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Review Paper

Progress on the Studies of *Pandanus amaryllifolius*, the Cultivation in Malaysia and Its Application in Various Fields

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Abstract: *Pandanus amaryllifolius* Roxb., commonly known as pandan, is a plant renowned for its main aromatic compound, 2-acetyl-1-pyrroline (2AP). Across Southeast Asia, pandan is widely utilized in culinary practices for flavouring and colouring dishes and desserts. This paper aims to review the progress of studies on pandan, including its cultivation and various health benefits attributed to its flavonoid and phenolic content. Research has highlighted pandan's potential as an anticancer, antidiabetic, antibacterial, and anti-inflammatory agent. Beyond its culinary applications, investigations have explored pandan's suitability in pharmaceuticals, cosmetics, and other industrial sectors. The review discusses key processes involved in pandan powder production and compares different methodologies. Additionally, factors influencing the quality of pandan products are analysed. This compilation of information aims to guide the researchers and industry players in optimizing processing conditions and upscaling the production line, so that high end value pandan products could be made.

Keywords: *Pandanus amaryllifolius*; 2-acetyl-1-pyrroline; anticancer; antidiabetic; antioxidant

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1. Introduction

Pandanus amaryllifolius Roxb., commonly known as pandan, is a tropical plant native to Southeast Asia and extensively cultivated in the region (Amnan *et al.*, 2022). In Asian culinary traditions, pandan is prized for enhancing desserts and flavoured rice dishes, imparting both a vibrant colour and a distinctive aromatic flavour. The key aromatic compound responsible for pandan's fragrance is 2-acetyl-1-pyrroline (2AP) (Omer *et al.*, 2021; Yahya *et al.*, 2010), which has an incredibly low odour threshold of 0.1 ppb in water (Buttery *et al.*, 1988). Studies have shown that pandan contains concentrations of 2AP that are ten times higher than aromatic rice varieties and a hundred times higher than non-aromatic rice varieties (Bhattacharjee *et al.*, 2005). However, the challenge lies in maintaining its quality during storage and transport due to the volatility of this compound (Omer *et al.*, 2021). Therefore, optimizing processing methods is crucial to preserve the superior quality of pandan-based products.

Previous research has identified various phytochemicals in pandan leaves, including alkaloids, flavonoids, terpenoids, and coumarin (Quyen *et al.*, 2020). Additionally, quercetin and β-sitosterol have been specifically confirmed to be present in pandan (Gopalkrishnan *et al.*, 2015). The composition of these compounds in pandan can vary depending on growth conditions, processing parameters, and analytical methods used during analysis and processing. Studies have focused on preserving these phytochemicals, as well as the aromatic and volatile compounds present in pandan. This includes research on extraction methods, drying techniques, and compound encapsulation (Omer *et al.*, 2021; Surojanametakul *et al.*, 2019).

Traditionally, pandan has been primarily used in food preparation and as an herbal remedy for various ailments. In Southeast Asian countries such as Singapore, Thailand, and the Philippines, pandan roots have been employed in the treatment of diabetes (Benjamin *et al.*, 2024; Chinsembu, 2019). Pandan is also traditionally used to refresh the body, alleviate indigestion, and reduce fever (Laluces *et al.*, 2015). Moreover, it has been utilized in the treatment of conditions such as rheumatism, hyperglycaemia, hypertension, and gout (Cheng *et al.*, 2017).

Ningrum and Schreiner (2014) have compiled evidence and studies highlighting the potential uses of pandan as a natural colourant, flavouring agent, and functional herbal medicine for human health. Their review concludes that pandan leaves serve as a food colourant either in their natural form or as juice, primarily due to the presence of chlorophyll a and b. As a flavouring agent, pandan leaves are commonly used to enhance food aroma, such as in non-aromatic rice to simulate the flavours of more expensive varieties like Basmati and Jasmine rice, as well as in wrapping food and adding flavour during deep frying processes. From a medical perspective, pandan is recognized for its therapeutic potential in treating various ailments including typhoid fever, oxidative damage, inflammation, colds, coughs, measles, urinary infections, and degenerative conditions such as cancer.

In another comprehensive review by Bhuyan and Sonowal (2021), the compounds present in pandan and their applications, particularly in the medical field, were extensively examined. The literature suggests that pandan exhibits various pharmacological benefits, including antidiabetic, anticancer, antitubercular, antioxidant, and antiviral properties. Additionally, it has been suggested that pandan could potentially alleviate dental anxiety. Southeast Asian communities have traditionally utilized this valuable plant in their medicinal practices. The presence of compounds with antioxidant, anti-inflammatory, and antimicrobial properties is believed to underlie these therapeutic functions. A detailed discussion on these compounds will be further explored in subsequent sections of this paper.

Delving deeper into the original papers, several studies have measured the antioxidant, antibacterial, and anticancer effects of pandan leaves. Observing the progression of research trends, early studies primarily focused on identifying the compounds present and understanding the plant's nature (Buttery *et al.*, 1988; Jiang, 1999). Subsequently, there was a shift towards investigating various processing methods, particularly drying techniques (Adhamatika *et al.*, 2021; Jusril *et al.*, 2016; Rayaguru & Routray, 2010; Son *et al.*, 2023). More recently, research has increasingly explored applications of pandan in pharmaceuticals, nutraceuticals, and cosmetics industries (Diana *et al.*, 2022; Forestryana *et al.*, 2022; Thanebal *et al.*, 2021). There has also been significant interest in utilizing green extraction technologies as alternatives to conventional methods, aiming to produce safer products for both human consumption and the environment (Azhar *et al.*, 2022; Omer *et al.*, 2021). Beyond its benefits in food and medicine, pandan has also shown potential applications in other industries such as polymer production (Diyana *et al.*, 2021).

This paper will extensively discuss previous findings on *Pandanus amaryllifolius*, commonly known as pandan, encompassing various aspects related to the plant. The discussion will include information about the plant itself, cultivation practices particularly in Malaysia, the potential market for pandan products, the compounds and phytochemicals present in pandan, the processes involved in extracting volatile compounds and other extracts, and its applications in three specific areas: food, medical, and other industries or research and development (R&D) projects.

Despite its ease of cultivation, pandan is not favoured by farmers for large-scale production due to insufficient market demand. The flexibility in cultivation allows individuals to grow it for personal use, but the government is not giving priority to enhance pandan cultivation, possibly due to it being overshadowed by other plants. However, previous research highlights pandan's potential, particularly in traditional medicine. There is a need for scientific validation to demonstrate its efficacy and reduce reliance on synthetic products that could be harmful to humans and the environment. This review aims to emphasize pandan's versatility and provide foundational knowledge to help industry stakeholders to optimize processing conditions to produce high-value products from pandan.

