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Review

Research Progress on Nutritional Properties of Noni (*Morinda citrifolia* L.) Fruit and Its Fermented Foods

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Abstract

Noni fruit is a tropical fruit that is widespread in the Pacific Island region and in the province of Hainan in China. Noni fruit is rich in various active compounds and has long been consumed in Pacific Island countries as a traditional food and medicinal plant with anti-inflammatory and immunomodulatory properties. While recent studies have reported on the constituents and effects of noni fruit, there are few comprehensive summaries on the functionality and development of its applications. Therefore, based on the varieties, origin, ripening stage, and extraction methods of noni fruit, this manuscript summarizes the constituents and content changes of noni fruit, explains its important health benefits and mechanisms of action, analyzes the process of fermented food production and the fermentation strains of noni fruit on the quality of the product and its taste, and aims to support the scientific development and utilization of noni fruit as well as the healthy growth of its industry.

Keywords: noni fruit; nutritional properties; functional activities; fermented foods

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1. Introduction

Noni fruit is the alice family seashore wood barberry (*Morinda citrifolia* L.) fruit, native to Hawaiian and Polynesian regions. The Pacific Islands, India, China's Hainan, Taiwan, and other regions have a wide range of its distribution. In 2010, China listed noni fruit pulp as a "new resource food". Noni fruit as a tropical fruit because of its rich nutrients and functional active substances. It is known as the "Queen of Fruits". Its fruit is oval, the surface is rough, it has a large number of irregular protruding points distributed throughout, and there are many black–brown seeds inside [1]. During the ripening process, the color and texture of noni fruit change obviously. Noni fruits at different maturity stages are shown in Figure 1. It changes from a dark green, hard fruit to a light green, slightly hard fruit. Then, noni fruit gradually becomes a dark yellow, softer fruit and finally turns into a yellow–white, soft fruit. Noni fruit is rich in nutrients, and the bioactive compounds that have been identified in the fruit include phenolic compounds, polysaccharides, fatty acids, alkaloids, anthraquinones, esters, and triterpenoids [2].

In vivo and in vitro studies have shown that noni has functional properties, such as hepatoprotection [3], antibacterial and anti-inflammatory activities [4], immune enhancement [5], hypolipidemic [6], and hypoglycemic effects [7]. We have summarized the

bioactive functions of noni fruit and its fermented products, as detailed in Figure 2. With people's increasing attention to a healthy life and with the development and utilization of natural active products, due to its rich nutrients and traditional medicinal value, noni fruit will attract the attention of more and more researchers. However, because it contains pungent odors, such as caproic acid and butyric acid, it is not suitable for direct consumption. Therefore, using fermented noni fruit as a raw material to produce noni juice is the main form of the development and application of noni fruit resources. Noni juice was also proposed by the European Union in 2003 to be a new type of beverage [8]. Therefore, this paper summarizes the nutritional composition and efficacy mechanism of noni fruit and the current research status of its fermented food in order to provide data support and new research ideas for noni fruit resource development.



Figure 1. Noni fruit at different ripening stages.

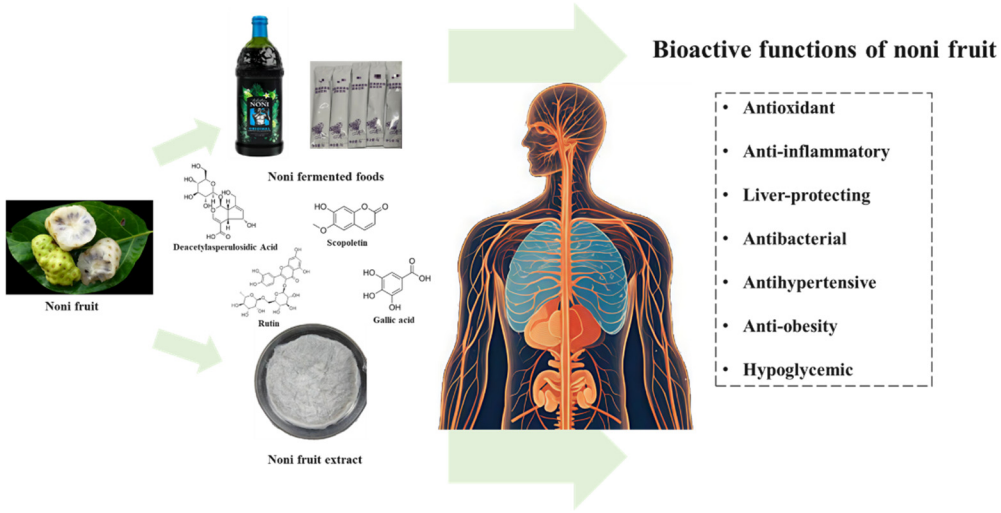


Figure 2. Nutritional properties of noni (*Morinda citrifolia* L.) fruit and its fermented foods.

2. Noni Fruit Nutritional Composition

The water content of noni fruit is about 90%. It is rich in a variety of nutrient substances, including proteins, minerals, polysaccharides, as well as phenols, iridoids, organic acids, anthraquinones and alkaloids, and other characteristic components.

2.1. Polysaccharides

Polysaccharides are important functional components of noni fruit and have health benefits, such as anti-inflammatory [9] and hepatoprotective [10] effects. Noni fruit polysaccharides are present in the interstices between noni fruit cells and their primary walls and play an important role in the softening and binding of cellular tissues. The content and monosaccharide composition of noni polysaccharides are affected by the varietal origin, maturity, and extraction method of noni fruit.

The noni fruit polysaccharide is an acidic heteropolysaccharide, and its main monosaccharide composition is galacturonic acid and galactose. Rhamnose and glucose are the

minor components of noni fruit polysaccharides [9], so these polysaccharides are also present in neutral polysaccharides. Sousa et al. [4] examined Brazilian noni fruit and found that galacturonic acid (29.1%), galactose (30.9%), and arabinose (31.0%) were the main components of its polysaccharides. Galacturonic acid is mostly found in fruits and vegetables and is widely used as an important component of pectin in the food as well as pharmaceutical industries. Noni fruit pectin, containing about 50% galacturonic acid, was able to inhibit pancreatic lipase activity more than commercially available citrus pectin, with a half-maximum inhibitory concentration value of 16.57 μmol/L for lipase inhibition, and, therefore, may serve as a potential obesity inhibitor in foods [11]. Based on previous studies [4,9], we have compiled the composition of polysaccharides from noni fruits of different origins, which are shown in Table 1. The ripeness of noni fruits has a greater effect on noni polysaccharides. As noni fruit gradually transitions from the green, unripe stage to the gray–brown, overripe stage, the extraction rate of polysaccharides also gradually increases from 3.81% to 8.26%, and the sugar content of polysaccharide extract increases from 57.85% to 61.94%. With the growth and ripening of the fruit, cell wall polysaccharides, such as pectin, cellulose, and hemicellulose, were solubilized, catabolized, and de-esterified by enzymes, such as pectin methyl esterases and polygalacturonidases, resulting in the fruit softening, making the polysaccharides of noni fruit at the overripe stage easier to extract [12]. Additionally, some researchers analyzed and found that the crude polysaccharide content of yellow–white noni fruits was the lowest at 1.07 g/100 g, and the trend decreased with an increase in ripeness [13]. This may be related to factors such as the variety of raw materials and the lack of purification of the extract. This still requires further research to obtain more evidence.

Table 1. Comparison of monosaccharide composition (mol%) of noni fruit from different origins.

Carbohydrate	China's Hainan Noni Fruit	Brazilian Noni Fruit	Vietnam Noni Fruit
Galacturonic acid	58.4	29.1	53.6
Galactose	4.4	30.9	17.9
Rhamnose	4.8	5.4	9.5
Arabinose	2.2	31.0	13.6
Mannose	Not analyzed	3.6	0.7
Xylose	Not analyzed	Not identified	1.2
Glucose	21.1	Not identified	2.2
Glucuronic acid	Not analyzed	Not identified	1.1
Fucose	Not analyzed	Not analyzed	0.3

There are many extraction methods for noni polysaccharides, and the "aqueous alcohol precipitation" method is one of the commonly used methods. That is, dehydrated noni fruit slices are extracted with distilled water, and then, the obtained aqueous extract is concentrated under reduced pressure and precipitated with ethanol overnight [6], and the extraction rate of noni polysaccharides in this method is related to the solvent concentration, the liquid-to-material ratio, the extraction time, the extraction temperature, and other factors. Zuo et al. [14] analyzed the effects of different ethanol concentrations on the yield of noni fruit polysaccharides. Their results show that when the final ethanol concentration reached 90%, the extraction rate of noni polysaccharides was the highest, reaching 7.59%. Moreover, the extraction rate decreased as the ethanol concentration declined. There are many reports which show that the "aqueous ethanol precipitation" method often has problems, such as the high temperature of the water resulting in the destruction of the bioactive capacity, and the extraction rate is low, about 6–8%. Recently, researchers have developed some new techniques for noni polysaccharide extraction, such as ultrasound-assisted extraction and pulsed electric field-assisted extraction. The advantages of ultrasound-assisted

extraction mainly lie in the fact that noni polysaccharides can be extracted at lower temperatures, while ultrasonic cavitation can enhance the extraction efficiency and reduce the energy consumption of the extraction [15]. Meanwhile, pulsed electric field-assisted extraction can enhance the effect of solvent extraction, accelerate the diffusion of substances, and also enable the objects to be extracted and separated at a lower temperature [16,17]. The researchers extracted polysaccharides from noni fruit by three methods, water extraction, ultrasound-assisted extraction, and pulsed electric field-assisted extraction, and found that the ultrasound-assisted extraction method obtained the highest yield of polysaccharides, about 11.13%. They further analyzed the antioxidant function of the three extracted noni fruit polysaccharides and found that the polysaccharides obtained by the ultrasound-assisted extraction method had the strongest antioxidant capacity, and a correlation analysis showed that the galacturonic acid content of noni fruit polysaccharides was negatively correlated with the half maximal inhibitory concentration (IC_{50}) values of the 2,2-Diphenyl-1-picrylhydrazyl radical (DPPH), the 2,2′-Azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) radical cation (ABTS), and the hydroxyl radical scavenging rate. Additionally, many studies have also reported that polysaccharides with a high glucuronide content due to the presence of electrophilic groups (e.g., ketones or aldehydes) in them contribute to the release of hydrogen from the O-H bond, and these groups can enhance free radical scavenging activity [18].

