From fragrance to ecosystems - exploring the traditional medicine and socio-economic-cultural heritage of *Pandanus odorifer* (Forssk.) Kuntze: A review

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Review

Abstract

Background: *Pandanus odorifer* (Forssk.) Kuntze, known as kewda, is a widely distributed plant species in tropical regions. This article explores the botanical features, traditional applications, and the socio-cultural and economic significance of *P. odorifer.*

Methods: The methodology involved an extensive search of peer-reviewed literature, scientific databases, and relevant sources to compile data on diverse attributes of *P. odorifer*.

*Results :*The Paleotropical monocot family Pandanaceae includes approximately 700 species spread across five genera: *Pandanus* Parkinson, *Freycinetia* Gaudich., *Martellidendron* (Pic. Serm.) Callm. & Chassot, *Sararanga* Helms, and *Benstonea* Callm. & Buerki. Of the five genera: three (*Pandanus, Benstonea*, and *Freycinetia*) are found in India. The unique morphology and ecological adaptations of *Pandanus odorifer* contribute to its widespread distribution and resilience. Additionally, it possesses aromatic and medicinal properties. Rich in phytochemicals like lignans, isoflavones, and alkaloids, alongside essential nutrients, it offers therapeutic and nutritional benefits. The oil extracted from its male flowers, containing phenylethyl methyl ether, finds applications in various industries such as aromatherapy, cosmetics, and food. Traditional medicinal practices utilize *P. odorifer* for treating headaches, inflammation, and colds, among other ailments. It also holds cultural significance and is utilized in handicrafts and as a flavoring agent.

Conclusions: Pandanus odorifer is a valuable botanical resource with significant ecological, cultural, and economic importance. Its traditional uses and diverse chemical composition demonstrate its multifunctionality. Continued research and conservation are essential to harness its potential for sustainable development and ensure its survival amid environmental changes.

Keywords: Ethnic utility, Kewda, Pandanaceae, Phytochemical constituents, Therapeutic applications

Background

Plants play a crucial role as major sources of natural products, contributing to numerous industries such as pharmaceuticals, agrochemicals, flavor and fragrance ingredients, food additives, and pesticides (Grigoriadou *et al.* 2023; Sulieman *et al.* 2023). Secondary compounds found in plants are unique to each species or group, serving important functions by defending against herbivores, inhibiting competitors, pests, and pathogens, and attracting beneficial organisms like pollinators (Stevenson *et al.* 2017; Ramawat & Goyal, 2020; Divekar *et al.* 2022; Al-Khayri *et al.* 2023; Anjali *et al.* 2023). Additionally, many of these secondary metabolites are widely utilized in various applications, such as flavorings and pharmaceuticals. One notable plant family in this context is the screw-pine family, Pandanaceae, comprises arborescent or lianoid dioecious monocotyledonous primarily found in paleotropical regions. The family Pandanaceae represents trees, shrubs, lianas, and epiphytes with long, narrow, rigid, spirally arranged pineapple-like leaves and prop roots (Gallaher 2015; Simpson 2019). Members of the family thrive from sea level to elevations around 3000 m on diverse substrates, such as granites, limestones, ultrabasic rocks, and muddy, peaty, or clay soils. Additionally, these plants are commonly associated with littoral mangrove communities and exhibit epiphytic growth in rainforests (Stone *et al.* 1998). The family holds botanical significance due to its suggested pivotal role in the evolution of monocotyledons (Meeuse 1965; 1966), unusual growth forms (Guillaumet 1973; Tomlinson *et al.* 1970), and breeding systems (Warburg 1900; Hutchinson 1973; Stone 1968). The center of origin of Pandanaceae remains unconfirmed due to limited fossil records. Audley-Charles (1987) proposed a Gondwana origin during the later Mesozoic period, suggesting migration from eastern Gondwana through Asia and Australia via the Malay Archipelago in the Late Cretaceous period (Nadaf & Zanan 2012a). However, recent molecular studies propose that most Pandanaceae species dispersed via long-distance transport during the late Eocene, after the divergence of the Gondwana continents (Gallaher *et al.* 2015). Zdravchev *et al.* (2023) suggest that the order Pandanales likely originated in Laurasia, with its differentiation beginning in the region of Tibet. The Pandanaceae family then diverged in West Africa and subsequently spread eastward into Southeast Asia, northern Australia, and New Zealand. The largest genus, *Pandanus*, later repopulated Africa from Southeast Asia through long-distance transport (Zdravchev *et al.* 2023). The family Pandanaceae comprises around 700 species distributed among five genera: *Pandanus* Parkinson, *Freycinetia* Gaudich., *Martellidendron* (Pic. Serm.) Callm. & Chassot, *Sararanga* Helms, and *Benstonea* Callm. & Buerki (Stone et al 1998; Callmander *et al.* 2003; Buerki *et al.* 2012; Tan & Takayama 2019; Zdravchev *et al.* 2023).