Also, it targeted that the optimization on pandan processing conditions will help the farmers, industry players and the end-user or consumers. By converting the whole pandan plant into powder form, zero-waste policy could be followed, hence will benefit the farmers as no part from the plant will need to be eliminated. Also, this means that no additional processes need to be done to manage the waste and reduces the cost. In terms of industry players and consumers, applying the optimum processing condition will help to retain the quality of pandan product for longer period. From industrial perspective, using optimum processing condition means that greater efficiency could be achieved as lower production cost with greater yield will be achieved. Meanwhile, the consumer may benefit from greater shelf life of the product. The price of commodities tends to increase with years. Hence, longer shelf life means that the product could be purchased in bulk at lower price at the current time and used in the future. Hence, it is proven that this review will especially be critical to help farmers and industry players to adapt with the demand of pandan products, while assisting the consumers to make better purchases.

2. General Information on Pandan

2.1. Growing Conditions

Cultivating pandan is relatively straightforward, as the plant can thrive in various soil types, though it prefers spacious areas with moderate sunlight exposure. While specific soil requirements are not stringent, Kahar (2020) recommends using a soil mixture comprising three parts soil, one-part decomposed chicken manure or compost, and one part sand. This mixture should fill a polybag or vase up to 5 cm below the surface. For direct cultivation in soil, pandan seeds, which can be in the form of root-consisting cuts or shoots from the plant base, should be placed in a prepared 25 cm × 25 cm hole. The soil should be compacted, and the plant should receive adequate watering, ideally twice daily—morning and evening.

Regular maintenance involves removing weeds and dry leaves as necessary. Regarding fertilizer, NPK fertilizer with a 21:21:21 ratio is recommended for leaf growth. For plants in vases or polybags, 5 g of fertilizer is appropriate, while those cultivated directly in the soil require 10 g per plant. Pandan leaves are typically ready for harvest after 12 months by cutting at the base of the shrub.

According to statistics from *Bahagian Pengesanan dan Penilaian Jabatan Pertanian Negeri Johor (2017)*, pandan cultivation in Johor is concentrated primarily in Kulai and Segamat districts, covering a total area of 112.90 hectares, of which 105.70 hectares were harvested. This resulted in a production of 1,340.25 metric tons (MT) with a production value of RM2,747,520. The statistics also highlight that Johor, Pahang, and Selangor are the main pandan-producing states in Malaysia, with Johor leading at 113 hectares and a production of 1,340 MT, followed by Pahang (71 hectares, 243 MT) and Selangor (6 hectares, 113 MT). In pandan cultivation, it is common to cultivate two plants per quadrat with dimensions of 1 meter by 1 meter. The potential production is estimated at 39,000 kilograms per hectare.

The responsible authority overseeing pandan cultivation in Malaysia is the Department of Agriculture, Malaysia, also known as *Jabatan Pertanian Malaysia*. This department plays a crucial role in ensuring food safety and security, providing a skilled workforce for the agricultural industry, and facilitating agricultural development initiatives (*Portal Rasmi Jabatan Pertanian*, n.d.). According to the Herbs and Spices statistics released by the Department of Agriculture Malaysia (2021), the botanical name for pandan is *Pandanus odorus*. Additionally, *Pandanus amaryllifolius* is synonymous with other botanical names such as *Pandanus hasskarlii* Merr. and *Pandanus latifolius* Hassk. (Bhuyan & Sonowal, 2021; Malaysia Biodiversity Information System, n.d.). In Malaysia, the commonly available varieties of pandan are fragrant pandan and common pandan (Hosnan, 2014).

2.2. Species and Varieties of Pandan

The Pandanaceae family comprises over 600–700 known species, but *Pandanus amaryllifolius* is unique in its ability to emit a distinctive fragrance. Orientals describe the scent of *Pandanus amaryllifolius* leaves as pandan-like, while non-Orientals liken it to the aroma of popcorn (Azhar *et al.*, 2022). This characteristic aroma is attributed to the presence of a specific compound called 2-acetyl-1-pyrroline, or 2AP (Omer *et al.*, 2021; Yahya *et al.*, 2010), which is also found in aromatic rice varieties such as Basmati (Nor *et al.*, 2008).

Pandan contains approximately 1 part per million (ppm) of 2AP, which is ten times higher than the concentration found in aromatic rice and a hundred times higher than in non-aromatic rice (Yahya *et al.*, 2011). The odour threshold value of 2AP in water is remarkably low at 0.1 parts per billion (ppb) (Buttery *et al.*, 1988).

According to Hosnan (2014), common varieties of pandan in Southeast Asia include fragrant pandan and normal pandan. Normal pandan is typically used in culinary dishes, whereas fragrant pandan finds more application in cosmetics and medicinal purposes. Pandan is classified as a monocot. It features adventitious prop roots that develop from the nodes to provide aerial support (Lomthong *et al.*, 2022). Structurally, pandan leaves are dark green on the upper surface and light green underneath. They are simple and linear with entire margins, slightly spiny at the apex. The leaf surface is tough and fibrous in texture, with parallel venation converging at a prominent midrib and distinct twin lateral pleats (Gopalkrishnan *et al.*, 2015). The plant grows in clumps as a short shrub, reaching heights of approximately 1.2 to 1.5 meters and widths of 60 to 90 cm. Its stout stem typically branches close to the ground. Pandan is naturally distributed in Southern India, the Southeast Asian peninsula, Indonesia, and Western New Guinea (Ningrum & Schreiner, 2014).

Pandan is often referred to as the 'vanilla of the East' due to its use in various foods for its vanilla-like aroma. Depending on the country, pandan is known by different names among locals. In Malaysia, it is called pandan or '*pandan wangi*' (fragrant pandan), while in Thailand it is known as '*baitoey*' or '*toeyhom*'. In Laos, it is referred to as '*teyhom*', in China as '*ban yan le*', and in Vietnam as '*duathom*' (Ningrum & Schreiner, 2014). Understanding the growing conditions, species, varieties, and origin of the pandan plant is crucial as it can impact the yield of 2AP and other compounds present in pandan leaves (Yahya *et al.*, 2010). This aspect will be explored further in the subsequent subsections of this paper.

2.3. Components and Compounds Present

Nor *et al.* (2008) identified a variety of compounds in pandan leaves, including essential oils, carotenoids, tocopherols, tocotrienols, quercetin, alkaloids, fatty acids, esters, and non-specific lipid transfer proteins. Additionally, Laluces *et al.* (2015) isolated alkaloids known as pandamarilactone-1, pandamarilactone-32, pandamarilactonine-A, and pandamarilactonine-B from pandan leaves. Zakaria *et al.* (2020) found squalene, phytol, and steroids to be major compounds in pandan leaves. In terms of aroma, besides 2AP, 3-methyl-2(5H)-furanone has been identified as another predominant volatile component contributing to the overall aroma of pandan (Cheetangdee & Chaiseri, 2006; Jiang, 1999). Furthermore, glutamic acid, aspartic acid, threonine, serine, histidine, alanine, and proline were identified as the major free amino acids in pandan (Cheetangdee & Chaiseri, 2006).