In conclusion, the polysaccharide content of noni fruit and its monosaccharide composition are affected by factors such as varietal origin, ripeness, and the extraction method, which in turn may affect the biological activity of the polysaccharides. As the fruit grows and matures, the galactose and galacturonic acid content of the polysaccharides will peak. The galacturonic acid content tends to correlate with antioxidant activity, and polysaccharides containing high levels of galacturonic acid usually have stronger antioxidant properties [19]. Although mature fruits have the advantage of yielding polysaccharides, their accompanying conformational deterioration and microbial fermentation can lead to the accumulation of undesirable volatile substances, such as butyric acid. Therefore, suitable varieties as well as maturity of noni fruits should be selected according to the quality characteristics of the processed products. In addition, with the emergence of new physical, chemical, and biological extraction techniques, such as ultrasound-assisted extraction, enzymatic wall-breaking, etc., the extraction rate of noni polysaccharides can be improved, but there is still a lack of in-depth research on the activity of noni polysaccharides obtained from different extraction methods.

2.2. Polyphenols

The chemical structure of polyphenols contains a benzene ring and one or more hydroxyl groups with the structural unit (C_6H_6O), and polyphenols can be categorized as phenolic acids, flavonoids, and non-flavonoids [20]. Polyphenols have a large molecular structure and have a low digestive absorption rate of about 5–10% in the human body and are mainly metabolized and utilized by microorganisms in the intestine [21].

Variety and origin are important factors affecting the polyphenol content of noni fruit. The results of total phenol determination of noni fruit from Samoa, Indonesia, China (Hainan), Hawaii, Thailand, and Tahiti show that the total phenol content of noni fruit of Indonesian origin was the highest at 1.67 mg GAE/mL (Gallic Acid Equivalent, GAE), which may be related to the local soil environment, temperature, water source, and fruit tree varieties [20].

Salicylic acid, gallic acid, kaempferol-3-O-glucoside, and rutin are the main phenolic compounds in noni fruit, and the contents of the above substances in 70% ethanol extract of noni fruit were 2039.49, 1179.44, 909.31, and 389 μg/g Dry Weight (m_d), respectively [22].

Different solvents have an effect on the content of phytocompound constituents in noni fruit extracts. The extraction of noni fruit phenols was carried out using conventional solvents and deep eutectic solvents, and it was found that the noni fruit polyphenol content of 70% ethanol extracts was higher than the other groups, except for the betaine:glycerol-treated group [22]. Polyphenols have high polarity, so according to the principle of "similarity and solubility", in noni fruit, they are more likely to be extracted by high-polarity solvents [23]. Recently, it was found that the use of ultrasonic treatment of noni juice could increase the content of scopolamine, asperulosidic acid, and deacetylasperulosidic acid by 6.17%, 10.9%, and 27.71%, respectively, compared with a blank control group. The researchers also compared the effects of first ultrasonic treatment followed by the application of pectinase and cellulase to the juice with that of enzymatic digestion followed by ultrasonic treatment on the active substances in noni juice and found that enzymatic digestion followed by ultrasonic treatment was able to enhance the content of the characteristic active substances in the juice, but it is worth noting that there was no statistical difference between the two treatments ($p > 0.05$) [24].

The study of noni fruit maturity will provide important theoretical and data support for determining the optimal picking time, as well as for maximizing the enrichment of active substances during extraction. Dzah et al. [25] analyzed the total phenol content of different parts of noni fruits at different maturity levels, and the results show that the total phenol content of the green immature pulp was 8.69 mg GAE/g m_d, which was much higher than that of the white ripe (ripened and softened) pulp, which was 4.47 mg GAE/g m_d. Interestingly, the total phenol content in the noni seeds was overall higher than that in the pulp, peel, and leaf sites at all sites. However, it has also been shown [26] that with increasing maturity of noni fruits, the total phenolic content of green unripe fruits gradually increased from 0.45 mg GAE/g m_d to 1.44 mg GAE/g m_d in white ripe fruits, and the total flavonoid content also gradually increased from 3.21 mg RE/g m_d (Rutin Equivalent, RE) to 4.24 mg RE/g m_d. Similar trend results were also observed in a study by Chen et al. [13]. The polyphenol content of most fruits tends to decline during ripening, but the opposite trend was observed in noni fruits. A possible reason for this is the continuous increase in respiratory intensity and the high metabolism of the fruit, which stimulates the synthesis of polyphenolic substances within the fruit [27]. It is noteworthy that the total phenolic content in white overripe noni fruits decreased significantly compared to ripe fruits, which corroborates the claim that aging fruits may limit the metabolic integrity in the fruit, disrupt the balance of the antioxidant system, and ultimately reduce the antioxidant capacity of the fruit [25]. Further analysis of the polyphenols of noni fruits at different stages of ripening using High-Performance Liquid Chromatography (HPLC) showed that the rutin content was not significantly different at different stages, whereas the scopolamine content increased with fruit ripening, and the same result was observed for catechins [28]. Based on the results of previous studies, we have compiled the polyphenolic content in noni fruits, which is presented in Table 2.

Table 2. Polyphenolic compounds in noni fruit.

Polyphenol Compound	Monomers	Place of Origin, Variety	Fruit Organizations	Maturity Level	Concentration	Reference
Phenolic acid	Gallic acid	Hainan, China and Fiji	Fresh fruit (dry powder)	Not analyzed	1181.29–1497.42 μg/g	[29]
	Protocatechuic acid				155.34–330.01 μg/g	
	Caffeic acid				25.12–251.52 μg/g	
	Chlorogenic acid				97.31–128.36 μg/g	
	4-Hydroxybenzoic acid				16.54–126.19 μg/g	
	Tannins				383.90–653.16 μg/g	

Table 2. *Cont.*

Polyphenol Compound	Monomers	Place of Origin, Variety	Fruit Organizations	Maturity Level	Concentration	Reference
	Gentianic acid	Hainan, China			336.96–390.63 μg/g	[22]
	Salicylic acid				169.08–3109.23 μg/g	
	Ferulic acid				0–29.69 μg/g	
	Ursolic acid	French Polynesia	Seeds (dry powder)		not analyzed	[30]
Flavonoids	Rhinocerosin	Hainan, China and Fiji			0–6.67 μg/g	[29]
	Naringin				77.12–487.25 μg/g	
	Eriocitrin				41.37–134.24 μg/g	
	Floridzin				0–55.38 μg/g	
	Nobiletin				0–25.31 μg/g	
	Epicatechin				0–176.64 μg/g	
	Catechin				0–388.01 μg/g	
	Kaempferol				0–28.50 μg/g	
	Quercetin-3-rhamnoside				431.07–860.21 μg/g	
	Rutin				298.55–514.72 μg/g	
	Naringin dihydrochalcone				0–48.37 μg/g	
	Naringenin				0–15.30 μg/g	
	Hesperidin				0–8.21 μg/g	
	Neohesperidin				82.46–140.29 μg/g	
	Isorhamnetin 3-O-galactoside	Hainan, China			131.52–246.51 μg/g	[22]
	Kaempferol 3-O-rutinoside				39.45–84.86 μg/g	
	Kaempferol 3-O-glucoside				699.47–949.50 μg/g	
	Quercetin				232.88–528.30 μg/g	
	Brazilin		Fresh fruit (dry powder)	Unripe	0.28 ± 0.02 μg/kg	[26]
				Partially mature	0.34 ± 0.02 μg/kg	
				Mature	0.32 ± 0.01 μg/kg	
				Overripe	0.34 ± 0.01 μg/kg	
	Robinetin			Unripe	1.85 ± 0.07 μg/kg	
				Partially mature	1.34 ± 0.08 μg/kg	
				Mature	1.70 ± 0.28 μg/kg	
				Overripe	1.15 ± 0.09 μg/kg	
	Spinosin			Unripe	6.46 ± 0.35 μg/kg	
				Partially mature	5.48 ± 0.13 μg/kg	
				Mature	3.68 ± 0.23 μg/kg	
				Overripe	3.89 ± 0.08 μg/kg	
	Isorhamnetin 3-O-neohesperidin			Unripe	0.36 ± 0.01 μg/kg	
				Partially mature	0.21 ± 0.02 μg/kg	
				Mature	0.24 ± 0.02 μg/kg	
				Overripe	0.12 ± 0.01 μg/kg	
	Tricin			Unripe	0.01 ± 0.00 μg/kg	
				Partially mature	0.07 ± 0.05 μg/kg	
				Mature	not detected	
				Overripe	0.02 ± 0.01 μg/kg	
Lignins	Vanillin				6.77–11.20 μg/g	[22]

Table 2. *Cont.*

Polyphenol Compound	Monomers	Place of Origin, Variety	Fruit Organizations	Maturity Level	Concentration	Reference
	Moricitan A		Seeds (dry powder)	Not analyzed	0.3 mg/kg	[31]
	3,3′-Bisdemethylpinoresinol	French Polynesia			Not analyzed	[30]
Coumarins	Scopolamine	Tahiti and Jasmine Island in French Polynesia, Tonga, Dominican Republic, Okinawa, Thailand, and Hawaii	Fresh fruit (fruit pulp)		0.064–6.87 mg/g	[32]

In conclusion, noni polyphenols are one of the key components of the overall bioactivity of noni fruit, which endow noni fruit with excellent antioxidant, antibacterial [22], and other activities. Currently, there is a lack of research on polyphenol compounds in noni fruits of different origins and varieties, which still poses difficulties for the selection of raw materials for noni fruit-processed products. Many researchers have used multiple extraction techniques to successfully study noni fruit polyphenols, and the ultrasonic synergistic enzyme method provides a new idea for noni fruit polyphenol extraction. Additionally, deep eutectic solvents can also increase the content of polyphenol substances in the extract. However, the difficulty of the separation of deep eutectic solvents also brings troubles for the utilization of noni fruit polyphenols. In addition, many studies have reported that there are large differences in the polyphenol content of noni fruits at different maturity levels. In general, the polyphenol content increases as the fruit matures, and the polyphenol compounds in ripe white and soft noni fruits are more abundant than those in other stages. However, due to senescence, the decrease in synthesis and the increase in polyphenol metabolism lead to a reduction in polyphenol content in white overripe fruits. In the future, researchers should pay more attention to the polyphenol content and composition of noni fruits from different origins and varieties, improve the extraction process based on deep eutectic solvents, and gain a deeper understanding of their molecular dynamics.