Freycinetia is found in Southeast Asia, the Pacific Islands, and Australasia (Stone 1990). *Martellidendron* is limited to Madagascar and the granitic Seychelles (Callmander 2000, 2001; Callmander *et al.* 2003). *Sararanga* is restricted to the Philippines, New Guinea, and the Solomon Islands (Huynh 2001). *Benstonea* ranges from India to Australia, with a high diversity in Borneo and Peninsular Malaysia (Callmander 2012). Within the Pandanaceae family, the genus *Pandanus* is the most widespread, thriving in tropical and subtropical regions, including the Pacific Islands, Malaysian islands, and Australia (Stone 1974, 1982; Stone *et al.* 1998; Callmander *et al.* 2003, 2012; Buerki *et al.* 2012; Loa *et al.* 2016; Tan & Takayama 2019). *Pandanus* species adapt to diverse habitats, from coastal areas to mountainous regions, providing crucial food and habitat for various animals (Grushvitsky 1982; Frank & Lounibos 1983; Lehtinen 2002; Loa *et al.* 2016; Fusi *et al.* 2021). In many tropical regions, members of the Pandanaceae family are traditionally used for food and medicine (Langenberger *et al.* 2009; Baddu & Ouano 2018). Additionally, they serve as raw materials for woven crafts, ritual items, and construction materials for houses (Wardah 2009; Fedele *et al.* 2011; Ragragio *et al.* 2013; Ordas *et al.* 2021).

The Pandanaceae in India is represented by three genera: *Pandanus*, *Benstonea,* and *Freycinetia* (Nadaf & Zanan 2012b). In India, about 30 to 40 species of *Pandanus* are found in states including Odisha, Andhra Pradesh, Kerala, Tamil Nadu, West Bengal, Uttar Pradesh, Assam, Meghalaya, Andaman and Nicobar Islands, and Gujarat (Kirtikar *et al.* 1991; Chatterjee & Pakrashi 2001; Padhy *et al.* 2016; Nasim *et al.* 2018). Humans widely use various parts of the *Pandanus*, such as its fruits, leaves, inflorescences, and trunks, for a variety of purposes including food, flavoring, perfume, and fiber (Limbongan *et al.* 2009; Adkar & Bhaskar 2014).

Pandanus odorifer, commonly known as the Screw pine (also referred to as the umbrella tree), is known by various vernacular or local names such as Ketakee, Gandha pushpa, Sthira gandha, Indu Kalika, and Jambala (in Sanskrit); Kewra, Keora, Kewda, and Gagandhul (Hindi); Kedgi, Kevda, and Keora (Marathi); Kewoda (Gujarati); Kiya and Ketakee (Odia); Keya, Kedki, and Keori (Bengali); Kedige, ketake, and tale hu (Kannada); Thazhai, Thalay, and Thazhampoo (Tamil); Mogali and Gajangi (Telugu); Keura, kerada, and tarika Kiora, keura, and kevra (Nepali); Kaitha, Kaida, and Thala (Malayalam); Kiura, kevara, jambala, jambul, panshuka, and ketaki (Urdu); Adan, takonoki (Japanese) and Pandanus aromatnejshi (Russian) (Adkar & Bhaskar 2014; Padhy *et al.* 2016; Savaliram & Zanan 2022). In Odisha, *Pandanus odorifer* thrives in various natural habitats across the coastal districts of Ganjam, Jajpur, Jagatsinghpur, Khurda, Puri, Cuttack, Bhadrak, and Balasore. The plant plays a vital role in local culture, with its parts used for food, flavoring, perfume, and fiber. It serves multiple purposes, offering aromatic luxury to the affluent and essential sustenance to rural communities, underscoring its ethno-ecological significance. Despite numerous ethnobotanical studies, comprehensive reviews on *P. odorifer*'s traditional uses, socio-cultural impact, and economic significance are lacking. This study aims to fill this gap by documenting and highlighting the integration of *P. odorifer* into local culture, emphasizing its multifaceted importance. Ongoing research and conservation efforts are crucial to unlock the plant's full potential and ensure its long-term survival amid changing environmental dynamics.

Materials and Methods

Study area

Situated on the eastern coast of India, Odisha (formerly Orissa) lies between the parallels of 17°49'N and 22°34'N latitudes and meridians of 81°27'E and 87°29'E longitudes (Figure 1). Bordered by Jharkhand to the north, Chhattisgarh to the west, Andhra Pradesh to the south, West Bengal to the northeast, and the Bay of Bengal to the southeast, it covers an area of 155,707 km², contributing 4.87% of India's landmass. With the Bay of Bengal forming its eastern and southeastern frontiers, the Eastern Ghats range of hills almost passes through the heart of the state, with high Similipala hills to its north and around 482 km of coastline to its east. Odisha comprises 30 districts housing a total population of 4.2 crores (Census 2011. The populace is distributed across 51,349 villages and 138 urban centers. Notably, the state is home to 62 types of scheduled tribes, constituting 22.85% of the population, and 93 types of scheduled caste communities, making up 17.13% of the populace, primarily dwelling in rural and hilly regions, where they derive sustenance from traditional livelihood practices. Odisha's climate varies across its diverse topography. While the coastal regions experience a moderated climate due to the influence of the sea, with high temperatures typically recorded during April-May, the hill tracts endure more extreme climatic conditions. The vegetation prevalent in the region is primarily of the tropical moist deciduous forest type (Champion & Seth 1968).