Studies on pandan prop roots have identified cellulose as the major component, along with hemicellulose, lignin, protein, carbohydrates, fats, moisture, and ash. The high cellulose content suggests potential for fermentable sugars and bioactive compounds through cellulase enzyme hydrolysis (Lomthong *et al.*, 2022). Comparative analysis of existing studies reveals several recurring compounds. Phytol, for instance, has been consistently observed across various studies (Mar *et al.*, 2019; Wakte *et al.*, 2010; Zakaria *et al.*, 2020). Additionally, steroids have been documented in several studies (Dumaoal *et al.*, 2010; Putri *et al.*, 2022; Zakaria *et al.*, 2020), along with terpenoids (Gopalkrishnan *et al.*, 2015; Jusril *et al.*, 2016; Quyen *et al.*, 2020; Thanebal *et al.*, 2021), saponins (Jusril *et al.*, 2016; Putri *et al.*, 2022), and tannins (Gopalkrishnan *et al.*, 2015; Putri *et al.*, 2022; Sa'adah *et al.*, 2023). Table 1 below presents a comparison of common compounds and phytochemicals found in previous research findings.

Table 1. Common compounds and phytochemicals present in pandan.

	Compounds / Phytochemicals												
Reference	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Zakaria *et al.* (2020)					√			√	√	√	√		
Omer *et al.* (2021)													
Laluces *et al.* (2015)	√												
Forestryana *et al.* (2022)			√										
Quyen *et al.* (2020)	√		√			√	√					√	√
Jusril *et al.* (2016)			√	√		√	√						
Mar *et al.* (2019)									√				
Sa'adah *et al.* (2023)		√	√	√									
Gopalkrishnan *et al.* (2015)	√	√	√			√	√						
Putri *et al.* (2022)	√	√	√			√							
Thanebal *et al.* (2021)	√	√	√			√	√						
Dumaoal *et al.* (2010)	√		√										

*Number representation: (1) alkaloid (2) tannin (3) flavonoid (4) phenolic (5) coumaran (6) saponin (7) terpenoid (8) squalene (9) phytol (10) stigmasterol (11) tocopherol (12) coumarin (13) reducing sugar

Similar to other plant materials, pandan contains phytochemical compounds belonging to the classes of phenolics and flavonoids, which are well-known natural sources of antioxidants and possess broad pharmacological activities. The content of flavonoids and phenolics in pandan is reported to be relatively high. Flavonoids not only inhibit cancer cells and tumour growth but are also purported to reduce blood glucose levels and enhance the human immune system (Quyen *et al.*, 2020). Additionally, more than 50% of the antioxidant activity of pandan extract is attributed to its phenolic compounds (Suwannakul *et al.*, 2018).

Overall, the presence of phenolic and flavonoid content accounts for the anticancer, antimicrobial, and antioxidant properties observed in pandan (Jusril *et al.*, 2016).

The choice of extraction method or solvent significantly influences the yield of compounds obtained from pandan. For example, ethanol has been shown to be a more effective solvent, yielding higher values of total flavonoid content (TFC) and total phenolic content (TPC) compared to water (Quyen *et al.*, 2020). In another study, comparing ethanol and propylene glycol extracts of pandan, the latter exhibited higher TPC and 2,2-diphenyl-1-picrylhydrazyl (DPPH) antioxidant activity (Jimtaisong & Krisdaphong, 2013).

The impact of varying conditions on the quality of pandan has been explored in several studies. For instance, it has been observed that younger leaves have higher moisture content compared to older leaves, while older leaves contain greater amounts of total chlorophyll content (TCC) and TPC (Adhamatika *et al.*, 2021). Additionally, fresh pandan leaves exhibit superior antioxidant activity compared to dried leaves (Jusril *et al.*, 2016). Research conducted on pandan from different locations in Malaysia revealed that samples from Bachok, Kelantan possessed the highest TPC, TFC, and antioxidant activity compared to samples from Klang, Selangor, and Pontian, Johor (Ghasemzadeh & Jaafar, 2013). Table 2 below presents a comparison of selected values obtained for phytochemicals and antioxidants present in pandan leaves based on previous research findings.

Table 2. comparison on the TPC, TFC and antioxidant activity values in pandan obtained from different studies

TPC (mg GAE/g DW)	TFC (mg QE/g of extract)	IC_{50} (µg/mL)	Location	Reference
20.95 ± 0.39	23.57 ± 0.43	-	Medan, Indonesia	Putri *et al.* (2022)
57.02 ± 0.02	-	110.57 ± 36.42	Muang Phitsanulok, Thailand	Suwannakul *et al.* (2018)
100.67 ± 1.76	130.02 ± 2.24	900 ± 20	Mekong Delta, Vietnam	Son *et al.* (2023)
24.75 ± 0.74	-	230.24 ± 10.69	Chachoengsao Province, Thailand	Lomthong *et al.* (2022)
Leaf: 3.192 ± 0.159 Root: 0.288 ± 0.011	-	Leaf: 810 ± 9 Root: 2340 ± 40	Chiangrai Province, Thailand	Jimtaisong & Krisdaphong (2013)
-	65.88	-	Martapura, South Kalimantan, Indonesia	Forestryana *et al.* (2022)
Ethanol extract: 38.12 ± 1.49	Ethanol extract: 11.79 ± 0.44	Ethanol extract: 129.32	Ho Chi Minh City, Vietnam	Quyen *et al.* (2020)

TPC (mg GAE/g DW)	TFC (mg QE/g of extract)	IC_{50} (µg/mL)	Location	Reference
Aqueous extract: 10.97 ± 0.29	Aqueous extract: 3.56 ± 0.14	Aqueous extract: 265.73		
Microwave drying: 0.623 Oven drying: 0.417		Microwave drying: 6.379 Oven drying: 9.339	Ampang, Selangor, Malaysia	Jusril *et al.* (2016)
Bachok: 6.72 ± 0.355 Klang: 5.07 ± 0.406 Pontian: 4.88 ± 0.477	Bachok: 1.87 ± 0.246 Klang: 1.32 ± 0.211 Pontian: 1.12 ± 0.177	Bachok: 9250 Klang: 11,600 Pontian: 12,500	Kelantan, Selangor & Johor, Malaysia	Ghasemzadeh & Jaafar (2013)
35.99 ± 0.04	59.96 ± 0.013 *unit: mg CAE/g extract	46.8	Sabah, Malaysia	Thanebal *et al.* (2021)

*TPC = total phenolic content, TFC = total flavonoid content, IC_{50} = concentration of sample required to scavenge 50% of DPPH free radicals

In general, higher TPC and TFC in pandan leaves are associated with greater antioxidant activity (Quyen *et al.*, 2020). Many previous studies have utilized the IC_{50} value to quantify the antioxidant activity of pandan extracts (Son *et al.*, 2023; Suwannakul *et al.*, 2018). A lower IC_{50} value indicates better antioxidant activity, as it signifies the concentration of antioxidants required to reduce free radicals by 50% (Quyen *et al.*, 2020; Suwannakul *et al.*, 2018). Referring to Table 2 above, it could be seen that IC_{50} values of pandan extracts in studies by Jusril *et al.* (2016) and Thanebal *et al.* (2021) from Malaysia were the lowest as compared to samples from other countries. Nonetheless, these values may have been significantly affected by other factors as well rather than just location, which explains far greater values obtained by Ghasemzadeh and Jaafar (2013) with their sample taken from different states in Malaysia.