2.3. Iridoids

Iridoids are a special class of monoterpenes, and most iridoids are often bound to glucose and exist as glycosides due to the unstable hemiacetal hydroxyl group in the structure of iridoids. Iridoids are widely distributed in traditional Chinese medicine and are more common in *Genisteaceae* and *Rubiaceae* [33]. Iridoids have a variety of physiological activities, such as hypoglycemic [34], antibacterial, and anti-inflammatory [35] effects, and are one of the main active ingredients in noni fruit.

Deacetylasperulosidic acid and asperulosidic acid were found to be the major iridoids in noni fruits [36], with contents of about 13.8–42.9 and 0.7–8.9 mg/g m_d, respectively. Deng et al. [37] analyzed the contents of deacetylasperulosidic acid and asperulosidic acid from noni fruits of different parts of noni and of different origins, and the results show that noni fruits were most enriched with deacetylasperulosidic acid and asperulosidic acid. Additionally, the total iridoid content of noni fruits from Tahiti was higher than that of noni fruits from Tonga, the Dominican Republic, Okinawa, Thailand, and Hawaii. Chen et al. [38] analyzed the content of asperulosidic acid in noni juice from different origins and found that the content of asperulosidic acid in noni fruit from Fiji, Thailand, and Xisha, Hainan, China, was about 0.218–0.294 mg/mL. Some studies reported that the content of deacetylasperulosidic acid in noni fruit juice was about twice as much as that of asperulosidic acid, and with a prolongation of the fermentation time by *Lactobacilli*, there was a tendency for the ratio of the two to widen, which may be the result of *Lactobacilli*

playing a role in deacetylation during the fermentation process [39]. In addition, the highest content of total iridoids was found in noni fruit powder obtained by lyophilization, which may be due to the easy degradation of the total iridoids at high temperature.

The use of organic solvents, such as methanol and ethanol, for extraction is the main method of extracting iridoids from noni fruit. After alcohol extraction, iridoids are separated and purified by large-pore adsorption resin. In addition to traditional organic solvents, green deep eutectic solvents can also be used to extract iridoids in noni fruit, and choline chloride–ethylene glycol (molar ratio of 1:2) extracts have a total iridoid content of 23.17 mg CE/g m_d (Catalpol Equivalent, CE), which is the highest among each deep eutectic solvent extract. Although this is slightly lower than 70% ethanol extracts, this also shows the potential application of deep eutectic solvents in phytochemical extraction [22]. Zhang et al.'s [40] study also reported that the total iridoid content of a glycine:glycerol (molar ratio of 1:3) extract was 19.76 mg/g m_d, which was much higher than methanol and ethanol treatment groups, and showed inhibition of α-glucosidase with blood glucose-lowering activity. The excellent extraction effect of deep eutectic solvents may be related to their suitable solubility, viscosity, and polarity [41], and the combination of hydrogen bond acceptors and hydrogen bond donors according to a certain molar ratio can form hydrogen bonding forces to generate a strong hydrogen bonding network to regulate the solubility and polarity of deep eutectic solvents and the addition of a certain amount of water or increase in temperature to reduce viscosity and increase the mass transfer capacity and diffusivity to improve the extraction efficiency [42]. In recent years, there have been many studies on deep eutectic solvents combined with ultrasound-assisted, microwave, and other physical field extraction techniques. Lu et al. [43] investigated the use of deep eutectic solvents, such as choline chloride–lactic acid combined with ultrasonication for the extraction of iridoids from *Phlomis medicinalis* Diels, and the results show that with n increase in the ultrasonication time from 15 min to 35 min, extraction increased dramatically, from about 12% to about 20%. Yu et al. [44] used microblogging-assisted deep eutectic solvents for the extraction of iridoids and phenolic acids from *Eucommia ulmoides* leaves and found that the total extraction rate was 1.40–1.35 times higher than that of ultrasound-assisted ethanol extraction and hot water extraction, and the extraction time was shorter, and the solvent toxicity was lower. Nevertheless, there are few research reports on the combined physical field extraction technique in noni fruit, which needs to be further explored in practical applications. According to previous studies, we have organized some iridoids in noni fruit in the following table. However, most of the studies focused on the extraction, isolation, and identification of iridoids in noni but lacked the targeted quantification of specific iridoid monomers.

HPLC was used to analyze the content of iridoids in noni fruits at different maturity levels, and the results show that the content of deacetylasperulosidic acid and asperulosidic acid showed a significant increasing trend during the maturation process, and the content of both compounds in white ripe noni fruits was more than 200 mg/L [28]. In addition, the use of noni fruits to produce fermented noni juice is a traditional processing method, and a comparison of different maturity noni fruits is particularly important for the content of iridoids and other actives in the final product, and a study showed that the content of deacetylasperulosidic acid in fermented juice from light–yellow ripened noni fruits was the highest, which was 805.89 mg/L, which may be attributed to the rich content of iridoids in the light yellow ripened noni fruits prior to the fermentation as well as the effects of microflora [45]. Therefore, light yellow as well as white noni fruits, at the ripening stage, are more suitable for the processing of health products with iridoids. Based on the results of previous studies, we have compiled the iridoids in noni fruits, which is presented in Table 3.

Table 3. Iridoids in noni fruit.

Chemical Composition	Chemical Formula	Place of Origin, Variety	Extraction Methods	Concentration	Reference
Asperulosidic acid	$C_{18}H_{24}O_{12}$	Okinawa, Japan	Methanol extraction 3 times and n-butanol extraction	2.57 mg/kg m_d	[46]
6α-Hydroxypolyglucoside	$C_{17}H_{26}O_{11}$	Nature's Sunshine Products, Inc., Lehi, UT, USA		7.50 mg/kg m_d	[47]
6beta,7beta-epoxy-8-epi-splendoside	$C_{17}H_{24}O_{12}$			1.80 mg/kg m_d	
Borreriagenin	$C_{10}H_{14}O_5$			unspecified	
4-epi-dunnisinin	$C_{11}H_{14}O_5$	Taiwan Hsieh Co, Taiwan, China	A total of 95% ethanol extraction 4 times and ethyl acetate extraction	4.40 mg/kg m_d	[48]
Asperuloside	$C_{18}H_{22}O_{11}$			50.00 mg/kg m_d	
Deacetylasperulosidic acid	$C_{16}H_{20}O_{10}$			4.00 mg/kg m_d	
deacetylasperulosidic acid	$C_{16}H_{22}O_{11}$	Hainan, China	A total of 75% ethanol extraction	22.65 mg/g m_d	[22]

Iridoids are key functional components of noni fruit with significant biological activities, and their pharmacological effects cover anti-inflammatory, hypoglycemic, and other multiple effects. Studies have shown that the composition and content of these compounds are synergistically regulated by ecological factors (such as light intensity, altitude gradience, soil physicochemical properties, and water characteristics) and varietal genetic characteristics, showing significant spatial heterogeneity. Moreover, with the ripening of noni fruit, the content of iridoids, such as deacetylasperulosidic acid and asperulosidic acid, increase continuously. Analyzing from the level of extraction technology, although the traditional solvent extraction method is still the current mainstream method, deep eutectic solvents have become a research hotspot of new extraction processes because of both their green chemical properties (low toxicity and degradability) and the high efficiency of their extraction ability. Currently, most existing studies are limited to the determination of the total content and lack accurate quantitative analyses of single compounds. Future research should focus on the following directions: (1) developing highly sensitive detection methods to achieve targeted quantification of specific iridoid monomers in complex matrices; (2) deepening the study on the extraction mechanism of deep eutectic solvents and optimizing their coupling with ultrasound/microwave-assisted technology; and (3) exploring the conformational relationship of iridoids and their dynamic transformation in fermented noni foods.

2.4. Anthraquinones

Anthraquinones are important characteristic compounds in the family *Rubiaceae* [49] and are present in large quantities in the roots and leaves as well as fruits of noni. Modern pharmacology has shown that anthraquinones possess various biological activities, such as anti-inflammatory, antioxidant, antitumor, and antiviral activities [35,50].

The maturity of noni fruit has a small effect on the anthraquinone content of the fruit, and anthraquinone is mainly present in the pericarp as well as in the seeds of noni fruit [51]. Currently, most studies have focused on the isolation and identification of anthraquinones in noni fruits, while few quantitative analyses of the anthraquinone composition of noni fruits have been conducted. Deng et al. [52] reported the determination of 5,15-dimethylmorindol, lucidin, alizarin, and rubiadin anthraquinones in noni fruit by Reversed-Phase High–Performance Liquid Chromatography, and the results show that the content of 5,15-dimethylmorindol in noni fruit puree was 0.186–0.202 μg/mL, while other anthraquinones were not detected. Damnacanthal is a very important anthraquinone compound in noni and has been reported to exert anticancer effects in many studies [53]. Kanokmedhakul K et al. [54] reported the cytotoxicity of damnacanthal against human breast carcinoma cell lines, as well as antifungal activity against *Candida albicans*. In addition,

damnacanthal has been shown to target the Hepatocyte Growth Factor Receptor and reduce the phosphorylation level of Protein Kinase B in Hep G2 cells, exerting an inhibitory effect on hepatocellular carcinoma [55]. In addition to the anticancer and antibacterial effects of anthraquinones in noni, 1,4-dihydroxy-2-methoxy-7-methyl anthraquinone, isolated and extracted from noni, has been shown to have type I collagen-stimulating effects and can be developed as a novel anti-wrinkle agent. Drawing on the findings from prior research, the anthraquinones in noni fruits have been compiled and are presented in Table 4.

Table 4. Anthraquinones in noni fruit.

Chemical Composition	Chemical Formula	Place of Origin, Variety	Fruit Organization	Concentration	Reference
3-Hydroxy-1,2-dimethoxy-anthraquinone	$C_{16}H_{12}O_5$	Haikou, Hainan, China	Seeds (dry powder)	0.40 mg/kg	[31]
2-Hydroxy-1,5-dimethoxy-6-(methoxymethyl)-9,10-anthracenedione	$C_{18}H_{16}O_6$			0.30 mg/kg	
2,4-Dihydroxy-3,8-dimethoxy-7-(methoxymethyl)-9,10-anthracenedione	$C_{18}H_{16}O_7$			0.80 mg/kg	
1,6-Dihydroxy-5-methoxy-2-(methoxymethyl)-9,10-anthracenedione	$C_{17}H_{14}O_6$	Haikou, Hainan, China		0.50 mg/kg	[31]
		Fiji noni fruit	Fresh fruit (dry powder)	0.80 mg/kg	[56]
1,5,7-Trihydroxy-6-methoxy-2-methoxymethylanthraquinone	$C_{16}H_{12}O_6$	Fiji noni fruit		0.15 mg/kg	
2-Methoxy-1,3,6-trihydroxyanthraquinone	$C_{15}H_{10}O_6$	Nature's Sunshine Products, Inc.		0.18 mg/kg	[57]

In sum, noni anthraquinones have a variety of biological activities. Although studies have explored the isolation and characterization of noni anthraquinones, there is still a paucity of studies focusing on their quantitative analysis. Secondly, if noni anthraquinones are to be used as medicinal substances, their genotoxicity and metabolic stability under long-term exposure must be systematically evaluated to provide safety threshold data for clinical translation.

