type 2 diabetes mellitus. As described previously, oleic acid (OA) is the principal monounsaturated fatty acid (MUFA) present in acorns. A randomized clinical trial determined that a high-MUFA diet improves glycated hemoglobin and fasting blood glucose levels in patients with diabetes [34]. An OA-rich diet was shown to be effective in improving insulin resistance in patients with T2DM [53]. Several studies demonstrated that daily supplementation with PUFA increases the level of circulating adiponectin, which is a hormone that helps to regulate glucose level and the fatty acid breakdown and increase insulin sensitivity [42]. Linoleic acid in pecan nut is proved to be effective in stimulating insulin secretion in rat pancreatic cells [48]. Thus, PUFA and MUFA are also present in oil; this supports that acorn oil has the ability to prevent T2DM.

As previously indicated, acorns are also an excellent source of tocopherols (γ-tocopherol is the most abundant vitamer). These compounds have shown efficacy as a powerful lipid-soluble antioxidant that prevents the propagation of lipid peroxidation [54]. Tocopherols have been largely investigated for their anticancer, antiaging, and antiatherosclerosis effects [17] In addition, γ-tocopherol has been shown to reduce proinflammatory eicosanoids and inflammation response in rats [55]. Furthermore, γ-tocopherol supplementation in vivo modulates T-cell genes related to anti-inflammatory functions [56]. It also inhibits the growth of human prostate cancer cells [57] and protects cells against malignant transformation [18]; thereby, acorn oil can be considered as an interesting natural source of these compounds for applications in dietary and pharmaceutical products.

The antioxidant activity in the oil can help to protect humans from oxidative stress and prevent lipids and lipid-containing foodstuffs from oxidation. The presence of the hydroxyl group (-OH) in phenolic, tocopherol, and phytosterol helps to scavenge the free radicals to prevent oxidation [42]. Thus, acorn oil is suggested to be used as new functional oil as it contains high amounts of phenolic compounds, tocopherol, and phytosterol. It has been reported that acorn oils presented a remarkable antioxidant activity, up to 3.34 and 3.79 μmol TE g^{-1} oil (DPPH and ABTS test, respectively) [21]. In addition, [30] suggested that the strong antioxidant ability of acorn oil (IC50 : 170.5 μg/ml and 265.5 μg/ml, by DPPH and β-carotene bleaching assay, respectively) is possibly due to the presence of the phenolic compounds, α-tocopherol, flavonoids, and numerous different fatty acids.

6. Applications

Acorn can be considered as a new source of valuable chemical compounds, potentially used as an antioxidant food supplement. In this context, Özünlü et al. [58] evaluated the effect of acorn extracts on the physicochemical, antioxidative, and sensory properties of chicken thigh meat during refrigerated storage (2°C/14 days). According to the results, acorn extracts showed efficiency as an antioxidant against lipid and protein oxidation. The incorporation of acorn extracts also helped to improve sensory characteristics (color, juiciness, astringency, and overall acceptability) of chicken meat. Another study showed that acorn extract could be used as a natural antioxidant for maintaining the stability of RTE chicken patties [31]. Acorn extract exhibited a high ability in controlling color and texture deterioration during chilled storage and reheating and also helped to improve the color and odor acceptance of the products. The antioxidant activity displayed by acorn could be attributed to their chemical composition such as phenolic compounds (200 ppm gallic acid equivalents). In addition, Parsaei et al. [59] reported the influence of replacement of wheat and corn flour by acorn flour in the shelf life of biscuit. This study showed that the addition of 45% acorn flour exhibited higher biscuit antioxidant activity and reduced peroxide value in comparison to other formulations. Likewise, it was reported that acorn flour contributed to higher growth (an average of 367%) of the antioxidant activity of the biscuits as well as improved sensory acceptance [60].

Currently, acorns are used in the human diet, specifically as flour (generally for bread and biscuit production) or as a coffee substitute beverage. Recently, acorn flour has been demonstrated efficient in the improvement of bread specific volume and crumb texture and enhanced the amount of phenolic compounds [61]. In addition, [62] investigated the influence of acorn flour on the rheological properties of gluten-free dough and the physical characteristics of the bread. They concluded that 20% of acorn flour had a positive impact on bread volume and physical properties of the crumb. Also, it was found that supplementation of bread with debittered acorn flour not only strengthened dough structure but also enriched bread with proteins, minerals, and dietary fiber, which makes acorn flour an interesting ingredient for the development of gluten-free bread. Sekeroglu et al. [8] produced a coffee from acorn and determined its mineral compositions. Based on the results of this study, this drink can be considered a good source of macronutrients (P, Ca, K, Mg, and S) and micronutrients (Fe, Cu, Mn, and Zn) without hazardous heavy metals.

Cosmetic preparation containing acorn oils as well as other ingredients like avocado oil and beeswax has been patented (Patent number, WO2017001707A1). That product is applied to skin irritation and eczema.

Apart from that, the potential use of acorn oil as feedstock to produce biodiesel was studied by [63]. In this study, the Taguchi experimental design was used for acorn kernel oil methyl ester production. The optimal process parameters are determined to be a catalyst concentration (KOH) of 0.7 wt%, an 8 : 1 alcohol: oil molar ratio, a 50°C reaction temperature, and 40 min of reaction time. Acorn kernel oil methyl ester yield was 90% under the optimal process parameters. Provine et al. [64] patented the use of acorn oil to produce a new lubricant which has outstanding advantages not found in the ordinary mineral lubricating oils, claiming that the oil contributes to increasing the viscosity index of the motor oil as well as resistance to sludging.

7. Conclusion and Future Research Implications

Acorn oil has gained wide attraction in the scientific community as functional oil. Some studies pertinent to acorn oil have been reviewed in this article. From the health point of view, acorn oil contains a higher proportion of MUFA, especially oleic acid (65%), and also linoleic acid (26.4%) and γ-linolenic acid (3.4%), which are important in the aspects of nutrition. The high MUFA and PUFA in acorn oil make it a promising supplement food product in preventing the risk of cardiovascular. Furthermore, β-sitosterol is the predominant phytosterol presented in acorn oil (90%). Acorn oil is also an excellent source of tocopherols, with γ-tocopherol being the most abundant. Antioxidant activity and polyphenol identification indicate potential health benefits. However, more research should focus on producing better quality acorn oil such as the application of more innovative and optimized techniques that can increase its health benefits. Likewise, toxicological effects, mechanism of action in the human body, and nutritional intake data are necessary before considering its use for food purposes. On the other hand, factors such as environmental conditions and masting tendency and their impact on acorn oil yields were not considered. Lack of this information is a great challenge for the industry in terms of the long-term use of acorns as a source of oil and therefore requires further studies.

Abbreviations

LDL: Low-density lipoprotein
Q: Quercus
MUFA: Monounsaturated fatty acid
PUFA: Polyunsaturated fatty acid
PV: Peroxide value
Spp.: Plural species
T2D: Type 2 diabetes.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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