Based on the discussed research findings, it can be summarized that the levels of TPC, TFC, TCC, 2AP, and other components in pandan leaves vary depending on several factors. These include the type of processing employed, such as variations in temperature range, extraction time, and solvent concentration. Additionally, the location where pandan is harvested and the age of the pandan sample also play significant roles (Adhamatika *et al.*, 2021; Ghasemzadeh & Jaafar, 2013; Son *et al.*, 2023). Studies have reported different concentrations of 2AP in pandan leaves, ranging from 0.04 ± 0.01 to 0.18 ± 0.01 ppm using supercritical carbon dioxide extraction, and from 0.06 ± 0.01 to 0.45 ± 0.01 ppm with hexane solvent extraction (Yahya *et al.*, 2010). Another study utilizing ultrasonic-assisted extraction found a higher concentration of 2AP at 1.43 ppm, accompanied by an average extract yield of 60.51% (Azhar *et al.*, 2022).

The identification of phytochemicals and other compounds in pandan is crucial for understanding its potential benefits. For instance, the presence of flavonoids may contribute to its antibacterial properties, which are beneficial for maintaining salivary pH and overall dental health (Safrida *et al.*, 2020). Ghasemzadeh and Jaafar (2013) identified five flavonoid compounds—rutin, epicatechin, catechin, kaempferol, and naringin—from pandan samples collected at three different locations. Additionally, alkaloids found in pandan may aid in managing anxiety by affecting gamma-aminobutyric acid (GABA) receptors, which are related to the human hypnotic sedative component (Pradopo *et al.*, 2017). Understanding these compounds helps in exploring the potential medicinal benefits of pandan beyond its culinary uses.

In conclusion, the comprehensive understanding of the compounds present in pandan, and their potential benefits opens avenues for developing new medicines or food products with fewer side effects, ultimately promoting better human health. The discussion on pandan's applications across various industries will be further explored in the latter sections of this review article.

2.4. Traditional Practise

Traditionally, pandan has been utilized predominantly in food preparation and as an herbal remedy for various ailments. It is commonly used to refresh the body, relieve indigestion, and reduce fever (Laluces *et al.*, 2015). Additionally, pandan has traditional applications in treating conditions such as rheumatism, hyperglycaemia, hypertension, and gout (Cheng *et al.*, 2017). Both the leaves and roots have been employed to alleviate headaches, sore throats, and thyroid issues (Bhuyan & Sonowal, 2021). The use of pandan for treating various health conditions is widespread in Southeast Asia (Chinsembu, 2019). Furthermore, pandan has been traditionally used as a cockroach repellent, a use that has been scientifically validated by Li and Ho (2002).

Another traditional use of pandan involves its essential oils (EO), which can be extracted through methods such as carbon dioxide extraction and hydrodistillation. Pandan essential oils typically contain complex compounds like esters, terpenes, and alcohols (Mar *et al.*, 2019). These essential oils find common applications as food flavourings, traditional medicines, and therapeutic agents (Zakaria *et al.*, 2020). They are valued not only for their aromatic qualities but also for their potential health benefits in various cultural and medicinal practices.

Pandan root and rhizome decoctions have traditionally been used to treat diabetes, particularly in Thailand, Singapore, and the Philippines, alongside various other plant species (Benjamin *et al.*, 2024; Chinsembu, 2019; Jimtaisong & Krisdaphong, 2013). Studies have also identified pandan prop roots as a source of bioactive compounds suitable for developing novel healthy food and functional drinks (Lomthong *et al.*, 2022). However, compared to pandan leaves, research on pandan roots in recent studies is relatively limited. This could be attributed to the lower concentrations of bioactive compounds found in roots compared to leaves. For example, studies have shown that pandan leaf extracts exhibit better DPPH activity and higher TPC compared to root extracts (Jimtaisong & Krisdaphong, 2013). Therefore, while pandan roots have traditional medicinal uses, current research tends to focus more on the leaves due to their superior bioactive compound content.

The traditional use of pandan leaves in dishes and desserts across Southeast Asian countries is primarily attributed to their aromatic compound, such as 2AP, which enhances food aroma. Scientific studies have shown that pandan's effectiveness in improving rice aroma correlates with its ability to bind with amylose, resulting in greater absorption of 2AP (Yahya *et al.*, 2011). Overall, pandan's traditional applications are deeply rooted in both medicinal and culinary practices, supported by scientific studies validating its effectiveness.

2.5. Current Supply and Demand

Pandan is a plant well-suited to tropical conditions, prevalent and extensively utilized in Asian countries such as Malaysia, Thailand, Indonesia, and India (Sowndhararajan *et al.*, 2016). Given its numerous benefits, further studies aimed at sustaining its key components could enhance its functionality and expand its usage both within its native regions and globally. In Malaysia, data indicates that pandan is cultivated across 217.24 hectares, with a harvested area of 209.90 hectares. This cultivation yielded approximately 1,496.62 metric tons, averaging 7.13 metric tons per hectare (Department of Agriculture Malaysia, 2022). Meanwhile, the data taken from the statistic of the previous year shown that the planted area and harvested area were 198.29 and 189.88 hectares, respectively (Department of Agriculture Malaysia, 2021). This number also has increased from the year 2019 (Department of Agriculture Malaysia, 2019). This shown that there is an increase in the cultivation of pandan along the years. Figure 1 below shows the trend of pandan cultivation in Malaysia based on the available data.