2.5. Alkaloids

Alkaloids are naturally occurring nitrogenous organic compounds, but they do not include open-chain simple fatty amines, such as amino acids and proteins. Noni fruit is rich in alkaloidal components, and it has been reported in the literature that alkaloids in noni fruit have various biological activities, such as hypoglycemic [7] and antibacterial [58] effects.

The effects of noni fruit varieties and maturity on alkaloid content have rarely been reported, and in recent years, most reports on noni alkaloids have been on their extraction and identification. The extraction methods of noni alkaloids include the following two: organic solvent extraction and physical field-assisted extraction. Zhang et al. [7] extracted alkaloidal components from noni fruit juice with organic solvents and determined their inhibitory effects on α-glucosidase in vitro. The results show that the alkaloidal extracts of noni (R)-p-hydroxy-4-(8-hydroxy-m-hydroxyphenylethyl) pyridinium have potential hypoglycemic activity. Shen et al. [59] analyzed the alkaloidal components of noni fruit using chromatographic separation techniques, such as silica gel column chromatography and preparative HPLC, and found that noni fruit extracts of 2′-deoxyt hymidine, cyclo-(L-Pro-L-Tyr), methyl-5-hydroxy-2-pyridinecarb-oxylate, and methyl pyroglutamate in the extract of noni fruit were at concentrations of 38.76, 57.87, 1452.81, and 150.56 μg/100 g.

2.6. Other Nutrients

The protein content of noni fruit is about 2.36–4.20% [60]. The protein content is relatively stable during the ripening process [13]. The main amino acids in noni fruit puree are aspartic acid, glutamic acid, and alanine, accounting for about 0.80, 0.64, and 0.45 mg/g,

respectively [61]. The protein content varies widely among the various parts of noni fruit, with the lowest protein content in the fruit parts and abundant amounts in noni seeds [62]. During noni fruit processing, the seeds are often discarded as waste. In view of the rich protein content in the seeds, a recent study extracted the protein in noni fruit seeds and measured the water/oil holding capacity and emulsification characteristics of the extract, and the results show that the water/oil holding capacity of noni fruit seed extracts can reach 4.36 g H_2O/g protein and 11.69 g oil/g protein. In addition, the emulsification stability of the extract was 50% higher than that of the protein of the fruit pepitas. Therefore, the protein extracted from noni fruit seeds can be used as an ingredient in foods such as breads, soups, salad dressings, mayonnaise, and processed meat products [63]. The mineral content of noni fruit is about 8.4% (dry basis weight), mainly including potassium, calcium, magnesium, iron, and phosphorus. The potassium content is up to about 2540–2180 mg/kg. With the fruit continuing to mature, the content of each mineral, except for iron, changes a little [13]. In addition, noni fruit is a typical high-potassium and low-sodium food. An increase in potassium intake can play the role of vascular protection, preventing hypertension and other cardiovascular diseases [64,65]. The most important vitamin in noni fruit is vitamin C, which is about 102–154 mg/100 g m_d. The content of vitamin E in noni fruit of different ripeness shows a decreasing and then increasing trend. Studies have shown that the fat content of noni fruit is about 0.2–0.98 g/100 g, and the mass fraction of saturated fatty acids in noni fruit is 23.88%, and the mass fraction of unsaturated fatty acids is 70.03%, of which linoleic and oleic acids have a mass fraction of 67.9% [13].

In summary, noni fruit is rich in basic nutrients. It is worth noting that the protein content in noni seeds is higher than in other parts of the fruit. In the future, more attention should be paid to extracting seed protein and developing seed protein-based functional foods. Additionally, given the "high potassium and low sodium" characteristics of noni fruit, we can design randomized double-blind trials to verify the effects of noni products on systolic blood pressure regulation in patients with essential hypertension. At the same time, we need to monitor the serum potassium dynamics of people at risk of hyperkalemia during the development of noni-based blood pressure-lowering and other functional foods.

3. Health Benefits of Noni Fruit

Many studies in recent years have shown that noni fruit, fermented noni juice, and products developed based on noni have a variety of biological activities, including antioxidant, anti-inflammatory, liver-protecting, antibacterial, hypotensive, anti-obesity, hypoglycemic, etc., effects. We have briefly summarized this information as shown in Figure 3. In addition, we have organized the active substances in noni and their mechanisms of action, with details presented in Table 5.

Table 5. Health benefits of noni fruit and its mechanism of action.

Health Benefits	Research Target	Mechanisms Explored	Reference
Antioxidant effects	Noni fruit polysaccharides	Noni fruit polysaccharides increased the content of Superoxide Dismutase (SOD) in serum; decreased the content of Malondialdehyde (MDA) in liver tissue; downregulated Nuclear Factor Erythroid 2-Related Factor 2 (Nrf2), Heme Oxygenase-1 (HO-1), NAD (P) H:Quinone Oxidoreductase 1 (NQO1) proteins, and genes related to the oxidative stress signaling pathway in RAW264.7 cells; and inhibited the abnormal decrease in Catalase (CAT), SOD, and Glutathione Peroxidase (GSH-Px) levels and the abnormal increase in MDA, respectively.	[62]

Table 5. *Cont.*

Health Benefits	Research Target	Mechanisms Explored	Reference
	Noni fruit deacetylasperulosidic acid	Noni fruit deacetylasperulosidic acid decreased MDA content and increased SOD activity in rat serum.	[66]
	Noni fruit extract	Noni fruit extract decreased MDA levels and increased SOD activity in rat testis.	[67]
	Noni fruit polysaccharide	Noni fruit polysaccharides reduced hepatic MDA levels and increased hepatic trolox equivalent antioxidant capacity levels and SOD and GSH-Px activities.	[10]
Anti-inflammatory effects	Noni juice-fortified yogurt	The addition of noni juice to yogurt alleviates dextrose sodium sulfate (DSS)-induced colitis in mice through downregulation of Interleukin-6 (IL-6) and Interferon-γ (IFN-γ) mRNA expression and up-regulation of Interleukin-10 (IL-10) mRNA expression.	[68]
	Noni juice	Noni juice treatment of rats with pneumonia reduced lung macrophages by 20–26%, lymphocytes by 34–58%, eosinophils by 30–53%, and neutrophils by 28–70%, and Noni juice showed dose-dependent Nitric Oxide (NO) scavenging effects.	[69]
	Noni juice	Treatment of DSS-induced colitis in mice with noni juice reduced serum Tumor Necrosis Factor-α (TNF-α) and IL-6 production and regulated intestinal flora communities to normal levels.	[70]
	Fermented noni juice	Fermented noni juice can reduce TNF-α and Interleukin-1β (IL-1β) protein expression levels and inhibit the Nuclear Factor kappa-light-chain-enhancer of activated B cells (NF-κB) signaling pathway in the renal cortical proximal tubular epithelial cells of hyperuricemia.	[71]
	Noni fruit polysaccharide	Noni fruit polysaccharides were able to reverse the trend of body weight loss and promote the expression of intestinal tight junction proteins (ZO-1 and occludin proteins) and mucus secretion in mice with colon injury, thereby reducing the damage to the colonic mucosal barrier caused by DSS.	[9]
	Noni fruit polysaccharides	Noni fruit polysaccharides reduced scores of paw tissue damage, decreased myeloperoxidase (MPO) activity, and inhibited leukocyte migration to sites of inflammation in dysfunctional mice.	[4]
Liver-protecting effects	Noni fruit polysaccharides	Noni fruit polysaccharides reduce the triglyceride (TG) and total cholesterol (TC) content in the liver of rats on a high-fat diet, reduce serum alanine aminotransferase (ALT) and AST (aspartate aminotransferase) activity, regulate intestinal flora, reduce the production of short-chain fatty acids, decrease the permeability of the colonic barrier, and alleviate metabolic endotoxemia.	[10]
	Noni fruit polyphenols	Noni fruit polyphenols reduced TC and TG levels and inhibited the increase in ALT and AST activities in the liver of mice with high-fat-diet-induced non-alcoholic steatohepatitis. Noni fruit phenolic administration ameliorates hepatic inflammation in high-fat-diet mice by inhibiting the NF-κB pathway.	[72]
	Noni juice and fermented noni juice	Noni juice and fermented noni juice reduced AST, ALT, alkaline phosphatase (ALP), and glutamyltransferase (GGT) activities in the serum of mice with acute alcoholic liver injury; maintained the integrity of hepatocytes; and increased the activities of GSH, GSH-PX, SOD, and CAT in the liver while inhibiting the production of MDA.	[3]
	Fermented noni juice	Fermented noni juice dose-dependently decreased AST and ALT activities in the serum of rats induced by thioacetamide. Juice treatment increased the activities of GSH, SOD, CAT, and GSH-PX in liver and increased the antioxidant capacity of liver.	[73]