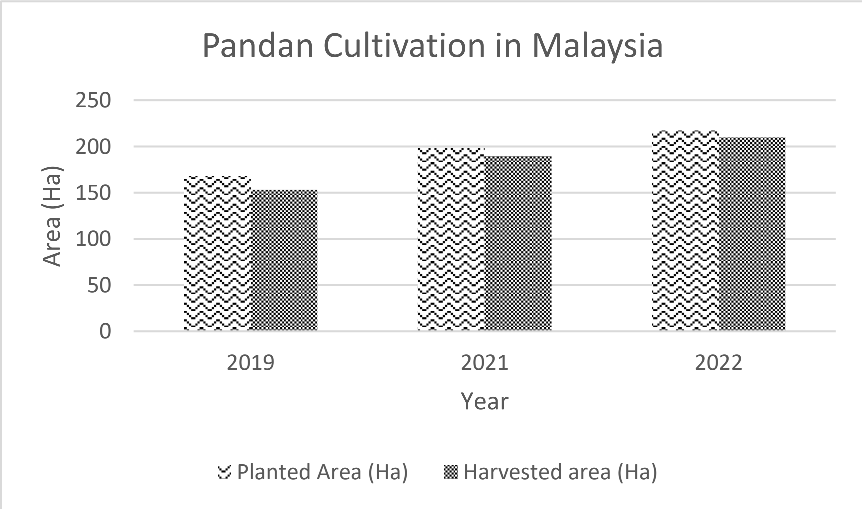

Figure 1. The trend of pandan cultivation in Malaysia

Comparing between the locations of cultivation, the latest statistic also stated that Johor was the state with the largest cultivation of pandan with 116.84 hectares planted area and 110.84 hectares harvested area. This is followed by Kedah and Pahang, but no data was available for the other states. This could be due to no proper census was done causing lack of data available. Also, this may be resulted from the absence of initiative by the government to highlight pandan as one of the main commodities in the agricultural sector. Nonetheless, the abundance of pandan cultivation in Johor could be due to a few reasons.

Firstly, the climate and soil conditions which provide conducive environment for pandan growth. The alluvial soil is good for growing the plant, alongside with the well-drained and fertile soil condition. Secondly, the advancement in agricultural infrastructure. This includes proper irrigation system, facilities for research purposes and extension services. This factor contributes to larger scale cultivation as it will assist farmers to effectively manage the crops and optimize the growing conditions. Thirdly, being the major agricultural hub in Malaysia, extensive land areas has been allocated in Johor for crop plantation which also includes pandan. All in all, these factors explain the largest cultivation area of pandan in Johor.

In countries where pandan is abundant, the plant tends to be available at relatively low prices. This affordability can be attributed to the ease of cultivation, as it is commonly grown by locals in residential areas. Although official price data is not available from the Department of Agriculture Malaysia (2022), market surveys in Malaysia indicate that fresh pandan leaves are sold for approximately RM1.50 to RM2.00 per bunch, weighing around 35 grams. Moreover, pandan extract powder is marketed at RM39.00 for 200 grams by Bionutricia Holding Sdn Bhd (2024), demonstrating the potential for pandan to be transformed into a high-value product. As mentioned previously, the IC_{50} values of pandan extract from Malaysia were among the lowest which means better antioxidant activity. Hence, this may indicate that pandan from Malaysia may be one of the best and more favoured especially when the antioxidant activity is to be prioritized.

According to an industrial report by Market Critics (2024) on LinkedIn, the compound annual growth rate (CAGR) of pandan is projected to be 15% from 2024 to 2031. Key market players identified in the report include Bionutricia, Nr. Instant Produce, and Shaanxi Fruiterco Biotechnology Co. Ltd., indicating the high competitiveness of pandan products in the current and projected markets. The increasing demand for natural source products can be attributed to growing consumer awareness of the health benefits provided by these natural products (Ghasemzadeh & Jaafar, 2013).z

3. Processes Involved in Pandan Products Processing Line

3.1. Drying

In the production of powdered products, higher moisture content can prevent fat oxidation but also create conditions conducive to mould, yeast, and bacterial growth (Seng *et al.*, 2005). Therefore, drying or dehydration is crucial to reduce moisture levels in plant material and maintain its quality. Various drying methods have been studied to assess their impact on the physical, mechanical, and biological properties of pandan. Heat application during drying can lead to chlorophyll degradation and loss of aroma (Jusril *et al.*, 2016). Research indicates that using lower temperatures during drying is preferable for preserving aroma (Rayaguru & Routray, 2010). Standardizing drying parameters is essential to ensure efficient processing. Methods such as cabinet drying, freeze drying, oven drying, microwave-assisted drying, vacuum drying, and shade drying have been investigated for their efficacy in pandan drying processes (Adhamatika *et al.*, 2021; Jusril *et al.*, 2016; Rayaguru & Routray, 2010; Son *et al.*, 2023; Yahya *et al.*, 2010). Each method offers unique benefits and challenges, impacting the final product's aroma, colour, and phytochemical composition.

Adhamatika *et al.* (2021) conducted a study comparing cabinet, vacuum, and freeze-drying methods and found that vacuum drying is the most effective for preserving valuable components in pandan leaves, such as chlorophyll and phenols, while also enhancing antioxidant activity. They observed that vacuum-dried older leaves exhibited higher oil and water absorption capacities compared to other drying methods tested. Additionally, Wakte *et al.* (2010) confirmed in their study that mature or older leaves synthesize and store higher levels of 2AP. Son *et al.* (2023) compared shade drying and oven drying methods, showing that shade drying resulted in higher TPC and TFC, with lower IC_{50} values indicating superior antioxidant activity. Despite these findings, Yahya *et al.* (2010) suggested that oven drying at low temperatures may preserve volatiles without significant depletion.

The quality of pandan leaves is significantly influenced by the drying time. Microwave drying, characterized by shorter drying times due to higher rates of mass transfer facilitated by the electromagnetic field's elevated temperatures, has been noted to yield higher TPC and antioxidant activity compared to conventional oven drying (Jusril *et al.*, 2016). Moreover, overall drying times decrease with higher temperatures due to increased vapor pressure, accelerating moisture migration to the product surface (Rayaguru & Routray, 2010).

To determine the moisture content of pandan leaves, gravimetric analysis is commonly employed, where the initial and final masses after drying are measured. It is assumed that the loss in mass corresponds to the loss of water. Typically, drying fresh plant materials results in approximately 80% water loss, a phenomenon also observed in pandan leaves. For instance, the moisture content of pandan leaves was reported as 86.5 ± 0.3% following oven drying at 105°C for 24 hours (Yahya *et al.*, 2010).

In terms of the effect of drying methods on the structure of pandan leaves, Yahya *et al.* (2010) observed that oven drying caused the destruction of papillae, resulting in smaller structures after water removal. In contrast, freeze drying preserved the shape and primary structure of the papillae. Additionally, the concentration of 2AP obtained from freeze drying using supercritical carbon dioxide extraction was the highest among methods studied. Freeze drying has been shown to yield the highest extraction efficiency due to its ability to preserve the plant's constituents (Zakaria *et al.*, 2020).

Pre-treatment through freeze-drying prior to the extraction process significantly enhances extraction efficiency. This improvement is primarily due to the formation of ice crystals within the plant matrix. These ice crystals cause rupturing of the plant's cellular structure, thereby facilitating better access for the solvent to the intracellular components. As a result, the overall efficiency of the extraction process is markedly improved (Yahya *et al.*, 2010).

Moreover, the inclusion of a foaming agent before freeze drying has been found to mitigate the degradation of physicochemical properties of pandan powder, particularly under high temperature storage conditions (Rin-ut & Rattanapitigorn, 2020).

In conclusion, the choice of drying method significantly impacts the quality of pandan products. For instance, research indicates that heating pandan leaves up to 100°C for 10 minutes at pH 7 does not negatively affect the pandan aroma (Cheetangdee & Chaiseri, 2006). However, this specific condition may not universally apply to all drying methods. Therefore, making careful selection of drying parameters such as temperature and duration is crucial to minimize compound degradation, enhance process efficiency, and reduce overall production costs.

3.2. Encapsulation

Encapsulation involves enclosing core materials within a protective shell to safeguard them against degradation and maintain the quality of plant extracts. This technique is essential for preserving volatile compounds and ensuring the extract's sensory attributes such as colour, moisture content, solubility, flavour, and odour remain optimal under desired conditions (Seng *et al.*, 2005). Methods like spray drying, freeze drying, emulsification, and fluid bed coating are commonly used for encapsulation purposes (Omer *et al.*, 2021). Encapsulation also enhances stability and ensures precise dosage delivery, which are critical for maintaining product efficacy (Surojanametakul *et al.*, 2019).

Omer *et al.* (2021) investigated the encapsulation of pandan extract using lysozyme and chitosan as shell materials, finding that sonication did not significantly alter the chemical composition, with 2AP identified as the predominant aroma compound. This study found that all pandan-encapsulated microspheres made using the sonication method portrayed excellent stability, except for the pandan in chitosan made using 0.3 cm probe where minor reduction in size was observed after a month.

In another study, Surojanametakul *et al.* (2019) employed rice starch to encapsulate 2AP and chlorophyll, demonstrating that 2AP could be released through gelatinization of the encapsulated rice starch, which also aided in extending the shelf life of pandan leaf extract. Monitoring the temperature and water content during spray drying encapsulation is crucial to prevent protein denaturation and maintain solubility (Seng *et al.*, 2005). These findings collectively support the application of encapsulation in processing to preserve the quality of pandan extract by reducing the risk of degradation of volatile compounds (Rin-ut & Rattanapitigorn, 2020).

3.3. Extraction

The extraction of pandan can be achieved through several methods, with water and ethanol being the most common solvents due to their polarity. Since 2AP, the main aroma compound in pandan, is also polar, these solvents effectively dissolve it (Azhar *et al.*, 2022). Other extraction methods include solid phase micro extraction (SP-ME) (Sowndhararajan *et al.*, 2016; Surojanametakul *et al.*, 2019; Wakte *et al.*, 2010), microwave-assisted extraction (Nguyen *et al.*, 2021), Soxhlet extraction (Tambun *et al.*, 2022), sonication-assisted or ultrasonic extraction (Azhar *et al.*, 2022; Jimtaisong & Krisdaphong, 2013), supercritical carbon dioxide extraction (Bhattacharjee *et al.*, 2005; Yahya *et al.*, 2010), and mechanical extraction (Sowndhararajan *et al.*, 2016; Thanebal *et al.*, 2021). Each method offers unique advantages depending on the desired compounds and efficiency required for the extraction process.

In general, prior to the extraction process, it is common to grind the leaves or roots into smaller pieces. This increases the total surface area, effectively rupturing the epidermal cells and facilitating more efficient extraction of compounds. This is because the rupturing of the epidermal cell causes the oil or compounds to be more accessible to the solvent, hence will result in greater yield from extraction process (Yahya *et al.*, 2010). Research has shown that the method and duration of blending can impact the colour of pandan extract and powder. A study comparing turbo blade and standard laboratory blenders found that the turbo blade blender produced a better colour profile for extracted pandan juice (Sowndhararajan *et al.*, 2016).

Comparing hexane solvent extraction with supercritical carbon dioxide (SC-CO_2) extraction, it was found that SC-CO_2 extraction yielded less compared to hexane extraction. This is attributed to the high selectivity of the SC-CO_2 solvent, which results in a cleaner extraction product free from unwanted compounds (Yahya *et al.*, 2010). The use of organic solvents in extraction may lead to issues such as contamination of the final product by residual solvent. This contamination can interfere with subsequent analyses, potentially resulting in the detection of unintended compounds. Therefore, it is essential to implement thorough solvent removal procedures following the extraction process to ensure the complete elimination of solvent residues and maximize the purity of the extracted product. Another study indicated that increasing temperature and pressure in SC-CO_2 extraction enhances the yield of 2AP, highlighting it as a superior extraction technique compared to solvent or Likens-Nickerson methods (Bhattacharjee *et al.*, 2005).

2AP is highly volatile and susceptible to degradation at elevated temperatures. As a result, prolonged exposure to heat can significantly reduce the aromatic intensity of pandan extract, potentially compromising the intended quality of the product. In addition to drying and extraction, milling or grinding processes can also generate heat through friction, which may further degrade volatile bioactive compounds. Therefore, it is crucial to carefully control processing conditions to minimize heat exposure and preserve the efficacy and aroma of these sensitive compounds.

It's important to consider the solid to solvent ratio during the extraction process, as highlighted by Ghasemzadeh and Jaafar (2014) and Son *et al.* (2023). Antioxidant dissolution typically requires ample solvent to facilitate effective mass transfer (Thatsanasuwan *et al.*, 2015). Additionally, parameters such as solvent type, extraction time, and solvent concentration significantly influence the extracted substance's content (Ghasemzadeh & Jaafar, 2014; Nguyen *et al.*, 2021; Son *et al.*, 2023). Jimtaisong and Krisdaphong (2013) noted that propylene glycol extract exhibits higher DPPH activity compared to ethanol extract. Yahya *et al.* (2010) reported that, in their study, the effect of extraction time had minimal impact on the yield of pandan extract. They attributed this finding to the high volatility of 2AP. However, this result contrasts with the findings of previous studies, where an increase in extraction time generally led to a higher yield.

Antioxidant activity is closely related to the presence of functional components, including phenols and chlorophyll. As the TPC increases, so does the antioxidant activity and vice versa. Hence, the degradation of phytochemicals or bioactive compounds such as flavonoids, phenolic acids, alkaloids etc. will lead to reduced efficacy especially in scavenging the free radicals. Adhamatika *et al.* (2021) concluded that elevated temperatures can enhance the likelihood of damaging these antioxidant components, including phenols and chlorophylls. Consequently, this damage results in a reduction of antioxidant activity.

Figure 2 summarizes the typical processing steps involved in the processing of fresh pandan into its powdered form. Nonetheless, the series of steps may vary depending on the needs of each study. The dotted line connections represent the selection of methods or conditions that have been used according to the past research projects, where the details have been elaborated in the related sections of the text.