Table 5. *Cont.*

Health Benefits	Research Target	Mechanisms Explored	Reference
	Noni fruit polyphenols	Supplementation with fermented noni juice reduced TC levels in the liver and serum of hamsters on a high-fat diet, alleviated microvesicular steatosis around the central vein of liver tissue, and reduced ALT activity in liver.	[74]
Antibacterial effects	Noni fruit extract	The effective minimum inhibitory concentration (MIC) of noni fruit ethanolic extract was 35.43 mg/mL against *Escherichia coli* and 47.80 mg/mL against *Candida albicans*. However, the MIC of noni fruit methanolic extract was 117.40 mg/mL against *Escherichia coli* and 108.01 mg/mL against *Candida albicans*, and noni fruit methanolic extract had a weaker antibacterial effect.	[75]
	Noni fruit polyphenols	The MIC values of 70% ethanol prepared polyphenolic extract of noni fruit against *Listeria monocytogenes*, *Staphylococcus aureus*, *Bacillus subtilis*, *Escherichia coli*, *Salmonella* spp., and *Pseudomonas aeruginosa* were 0.098, 0.049, 0.024, 0.024, 3.125, and 0.781 mg/mL, respectively.	[22]
	Noni juice	The diameter of the circle of inhibition of a mixture of acids consisting of malic, 3-methylvaleric, acetic, and capric acids was 16.49 mm, which was not significantly different from that of noni juice, which was 16.55 mm.	[76]
	Noni fruit extract	Increasing the concentration of noni fruit extract in the discs enhanced the inhibition of *Listeria monocytogenes*, and the diameter of the inhibition circle of the discs impregnated with 80 mg of noni fruit extract was 22.43 mm.	[77]
Antihypertensive effects	Noni fruit extract	Treatment of dexamethasone-induced hypertensive rats with ethanolic extract of noni fruit resulted in a decrease in systolic and diastolic blood pressure by 11.39% and 10.57%, respectively, compared to a model group.	[78]
Anti-obesity effects	Noni fruit polysaccharides	Noni fruit polysaccharides reduced the body weight and serum levels of TC, TG, Low-Density Lipoprotein Cholesterol (LDL-C), and total bile acids and increased the serum levels of High-Density Lipoprotein Cholesterol (HDL-C) in high-fat mice.	[6]
	Noni fruit polyphenols	Noni fruit polyphenols reduced body weight gain and improved steatosis as well as lipid accumulation in mice on a high-fat diet. Noni fruit polyphenols reduced the serum levels of TC, TG, and LDL-C and increased HDL-C.	[79]
	Noni juice	Noni juice reduced TC, TG, and LDL-C content in serum and increased HDL-C content in serum of mice on a high-fat diet.	[80]
	Fermented noni juice	Fermented noni juice was able to reduce the liver coefficient and visceral fat coefficient in mice on a high-fat diet in a dose-dependent manner. It reduced the content of TG and TC in the serum and liver of mice and improved hepatic steatosis.	[74]

3.1. Antioxidants

The excellent antioxidant activity in noni juice may be attributed to the presence of polysaccharides, flavonoids, phenols, iridoids, and other active components. Tests such as DPPH radical, ABTS radical, and hydroxyl radical scavenging capacity assays and Ferric Reducing/Antioxidant Power Assay (FRAP) are often used to evaluate the in vitro antioxidant capacity of a substance [81]. Guo et al. [3] compared the antioxidant capacity of fresh noni with that of fermented noni juice, and the results show that the juice's DPPH scavenging capacity was above 90%, but the antioxidant capacity of fresh noni juice was found to be superior to that of fermented noni juice using the reducing power assay. Drying is a commonly used method for food processing. A study that used hot air drying, vacuum freeze drying, microwave drying, and far-infrared drying

of noni fruit found that vacuum freeze-drying treatment can obtain the highest total phenolic content and showed good scavenging ability for ABTS and DPPH free radicals and excellent ferric iron reduction ability. Therefore, vacuum freeze drying is suitable for the processing of noni fruit crisps with good antioxidant function [82]. Studies have shown that the maximum scavenging rates of noni polysaccharides for ABTS, hydroxyl radicals, and DPPH radicals were 96.5%, 95.3%, and 95.6%, respectively. In addition, noni polysaccharides also showed an enhancement in antioxidant enzyme activities, such as SOD, in C57 mice and RAW264.7 cells [83]. A similar effect was also found in a study by Ma et al. [66]. They fed deacetylasperulosidic acid to Wistar rats at doses of 0, 15, 30, and 60 mg/kg/day for one week and found that the serum MDA and SOD enzyme activities of the rats decreased and increased according to the dose, suggesting that noni juice may play a role in modulating the activities of antioxidant enzymes through deacetylasperulosidic acid [72]. The results show that noni juice may work by regulating antioxidant enzyme activities through deacetylasperulosidic acid.

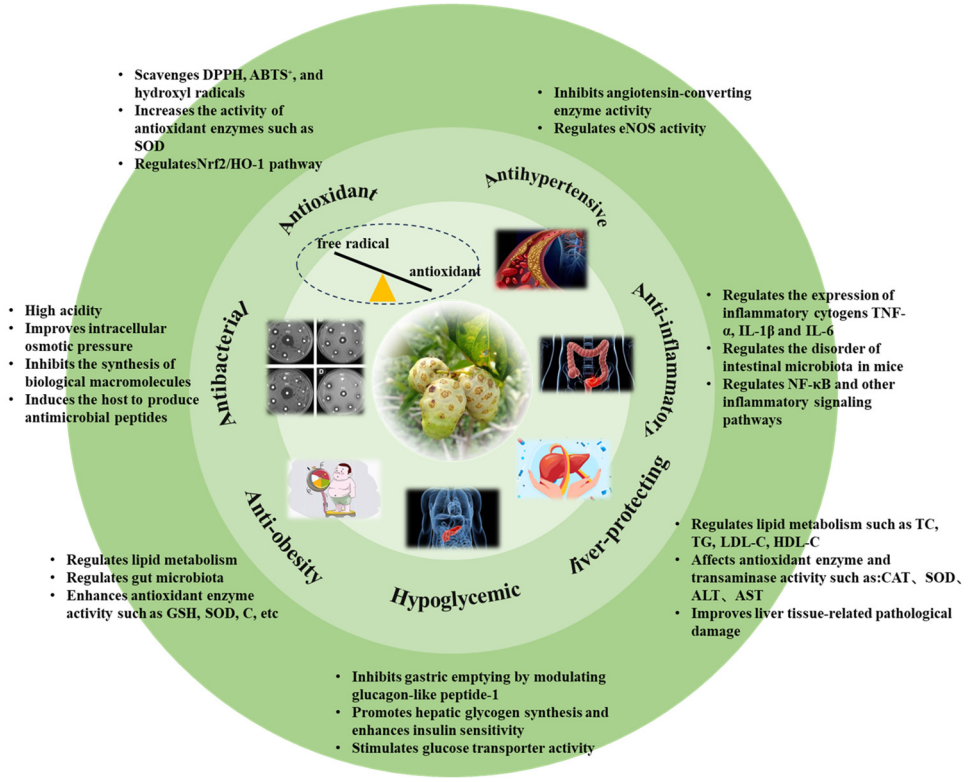


Figure 3. Key health benefits of noni fruit.

With the developments of the food industry, the manufacturing of new food packaging materials with antioxidant properties has received the attention of many researchers. Recently, leveraging the potent antioxidant effect of noni and blueberry, some researchers added blueberry leaf extract to noni polysaccharides to make films. They found that the total polyphenol content and total flavonoids in the new film packaging material increased significantly and had good flexibility. In the future, the film packaging material can be used as a biodegradable new material with antioxidant properties [84]. Lin et al. [85] used a small amount of noni fruit extract in the preparation of pectin and chitosan-based films. They discovered that the total phenolic content and total flavonoid content of the pectin films doped with 10% noni fruit extract increased by 9.26 times and 3.45 times, respectively, compared with a control group. Moreover, these films demonstrated significant antioxidant

activity in the ABTS free radical scavenging assay and FRAP ferric iron reduction assay, which can be attributed to the abundant phenolic compounds present in noni fruit extract.

In conclusion, noni has good antioxidant efficacy, and in vitro studies have shown that it can exert antioxidant effects through the mechanisms of scavenging DPPH, $ABTS^{+}$, and hydroxyl radicals and ferric ion reduction. Animal and cellular experiments further confirmed that noni polysaccharides can significantly enhance the activity of antioxidant enzymes, such as SOD, and improve oxidative stress damage by regulating the Nrf2/HO-1 pathway. In addition, the potential of noni extract in food packaging materials is beginning to show. When noni extract is composited with pectin, chitosan, and other substances, it can significantly enhance the antioxidant properties of the film, as well as endow the film with flexibility and degradability. Future research can further focus on the key components of noni fruit regulating the specific molecular mechanism of the Nrf2 pathway, and it is necessary to combine gene editing and histological technology for in-depth analysis. Secondly, the antioxidant activity and mechanical properties of noni composite films need to be balanced, and nano-embedding technology or a co-mingling modification strategy can be explored in the future to improve the antioxidant release efficiency and mechanical durability in real food-preservation environments.

3.2. Anti-Inflammatory Effects

Many studies have reported anti-inflammatory effects of plant compounds [86]. Polysaccharides, polyphenols, and other active compounds in noni fruit are the main components that exert their anti-inflammatory effects. Most anti-inflammatory studies of noni fruit have been reported in relation to mouse models of colitis and hepatitis. The burst of reactive oxygen species is an important pathogenesis of chronic relapsing inflammatory bowel disease [87]. Kwon S et al. [68] found that noni juice can increase the total phenol and total flavonoid content in a yogurt–noni juice complex to enhance the antioxidant activity, and the complex was able to enhance the antioxidant activity through the down-regulation of IL-6 and IFN-γ mRNA expression as well as the up-regulation of IL-10 mRNA expression. In other words, it inhibited pro-inflammatory factors and activated anti-inflammatory gene expression. Additionally, noni juice from Costa Rica has been shown to have an anti-inflammatory effect on bronchial inflammation and spasmodic activity, which may be due to calcium channel blocker activity. Phenolic compounds, such as flavonoids and coumarins, which are rich in noni fruit juice, can partially explain the anti-inflammatory activity of the juice [69]. Yang et al. [10] explored the inhibitory effects of noni polysaccharides on hepatic inflammation in rats on a high-fat diet and found that the noni polysaccharide-treated group was able to significantly reduce the serum levels of TNF-α in the rats. Moreover, compared with the high-fat-diet group, the administration of noni polysaccharides significantly lowered the hepatic TNF-α, IL-1β, and IL-10 mRNA relative expression levels in the liver and restored them to normal levels.

Noni fruit polysaccharides, polyphenols, and other active substances not only inhibit the production of inflammatory factors but also play an anti-inflammatory role by regulating intestinal microflora balance and its metabolic transformation. Noni fruit polyphenolic compounds play a very important role in relieving inflammation. However, the absorption rate of plant polyphenolic compounds in the human body is very low. It is estimated that the absorption rate of dietary polyphenols in the small intestine is only 5–10%. It has been shown in many studies that plant polyphenols can be metabolized by intestinal microorganisms and then act in the body after being transported in the bloodstream [88]. In a study by Qu et al. [70], the authors used fermented noni juice to treat DSS-induced colitis model mice and found that the intervention of fermented noni juice was able to ameliorate the symptoms of inflammatory edema of the colon in mice, as well as reduce the levels of

TNF-α and IL-6 in the serum. In addition, the authors analyzed the intestinal microorganisms in mice and found that fermented noni juice was able to modulate the disturbance of intestinal flora and increase the relative abundance of *Bacteroidetes* in a model of mice with inflammation, a result similar to that reported by Chen et al. [89]. Wang et al. [72] conducted a more in-depth study on intestinal flora-mediated noni polyphenol alleviation of intestinal inflammation. They found that compared with a control group with high-fat-diet noni, noni-fruit polyphenol treatment could reduce lipopolysaccharides, TNF-α, IL-6, and IL-1β by 22.80, 20.55, 14.82, and 22.86%, respectively. An analysis of the intestinal flora of mice revealed that noni fruit polyphenols could increase the relative abundance of short-chain fatty acid-producing bacteria and significantly up-regulate the expression of intestinal tight junction proteins, suggesting that there might be an important relationship between noni fruit polyphenols and intestinal flora. These results suggest that noni nut polyphenols may have important interactions with intestinal flora.

In summary, polysaccharides and polyphenols are the main anti-inflammatory components of noni fruit, which can play an anti-inflammatory role through the regulation of inflammatory factors and intestinal flora and other mechanisms. In future studies, researchers can, on the one hand, combine multi-omics techniques (e.g., metabolomics and macro-genomics) to systematically elucidate the regulatory network of noni fruit active ingredients on inflammatory signaling pathways, such as NF-κB and Mitogen-Activated Protein Kinase (MAPK). On the other hand, it is necessary to continue to focus on intestinal flora and its mechanism of action in metabolizing noni fruit polyphenols in order to clarify the signaling pathway of noni fruit polyphenols mediating intestinal flora to alleviate inflammation.

3.3. Liver-Protecting Effects

Currently, many studies have reported that noni fruit has a good effect on liver protection, and it has been verified that polysaccharides as well as polyphenols in noni fruit can play an important role. Chronic liver injury mainly includes alcoholic liver disease, non-alcoholic fatty liver disease, liver fibrosis, viral hepatitis, etc. Non-alcoholic fatty liver disease is related to oxidative stress and inflammation, and it is a clinicopathological syndrome characterized by abnormal accumulation of hepatic lipids. Yang et al. [10] intervened with noni fruit polysaccharides in rats induced by high-fat-diet feeding. The results show that the serum levels of ALT and AST were significantly higher in the high-fat-diet group than in a control group. In contrast, noni polysaccharide treatment reduced weight gain and lowered serum ALT and AST levels in rats fed a high-fat diet, thereby ameliorating hepatic injury. Guo et al. [3] treated alcohol-induced acute hepatic injury in mice using noni juice and fermented noni juice. They found that the two types of juices could regulate TC, TG LDL-C, and HDL-C levels. They also reversed the trend of AST and ALT transaminase elevation, significantly increased the GSH content in the liver, and improved the activities of SOD, CAT, and GSH-Px antioxidant enzymes. This suggests that noni fruit also has a protective effect in the case of alcoholic liver injury, and the hepatoprotective effect is related to polyphenol compounds in noni fruit juice. Interestingly, although the overall antioxidant capacity of noni juice is stronger than that of fermented juice, the hepatoprotective effect of fermented juice is better. Lin et al. [73] found that fermented noni juice can significantly reduce liver fibrosis scars in rats and dose-dependently reduce the serum levels of ALT and AST. In addition, liver fibrosis is due to the secretion of large amounts of collagen by myofibroblast-like cells, and fermented noni juice can improve liver fibrosis by regulating the expression of Matrix Metalloproteinase-9 and Matrix Metalloproteinase-2.

In summary, so far, noni fruit shows good liver protection effects, which is closely related to the fact that the fruit is rich in polysaccharides, polyphenols, and other active compounds. Noni fruit and its fermented juice can improve chronic liver injury by regulating lipid metabolism, affecting antioxidant enzymes and transaminase activity, and repairing pathological damage related to liver tissue. In the future, it is necessary to identify and analyze the key monomer components of noni fruit polyphenolic compounds for liver protection, and researchers should also incorporate transcriptomics and proteomics to systematically analyze the regulatory network of noni fruit active ingredients on liver inflammation. In addition, to explore the synergistic effects of noni fruit and other liver protection components (such as silymarin), the development of complex functional liver protection preparations is also a future development direction.

3.4. Antibacterial Effects

Noni fruit has good antibacterial effects. As reported in the literature, this may be related to its richness in active substances, such as polyphenols and iridoids, as well as its high acidity. Wang et al. [22] investigated the effects of noni polyphenol extract on some Gram-negative bacterial strains and Gram-positive strains. The results show that the polyphenol-rich noni fruit extract possessed a strong antibacterial effect and was able to inhibit the growth and multiplication of bacteria. Not only does noni fruit have antibacterial effects, but noni seeds also have good antibacterial effects. In a recent study, it was found that synthetic silver nanoparticles composed of individual parts of noni showed excellent antibacterial effects against *Escherichia coli* and *Staphylococcus aureus*. The silver nanoparticles synthesized from noni seeds had higher antibacterial activity than those synthesized from noni leaves as well as fruits. This may be attributed to their smaller size. The smaller size allows the nanoparticles to easily enter the bacterial interior and release silver ions. These silver ions interact with proteins in the respiratory chain of the cell membrane, subsequently inducing the production of reactive oxygen species, which leads to bacterial cell death [90]. West B J et al. [91] conducted antimicrobial experiments on noni fruit extracts with different concentrations of iridoids and found that the growth of *Candida albicans*, *Escherichia coli*, and *Staphylococcus aureus* decreased with an increase in iridoid concentration. The inhibitory effects of iridoids could reach 90% at 1.0 mg/mL. Therefore, it was inferred that iridoids are also a kind of antimicrobial active substance in noni fruit. In addition, noni is highly acidic (total acid 3.56 g/L and pH 3.82), belonging to high-acid foods. Noni juice contains a large amount of organic acids, such as malic acid, 3-methylglutaric acid, acetic acid, and hexanoic acid, which can exert bacteriostatic effects in several ways, such as through energy competition, permeabilizing the bacterial outer membrane and increasing the intracellular osmotic pressure, inhibiting the synthesis of biomolecules, and inducing the production of antimicrobial peptides in the host [76]. In a study by Lin et al. [85], the diameter of the inhibition zone of a film added with noni fruit powder against *Escherichia coli*, *Salmonella typhimurium*, *Staphylococcus aureus*, and *Listeria monocytogenes* was 9.21–11.00, 8.68–10.56, 8.47–11.42, and 9.30–12.64 mm, respectively, which was greater than that of a negative control (8.00 mm), showing that noni fruit had an antimicrobial effect on *E. coli*, *S. typhimurium*, *Staphylococcus aureus*, and *Listeria monocytogenes*, respectively. These results demonstrate the potential of antimicrobial applications of noni fruit.

Although a large number of studies have reported that noni can exert an excellent inhibitory effect on many bacteria, many researchers suggest that its antibacterial effects may be related to the polyphenolic compounds, iridoids, and organic acids in noni, and the mechanism of its inhibitory effects is still unexplored. In the future, it is necessary to integrate molecular biology and other technologies to break through the bottlenecks in

mechanism analysis and application, so as to provide innovative solutions for anti-infective treatment and to ensure food safety.

3.5. Antihypertensive Effects

The hypotensive activity of noni fruit is related to scopolamine, unsaturated fatty acids, iridoids, and other active substances in the fruit. D Wigati et al. [78] used a model of dexamethasone-induced hypertension in rats and found that the ethanolic extract of noni fruit was able to decrease systolic and diastolic blood pressure in rats by 11.39% and 10.57%, respectively, compared to a model group and suggested that scopolamine and rutin in noni fruit may be the active substances with hypotensive function. Purwaningroom et al. [92] used a bioinformatics approach to continue to investigate the possible hypotensive substances in noni fruit. They measured the inhibition of angiotensin-converting enzyme activity and found that noni methanolic extract dose-dependently inhibited angiotensin-converting enzyme activity, and molecular docking simulations showed that linoleic, palmitic, and oleic acids in noni fruit may be associated with Peroxisome Proliferator-Activated Receptor Alpha (PPARA). Oleic acid may further exert hypotensive effects with the PPARA protein. Yoshitomi et al. [93] further analyzed the mechanism of action of noni juice in lowering blood pressure. In vivo experiments showed that noni juice improved the excretion of NO metabolites and phosphorylated expression of Endothelial Nitric Oxide Synthase (eNOS) in the aorta of SHR/cp rats, and in vitro experiments further confirmed that noni juice extract stimulated NO production in human umbilical vein endothelial cells, which could reduce blood pressure by modulating the GLP-1R-induced Calmodulin-dependent Protein Kinase Kinase β–5′-Adenosine Monophosphate-Activated Protein Kinase–eNOS (CaMKKβ-AMPK-eNOS) pathway and that deacetylasperulosidic acid in noni fruit may be an active compound in lowering blood pressure. Furthermore, A-H Gilani et al. [94] studied the roots of noni and found that 70% ethanol aqueous extract of noni root possessed antispasmodic, vasodilatory, and cardiac depressant activities, which may be mediated by a blockade of calcium channels as well as the release of calcium from intracellular stores.

In summary, the above studies have elucidated the medicinal value of noni fruit in lowering blood pressure. Noni fruit can play a role in lowering blood pressure by inhibiting angiotensin-converting enzyme activity, regulating eNOS activity, etc. In the future, we should pay attention to the mechanism of action of noni fruit in regulating blood pressure. Such investigations will provide essential data and theoretical support for the development of functional foods aimed at lowering blood pressure.