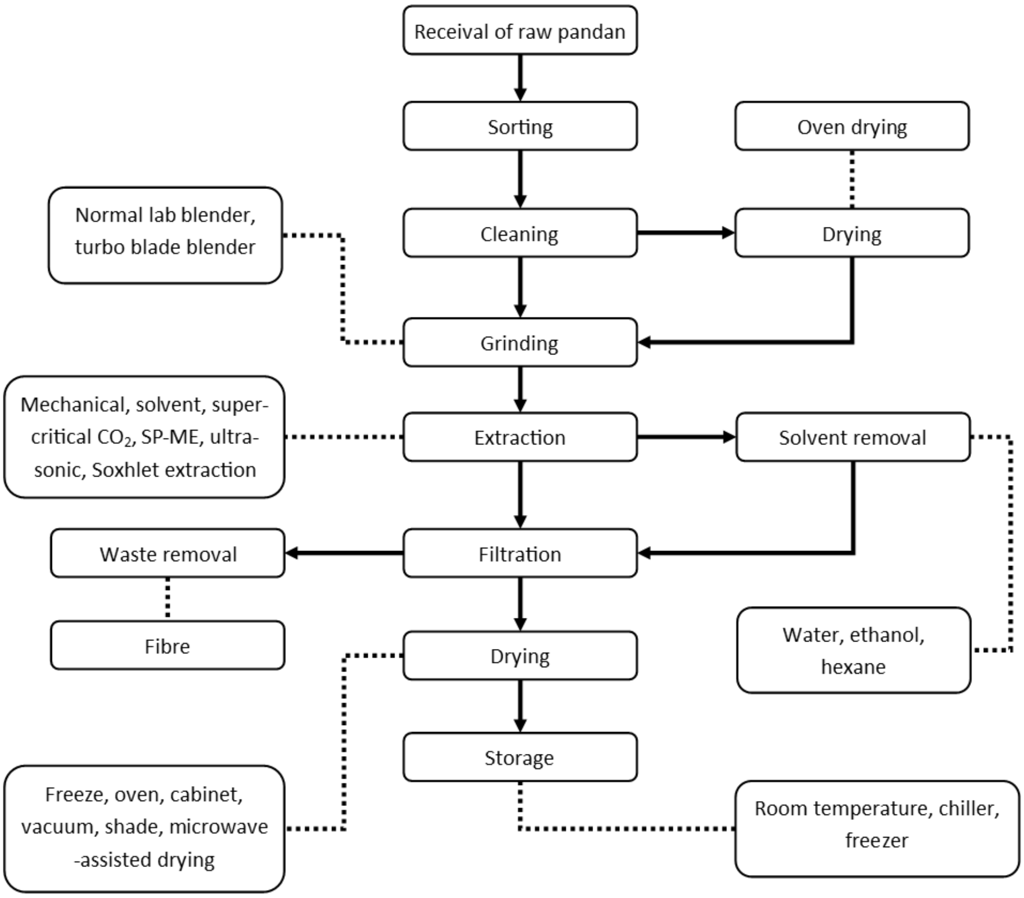

Figure 2. General pandan powder processing line with the products or methods used based on previous studies

In conclusion, the processing of pandan involves various methods that should be chosen based on their cost-effectiveness and efficacy. The selection of processing methods significantly affects the quantity of phytochemicals and aroma compounds present in the pandan extract, influenced by the volatile nature of these compounds and the conditions of the process. Therefore, careful selection of the optimal processing method and conditions is crucial to ensure the highest quality pandan product.

3.4. Challenges to Maintain Stability of Bioactive Compounds

One of the primary challenges in maintaining the stability of bioactive compounds in pandan is the volatility of these compounds. This issue is particularly concerning during processing steps such as drying and extraction, which often involve heat treatment. At elevated temperatures, the volatile compounds are prone to dissipation, leading to a reduction in their effectiveness. While low-temperature methods, such as freeze-drying, can help preserve these compounds, they generally require more time and incur higher costs.

Post-production stability issues may also arise during storage and distribution. Throughout these stages, the product is exposed to varying environmental conditions, such as fluctuations in temperature and light, which can negatively affect its stability. This may manifest as changes in colour or particle size. Therefore, selecting the right parameters for processing, packaging design, and storage conditions is crucial.

Looking at the challenges and problems stated above, some improvement could be suggested. As previously discussed, encapsulation techniques can be employed to enhance the stability of bioactive compounds, particularly in the form of microspheres. However, one drawback of conventional methods like spray drying is that they often result in a broad range of particle sizes (Omer *et al.*, 2021). Therefore, careful selection of the appropriate method is essential to improve product quality while minimizing production costs. As for the packaging of the product, it is suggested that the use of light protective packaging or vacuum sealing to be employed to retain the physicochemical characteristics of the products.

Ultimately, careful planning and the selection of the right techniques and parameters are critical to ensure high-quality products with maximized bioactive compound content and stability throughout the production process and up to distribution. Key factors to consider when choosing methods and processing conditions include process feasibility, potential impacts on product quality, time efficiency, and environmental sustainability.

4. Application of Pandan in Various Industries

4.1. Application in Food Industry

In the food industry, pandan is primarily utilized as a natural flavouring and colouring agent. Its role as a colouring agent stems from the high content of chlorophyll, which imparts a vibrant green colour naturally (Nabi *et al.*, 2023). For instance, research has explored the use of maltodextrin as a filler and stabilizer in pandan leaf extracts used for natural colouring and flavouring purposes (Arshimny & Syamsu, 2020). This study demonstrated that increasing the amount of maltodextrin resulted in higher yield, moisture content, total dissolved solids, water solubility, and brightness, while reducing the greenness of the pandan leaf preparation.

As a flavouring agent, pandan is utilized to enhance the aroma of non-aromatic rice varieties. Research indicates that the maximum absorption of 2AP by rice grains occurs when using an optimal amount of water and a cooking time of 15 minutes (Yahya *et al.*, 2011). Additionally, in studies involving the addition of pandan extract to refined, bleached, and deodorized (RBD) palm olein for deep frying, it was observed to effectively retard oxidation while preserving the quality of both the oil and the fried product (Nor *et al.*, 2008).

4.2. Application in Medical Industry

Pandan exhibits significant potential in the medical sector, with several studies exploring its efficacy as an alternative treatment for various health issues, including anticancer, antidiabetic, and antimicrobial properties (Suwannakul *et al.*, 2018). The growing trend towards alternative medicines is driven by the desire to mitigate the side effects associated with modern medications. For instance, commercial mouthwashes containing alcohol and chlorhexidine gluconate have been linked to increased cancer risk and teeth staining (Safrida *et al.*, 2020). Moreover, the overuse of antibiotics has contributed to bacterial resistance, posing challenges in disease treatment (Dumaoal *et al.*, 2010). As a result, natural sources like pandan are being researched extensively to offer safer treatment options for patients (Sulistiyati *et al.*, 2019).

The potential of pandan in combating diabetes has been extensively studied. Research indicates that pandan leaf extract can significantly reduce postprandial blood sugar levels, demonstrating antihyperglycemic effects (Chiabchalard & Nooron, 2015). Furthermore, studies on obese mice have shown that pandan extract improves conditions associated with diabetes such as hyperinsulinemia, glucose intolerance, hyperlipidaemia, and fatty liver. This improvement is attributed to enhanced glucose uptake in fat and muscle cells, which helps in controlling hyperglycaemia (Saenthaweesuk *et al.*, 2016). Additionally, treatment with pandan extract has been found to reverse metabolic changes, including reduced body weight gain, decreased body mass index (BMI), reduced abdominal adipose tissue deposition and adipocyte size, lower systolic and diastolic blood pressure, and increased levels of high-density lipoprotein (HDL) cholesterol (Reshidan *et al.*, 2019).

The antidiabetic properties of pandan can be attributed to its ability to inhibit the activity of α-glucosidase enzymes. These enzymes play a crucial role in breaking down starch and disaccharides into simpler forms such as glucose, facilitating their absorption in the intestine. Pandan extract has been shown to inhibit this hydrolysis process, thereby reducing the rate at which carbohydrates are converted into glucose and absorbed into the bloodstream. This mechanism leads to lower postprandial blood sugar levels. Additionally, pandan extract has been observed to stimulate insulin secretion, further contributing to its antidiabetic effects (Chiabchalard & Nooron, 2015).

The study by Lomthong *et al.* (2022) demonstrated that pandan exhibits significant antibacterial activity against *Staphylococcus aureus* across all tested concentrations. However, their research did not find any in vitro activity against *Escherichia coli* using pandan prop root extract, which aligns with findings from Dumaoal *et al.* (2010) who observed similar results with pandan leaf extract, showing activity against *S. aureus* but not *E. coli*. Conversely, pandan essential oil showed the largest inhibition zone against *E. coli* and *Micrococcus luteus* in a study by Mar *et al.* (2019). Among the alkaloids isolated from pandan leaves, pandamarilactonine-A was identified as the most active against *E. coli*, *S. aureus*, and *Pseudomonas aeruginosa* (Laluces *et al.*, 2015). These findings suggest that pandan extracts may selectively inhibit the activity of specific bacterial strains, with effectiveness influenced by concentration.

Pandan leaf extract has shown promising potential as an ingredient for both treating and preventing cancer. Studies have identified components such as lutein, known for its antioxidant properties and potential as a chemopreventive compound, in pandan leaves, in addition to its benefits for eye health (Ningrum *et al.*, 2015). Furthermore, compounds like rutin, epicatechin, kaempferol, and gallic acid, found in high concentrations in pandan, are recognized for their potent anticancer properties (Ghasemzadeh & Jaafar, 2013). Research by Suwannakul *et al.* (2018) and Ghasemzadeh and Jaafar (2013) has demonstrated the anticancer effects of pandan extract. Suwannakul *et al.* (2018) reported moderate potency against human neck and neck squamous cell carcinoma (HNSCC), while Ghasemzadeh and Jaafar (2013) investigated its effects on human breast carcinoma cells, highlighting its potential in combating cancer.

Pandan is recognized for its anti-inflammatory properties, as highlighted in studies by Bhuyan and Sonowal (2021) and Ningrum and Schreiner (2014). These properties have led to the development of gel formulations for treating wound injuries by Forestryana *et al.* (2022). In surgical applications, ethanolic extracts of pandan have demonstrated effectiveness in promoting incision wound healing. Pandan extract ointments accelerate the formation of new collagen and blood vessels, thereby enhancing the wound healing process (Putri *et al.*, 2022). The high antioxidant activity of pandan is also beneficial for hepatoprotective effects against oxidative stress-induced intoxication (Thanebal *et al.*, 2021). Additionally, pandan extract has been observed to aid in treating insomnia by promoting faster sleep induction (Sulistiyati *et al.*, 2019). These diverse health benefits underscore pandan's potential in therapeutic applications beyond its culinary uses.

Pandan has shown promising potential in dental treatments. Studies have explored its use in nano-emulsion form as a mouthwash, effectively increasing saliva pH (Safrida *et al.*, 2020). Additionally, pandan leaf aromatherapy has been suggested to alleviate dental anxiety in paediatric patients (Pradopo *et al.*, 2017). Furthermore, research has demonstrated strong antibacterial activity of pandan extract against oral bacteria like *Streptococcus salivarius* and *Porphyromonas gingivalis*, surpassing the effectiveness of commercial antibiotics like metronidazole and antiseptics such as chlorhexidine (Suwannakul *et al.*, 2018). These findings highlight pandan's potential in enhancing oral health through natural and effective means.

4.3. Application in Other Industries / R&D Projects

Pandan plants have shown potential benefits in the farming industry, particularly in environmental and pest management aspects. Research by Han *et al.* (2014) demonstrated that pandan plants thrive in hydrophytic conditions and effectively absorb nutrients, particularly nitrate, thereby reducing algal growth and mitigating eutrophication. Additionally, pandan has been investigated for its pest management properties. Studies have indicated both attractant and repellent properties in pandan, with a stronger tendency towards repelling pests such as cockroaches (Li & Ho, 2002). These findings suggest that pandan could serve as a natural and effective tool in sustainable agriculture practices.

In an investigation by Widodo *et al.* (2022), the addition of pandan leaf extract during the starter period in broiler production was found to have a negative impact on performance, likely due to its high fibre content which hindered protein digestion. However, another study explored the potential of pandan fibre, a byproduct of the processing line, for biopolymer production. Diyana *et al.* (2021) suggested that pandan fibre could serve as a bio-based polymer matrix, offering an alternative reinforcement material. These contrasting findings highlight both the challenges and potential applications of pandan in agricultural and industrial contexts.

Pandan's potential applications extend to the pharmaceutical and cosmetic industries. Studies have demonstrated that higher concentrations of pandan extract in body scrub formulations increase skin hydration, leading to smoother skin (Diana *et al.*, 2022). Additionally, pandan has been explored for use in topical emulsion production (Jimtaisong & Krisdaphong, 2013), highlighting its versatility in skincare formulations.

In addition to its applications in cosmetics and pharmaceuticals, pandan in various forms such as powder, concentrated extract, and tannin shows potential as an iron corrosion inhibitor. Tannins derived from pandan create a protective barrier on metal surfaces, effectively preventing damage and slowing down the rate of acid consumption (Tambun *et al.*, 2022). This highlights pandan's versatility in industrial applications beyond its traditional uses.

5. Conclusions

In conclusion, pandan demonstrates significant potential across various fields. The choice of processing method, growth conditions, and parameters greatly influence the type and concentration of compounds derived from pandan extract or oil. This review provides a comprehensive understanding of the pandan plant, spanning from cultivation to the production of value-added products that can address challenges across diverse industries. It is hoped that this review will aid researchers in enhancing their knowledge and practices related to pandan. Additionally, industry stakeholders can optimize their production lines by considering these factors. Notably, sub-critical water extraction methods have not been extensively explored in pandan research projects. Moreover, studies focusing on pandan roots are relatively limited compared to those on pandan leaves. Therefore, there is a potential for future research to explore sub-critical water extraction involving both leaves and roots of pandan. This could further broaden the applications and benefits of pandan in various sectors.

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