3.6. Anti-Obesity Effects

Polysaccharides and polyphenols in noni fruit have anti-obesity effects. Mo et al. [6] found that by gavage feeding noni fruit polysaccharide extract to high-fat-diet mice, the liver index and epididymal adiposity index could reduce. Moreover, the serum TC, TG, and LDL-C levels of these mice were reduced to varying degrees. The noni fruit polysaccharides were able to regulate lipid metabolism and intestinal flora and play an anti-obesity role by promoting the expression of the Farnesoid X Receptor (FXR) in the liver and FXR-FGF15 (Fibroblast Growth Factor 15) in the intestines. Wang et al. [79] also found that noni fruit polyphenols could improve high-fat-diet-induced intestinal dysbiosis in mice, reducing lipopolysaccharide-producing bacteria and increasing short-chain fatty acid-producing bacteria, which revealed that intestinal microbiota may be a potential target for noni fruit polyphenols to prevent high-fat-diet-induced obesity. The anti-obesity effects of noni fruit polyphenols were partially attributed to their ability to reorganize gut flora dysbiosis, ameliorate intestinal inflammation, and prevent intestinal barrier dysfunction. This was

achieved by inhibiting the endotoxin-TLR4-NF-κB pathway. A study by Lin et al. [74] showed that polyphenols in fermented noni juice enhanced the activities of antioxidant enzymes, such as GSH, SOD, CAT, and GSH-Px, and reduced the MDA content in the liver tissues of mice on a high-fat diet, as well as inhibited the expression of TNF-α and IL-1β. Therefore, polyphenols and other active substances in fermented noni juice can serve as natural antioxidants to mediate dyslipidemia, liver inflammation, and oxidative stress in high-fat-diet mice.

Although current studies suggest that noni may exert anti-obesity effects through the regulation of lipid metabolism, intestinal microbiota, and antioxidant pathways, the mechanisms behind the regulation of lipid metabolism mediated by noni have not yet been fully elucidated. As a key target of human nutritional research, intestinal flora can be further explored through metabolomics technology to elucidate how noni fruit affects the obesity mechanism via targeting intestinal flora.

3.7. Hypoglycemic Effects

Hyperglycemia is a metabolic disorder characterized by an abnormally high concentration of glucose in the blood and is commonly associated with diabetes. Prolonged hyperglycemia can cause a variety of harmful effects to the body, and obtaining active substances from natural plants to treat hyperglycemia is an effective strategy.

It has been reported that a variety of active substances, such as iridoids, polyphenols, quercetin, in noni fruit have good hypoglycemic effects. Nayak B S et al. [95] used naturally fermented noni juice to treat streptozotocin-induced type II diabetic rats and found that the fasting blood glucose of the rats was significantly reduced by 52.6% compared to the pre-treatment period and was comparable to the effects of the oral hypoglycemic drug glibenclamide. This suggests that noni fruit holds great promise for hypoglycemia treatment. A prolonged high-fat/high-fructose diet will lead to abnormal glucose–lipid metabolism. When noni fruit extract was used to gavage high-fat/high-fructose-diet mice, it was found to be able to reduce the blood glucose level of mice [96]. These findings indicate that noni fruit has great prospects in hypoglycemia. The saponins in fermented noni juice can inhibit gastric emptying by promoting the secretion of glucagon-like peptide-1 or inhibiting its degradation, thus slowing down the absorption of nutrients into the bloodstream [97]. Many researchers have deeply analyzed the hypoglycemic components of noni fruit. Zhang et al. [7] extracted and isolated alkaloids from fermented noni juice and found that alkaloids had an effective inhibitory activity against α-glucosidase by α-glucosidase activity assay with an IC_{50} value of 364.4 μM (positive control acarbose and IC_{50} = 235.7 μM). Moreover, Wang et al. [98] fed mice with type II diabetes with noni fruit polyphenol extract and found that noni fruit polyphenols could promote hepatic glycogen synthesis and increase insulin activity, activate the AMPK signaling pathway in the mouse liver, and then regulate blood glucose in mice. Noni fruit contains the unique Brazilian hematoxylin, which is an important bioactive marker. In a test of noni fruit administered to streptozotocin-induced diabetic rats, it showed its significant ability to exert hypoglycemic effects by stimulating glucose transport in cells [26].

In conclusion, noni can exert hypoglycemic activity by regulating glucagon-like peptide-1 to delay gastric emptying, promoting hepatic glycogen synthesis, enhancing insulin sensitivity, and stimulating glucose transporter protein activity. However, this study has limitations, such as insufficient analysis of the hypoglycemic mechanism and the lack of component synergy. In the future, the molecular mechanisms behind this study should be explored in depth to provide data support for the development and utilization of noni resources and the production of hypoglycemic supplements.

4. Fermented Noni Fruit Foods

Because of its bitter and sour taste and irritating odor, fresh noni fruit is difficult to consume raw. Therefore, choosing appropriate processing technologies for the deep processing of noni fruit represents an important development direction for the noni fruit industry, among which fermentation technology is the most crucial method for processing noni fruit.

4.1. Types and Production Processes of Fermented Noni Fruit Foods

The main types of fermented noni fruit foods on the market previously included fermented juice, noni fruit wine, solid fermented products (such as enzyme powder), and compound functional fermented foods. The types and production processes of fermented noni foods are summarized in Figure 4. Fermented noni juice is mainly of two types: natural fermentation and enhanced fermentation. In natural fermentation, washed noni fruits are sealed in a fermentation tank for several months to a year. The application of ascorbic acid as a pre-fermentation treatment during the preparation of fermented noni juice enhances the juice's antioxidant capacity [99]. With the rich nutrients in noni fruits serving as a substrate, bacteria can increase the content of active substances through their own metabolism, and various functional fermented noni juices can be obtained [100]. However, many researchers believe that the strains in the natural fermentation process are unknown, and the fermentation process cannot be controlled, which may ultimately make it difficult to control the quality of naturally fermented noni juice products. Based on the flora carried by noni fruits, researchers added *Lactobacillus* and other lactic acid bacteria for enhanced fermentation. Inoculating probiotics to ferment noni juice can not only improve the flavor of the juice but also enhance its nutritional quality, increasing the content of active substances in the juice, such as flavonoids and quercetin.

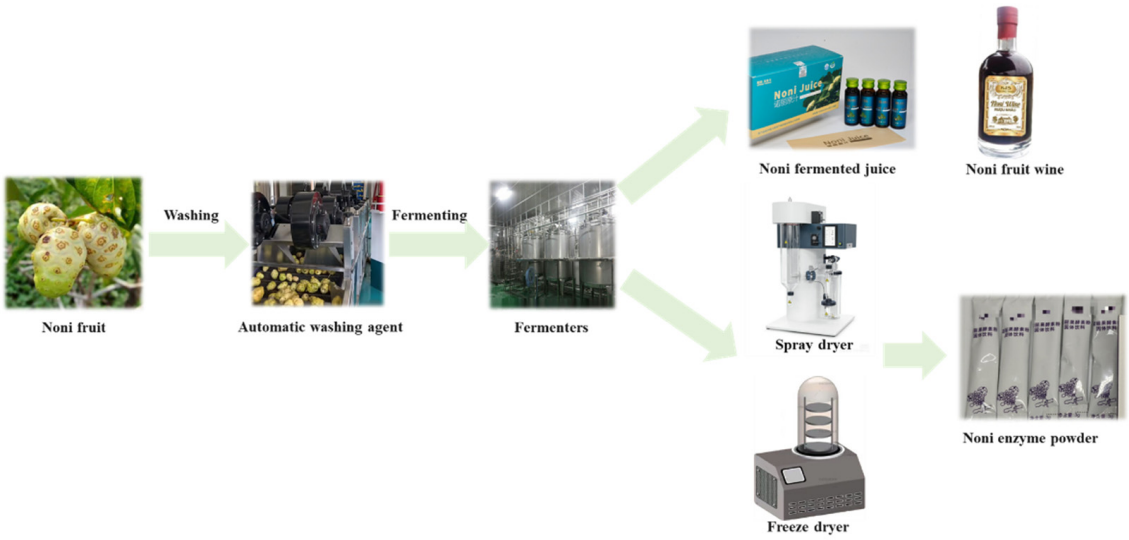


Figure 4. Types and production processes of fermented noni fruit foods.

Noni fruit wine is another important form of fermented noni fruit food. Compared with fermented noni juice, the main difference is that its alcohol content is more than 0.5% (v/v). Fruit wine is made by inoculating an appropriate amount of *Saccharomyces cerevisiae* into fresh fruit juice and fermenting it to obtain products with fruit flavor and a certain alcohol content. Fruit wine processing can realize the high-value utilization of fruits. The main factors affecting the quality of noni wine include the initial pH, initial sugar content, yeast inoculation amount, fermentation temperature, and fermentation time. Wang et al. [101] reported that *Saccharomyces cerevisiae* XYSF117 could be

employed in the fermentation of noni fruit wine. Moreover, their study showed that targeted supplementation of nutrients, such as threonine and riboflavin, during fermentation increased ethanol concentration by a factor of 6.3, from 1.76% to 11.21% (*v*/*v*).

Solid fermented noni fruit products, such as enzyme powder, have been commercially utilized for a long time. However, currently, there are few research reports on noni enzyme powder. The preparation process of enzyme powder can be simply summarized as follows: first, noni fruits are fermented into fermented noni juice, and then, the juice is dried to obtain enzyme powder. At present, the main drying technologies for the preparation of enzyme powder are the spray-drying method and the vacuum freeze-drying method. The spray-drying method has the advantages of high heat transfer efficiency and good continuity. However, it should be noted that fermented noni juice contains many carbohydrates, which have the potential to clog the atomization system [102]. To address the problems of noni juice stickiness and wall deposition during spray drying, microencapsulation of the juice by selecting a suitable wall material is a good strategy. It has been reported that the microencapsulation of fermented noni juice using maltodextrin not only improves the above problems but also enables the effective retention of iridoids, polyphenols, and flavonoids in the juice. This can be attributed to the thermal stability of these substances on the one hand and, on the other hand, to the breakage of phenol–glycosidic bonds to form phenolic glycosides as well as the formation of antioxidant compounds induced by heat treatment [103]. The vacuum freeze-drying method involves freezing the fermented fruit juice first and then sublimating the ice in the material into a gas form by continuously pumping the vacuum to achieve the drying purpose. This method has the significant advantage of protecting active substances, but its drying rate is much higher compared to spray drying. In conclusion, noni fruit enzyme powder, on the one hand, can concentrate the juice, reducing logistics costs; on the other hand, it can reduce the unpleasant smell of the fruit juice. In the future, research on the drying characteristics of noni fruit enzyme powder should be conducted by combining different drying methods.

The most common type of noni fruit composite functional fermented food is compound juice. It is well known that the prominent bad odor of octanoic acid, caproic acid, and butyric acid in fermented noni juice makes it difficult for people to accept. Combining fermented noni juice with other juices, such as blueberry, raspberry, and pineapple, is the main process and strategy for commercial fruit juice production. Kim et al. [104] incorporated an appropriate quantity of citrus juice and additives to mimic commercially available fermented noni juice, thereby mitigating the unpleasant odor characteristic of noni-based fermented products.

4.2. The Effects of Fermenting Strains on the Quality and Metabolites of Fermented Noni Juice

Fermentation strains have an important impact on fermented products. Besides natural fermentation, the main strains used in fermenting noni juice are *Lactobacillus* and *Acetobacter*, etc. Wang et al. [105] produced noni juice through natural fermentation and found that the total phenol content showed a decreasing trend during fermentation, while the total flavonoid content went in the opposite direction. This may be due to the fact that complex polyphenols were broken down by enzymes during the fermentation process into simpler flavanols. During fermentation, the polysaccharides in noni fruit may be degraded to soluble polysaccharides. Microorganisms produce hydrolytic enzymes that degrade insoluble pectin–cellulose cell walls and decompose polysaccharides into oligosaccharides or monosaccharides, resulting in a decreasing tendency of polysaccharide concentration. Some studies employed different lactic acid bacteria to enhance the fermentation of noni juice. For example, Zhang et al. [39] used eight lactic acid bacteria to ferment noni juice. After analysis, it was found that the total phenolic content of noni juice fermented by

Lactobacillus rhamnosus significantly increased compared to a blank group. This was attributed to the possible release of rutin from the conjugate form, which in turn increased the antioxidant activity of the fermented noni juice. Moreover, the content of scopolamine also increased after fermentation, rising from 0 to 0.39 mg/100 mL. In addition to using *Lactobacillus* to ferment noni juice, *Acetobacter aceti* can also be used in fermented juice production. During the fermentation of noni juice by *Acetobacter aceti*, the contents of total phenols and asperulosidic acid in noni juice decreased, while the contents of flavonoids and deacetylasperulosidic acid increased as the fermentation time prolonged [106]. Cheng et al. [107] explored the relationship between bacterial counts and volatile compounds in fermented fruit juices by using high-throughput sequencing techniques and correlation analysis methods. They found that *Gluconobacter*, *Acetobacter*, and *Lactobacillus* were important bacteria for the negative regulation of ethyl alcohol. Based on previous studies, we have compiled the changes in active substances and flavors of some strains in the production of fermented noni juice, as detailed in Table 6.

Table 6. Different strains were inoculated with volatile aroma compounds and active components in fermented noni juice.

Place of Origin, Variety	Fermentation Strains	Aroma Category	Related Characteristic Aroma Substances	Description of the Main Aromas	Active Ingredients and Functions	Reference
Wanning City, Hainan Province, China	Natural fermentation	Esters, alcohols, acids, ketones, etc.	Methyl caproate, methyl hexadecanoate, methyl salicylate, ethanol, 2-heptanol, caprylic acid, hexanoic acid, and 2-heptanone	Floral, fruity, cheesy, and sweaty	The total phenol content decreased first, then increased, and subsequently decreased again during the fermentation process. The highest total phenol content reached 199.77 mg GAE/100 mL and 185.60 mg GAE/100 mL in laboratory-fermented juice and factory-fermented juice, respectively, on the 28th day of fermentation. The total flavonoid content showed an increasing trend in both fermentation modes, reaching a maximum value of 36.73 mg RE/100 mL on the 63rd day of laboratory fermentation.	[105]
Haikou City, Hainan Province, China	*Lactobacillus plantarum*	Esters, alcohols, acids, ketones, and aldehydes	Caprylic acid, capric acid, ethyl caproate, methyl caproate, linalool, 2-heptanol, etc.	Cheesy scent, sweaty scent, citrus and floral scent, and mushroom scent	Not analyzed	[107]
Wanning City, Hainan Province, China	*Lactococcus lactis*	Acids, esters, aldehydes, alcohols, and ketones	Caprylic acid, nonanal, 1-nonanol, and 2-heptanone, etc.	Cheesy flavor, pungent acidity, and fruity flavor	Compared with a control group, the total phenol content in *Lactococcus lactis* juice was higher and showed an increase followed by a decrease. At the end of fermentation, the total phenol content was 67.00 mg GAE/100 mL, and the total flavonoid content was 30.11 mg RE/100 mL. Additionally, the content of deacetylasperulosidic acid increased significantly to 32.66 mg/100 mL.	[39]
Wanning City, Hainan Province, China	*Acetobacter*	Acids, esters, alcohols, ketones, aldehydes, and terpenes	Caprylic acid, capric acid, ethyl acetate, ethyl propionate, 1-octen-3-one, 2-pentanone, and α-watercressene	Floral, fruity, grassy, and mushroomy	With a prolongation of the fermentation time, the content of asperulosidic acid in fermented noni juice decreased continuously. The deacetylasperulosidic acid showed the opposite trend, with a concentration of more than 1200 μg/mL after 20 d of fermentation. The total phenol content showed a decreasing trend, but the total flavonoid content did not change significantly.	[106]

Although many studies have reported that microbial-driven noni fermentation can be used to realize the transformation and functional enhancement of fruit components, the

mechanism of the microbial enzyme system on the decomposition of noni components and product profiles has not yet been systematically analyzed. In the future, it is necessary to combine synthetic biology, food engineering, and systematic metabolic science to break through the functional limitations of strains and blind spots in metabolic regulation in order to provide theoretical and technological support for the development of high value-added fermentation products.

4.3. The Effects of Fermenting Strains on the Main Flavors of Fermented Noni Juice

Flavor is an important organoleptic quality indicator that determines the taste acceptability of fermented noni juice. Zhang et al. [39] conducted gas chromatography on noni juice fermented by eight lactic acid bacteria and found that 42 volatile compounds were produced by the fermented juice, including 10 acids, 2 esters, 14 aldehydes, 8 alcohols, and 8 keto butyric acids. Microorganisms participated in pyruvic acid metabolism and butyric acid metabolism during the fermentation process, reducing the formation of butyric acid and improving the flavor of the fermented juice. Cheng et al. [107] added *Lactobacillus plantarum* during noni fruit fermentation and found that the content of octanoic acid in probiotic-enhanced fermented noni juice was lower than that in naturally fermented juice and that octanoic acid was an important source of odor that led to the vomit-inducing odor of the juice. Moreover, the linalool content was elevated in the probiotic-enhanced fermented noni juice group, which formed a strong citrus and orange flavor and created a strong citrus and floral odor. In the microbial fermentation system of noni juice, besides *Lactobacillus*, which is a conventional fermenter, strains of *Acetobacter* should also be considered when screening preferred fermenting microorganisms. Zhang et al. [108] used macro-transcriptomics to show that *Acetobacter* spp. were the dominant strains in naturally fermented noni juice. The authors inoculated *Acetobacter* isolated from naturally fermented noni juice, and with the fermentation process, there was a significant increase in the concentration of ketones and aldehydes. These compounds mainly contributed to the floral and fruity aroma of fermented noni juice. On the 6th day after fermentation, the hexanoic acid content in the fermented noni juice inoculated with *Acetobacter* decreased from greater than 400 mg/L at the beginning to 20 mg/L [106]. These findings suggest that inoculation with suitable fermentation strains can improve the flavor of fermented noni juices. In addition to using some probiotics for producing fermented noni juice, the emergence of genetically engineered strains will provide new strategies to improve the poor flavor of fermented noni juice. Researchers co-fermented an O-methyl anthranilate-producing laboratory *Saccharomyces cerevisiae* strain with an industrial beer yeast strain (WLP644) and found that the genetically modified laboratory strain could endow the beer with a pleasantly subtle grape aroma, thereby improving its flavor [109]. Bennis et al. [110] designed transgenic *Saccharomyces pastorianus* strains using Clustered Regularly Interspaced Short Palindromic Repeats and CRISPR-Associated Protein 9 (CRISPR-Cas9) genetic engineering and fermented them in laboratory micro-fermenters. The results show that the transgenic strain could enhance the production of flavor substances, such as ethyl caproate and ethyl caprylate, which conferred fruity and floral aromas to the beverage. In another study, *Saccharomyces cerevisiae* was modified using CRISPR-Cas9 gene editing to overexpress glycerol-3-phosphate dehydrogenase 1 and alcohol acetyltransferase 1 and was used to ferment wine. This modification led to an increase in the fruity flavor of the fermented product [111]. Although transgenic technology has been applied in the food and biological fields, there are still few reports on the application of transgenic strains in the preparation of fermented noni juice. The metabolic pathways, fermentation performance, and safety of transgenic strains need further investigation [112].

In conclusion, the formation of flavor profiles during noni juice fermentation is mainly regulated by microbial metabolism, and its sensory quality is closely related to the dynamic changes of volatile organic compounds. In terms of microbial metabolism, *Lactobacillus* regulates the production of volatile acids through pyruvate metabolism and butyrate metabolism pathways. At the same time, it may promote the enrichment of terpenes, such as linalool, and other fruity and floral odors. It is worth noting that *Acetobacter*, as the dominant natural fermentation flora, can significantly reduce the concentration of hexanoic acid and optimize the flavor profile through the production of ketones and aldehydes. In the future, we can strengthen the analysis of the *Lactobacillus–Acetobacter* synergistic metabolic mechanisms and develop composite bacterial agents to balance acid degradation and the synthesis of aromatic compounds. In addition to combining multi-omics technology to locate the key flavor substances synthesized by rate-limiting enzyme genes, targeted modifications of the bacterial strain metabolic network will also inject new impetus into the noni fruit industry.

5. Summary and Outlook

As a "new food source", noni fruit is rich in polysaccharides, polyphenols, iridoids, coumarins, and other active ingredients and has a wide range of applications. This paper summarizes the progress of research on the antioxidant, anti-inflammatory, hepatoprotective, antibacterial, hypotensive, anti-obesity, hypoglycemic, and other physiological functions of noni fruit and its fermented foods. However, it was also found that there are still many aspects in the basic application research of noni fruit that need further exploration. First, the existing research has mainly been conducted with Hainan-produced noni fruit as the object, while there are few research reports on noni fruit resources in the Pacific Island region. It is worth investigating the differences between noni fruits of different origins. Second, in the research on the efficacy of noni fruit, the research objects are mostly noni juice, crude extracts, etc. However, the properties of functional substances are not yet clear enough, and there is a lack of in-depth research on the mechanisms of action. Third, the functional investigations of noni fruit and its products are mainly based on animal model studies. In future research, more clinical validation experiments should be conducted. Fourth, research on noni fruit fermentation focuses on the changes of active ingredient contents, but the regulatory mechanism underlying these changes has rarely been reported. It is encouraging that some researchers have analyzed the correlation between bacteria and active ingredients, and in the future, the regulatory mechanism of the active ingredients needs to be further investigated.

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