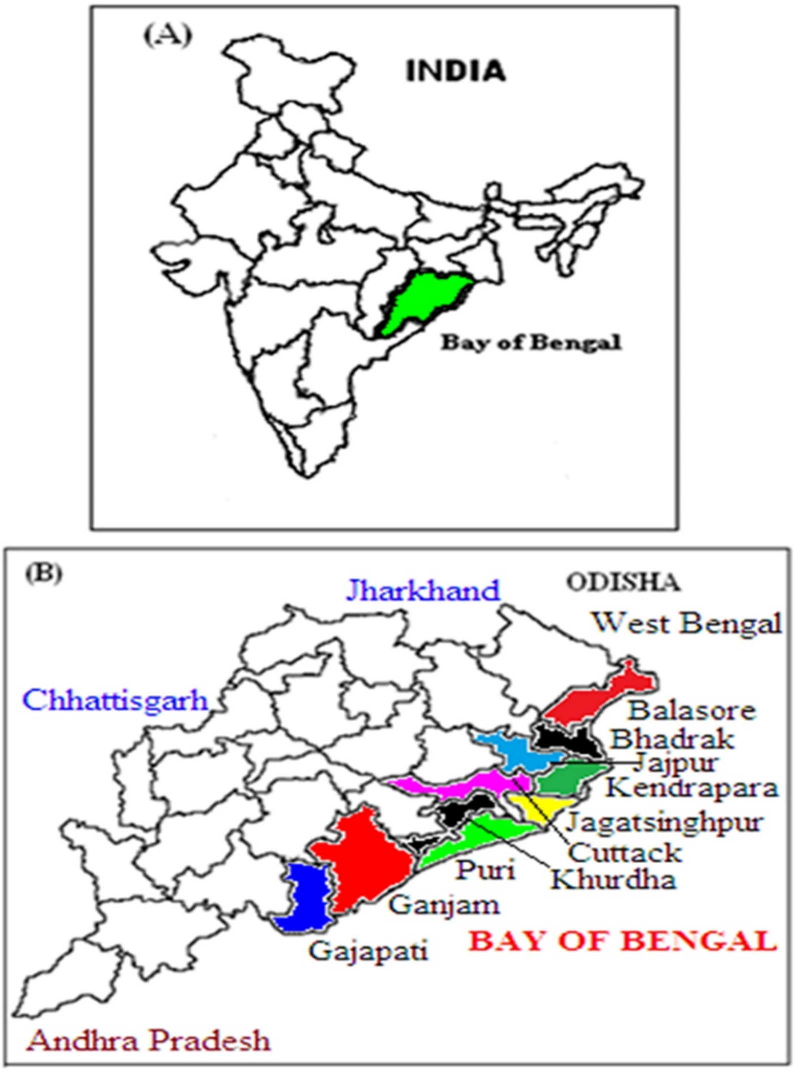

Figure 1. Figure 1. (A) Location of Odisha state in the eastern region of India (B) Study area showing different coastal districts

Data Analysis

The study focused on the ethnic utility and economic prospects of *P. odorifer* in coastal districts of Odisha, India (Figure 1). To gather information, a comprehensive review of published literature was conducted, and in-depth investigations into its indigenous usage were carried out. Pertinent articles were identified to ensure the validity of the suggested theory, avoid redundancy, and gather sufficient literature for analysis. PubMed, DOAJ, Web of Science, Science Direct (Scopus), and Google Scholar were searched using specific terms such as ethnobotanical study of *Pandanus odorifer*, *P. odoratissimus*, *P. fascicularis,* screw-pines, and Kewda. Studies about the plant's ethnic utility, socio-cultural, and economic prospects were considered in this investigation. Data were gathered on the various parts of the plant used for medicine, food, flavoring, perfume, and fiber, highlighting traditional knowledge and practices documented in the literature. Information on the socio-cultural importance was extracted from studies that explored its role in local customs, rituals, and daily life. The economic potential was assessed by reviewing studies that analyzed commercial uses of products. Articles with full free text access were accessed through various search engines, while requests for full-text access were made directly to authors via research platforms like ResearchGate. Relevant papers were selected for deeper understanding, and only complete texts were considered for analysis, excluding duplicates and unrelated abstracts.

Results and Discussion

Scientific ecological knowledge follows strict rules guided by academic disciplines and the scientific method (Raymond *et al.* 2010). In contrast, local ecological knowledge (LEK) is a collective body of traditional wisdom, practices, and beliefs passed down orally through generations, providing insight into local ecosystems and their management (Cebrian-Piqueras *et al.* 2020). LEK encompasses the understanding of the intricate relationship between humans and their environment, shaped by socio-historical changes within local populations (Reyes-Garcia *et al.* 2007; Fogliarini *et al.* 2021). This study analyzes the LEK of *P. odorifer* across socio-economic and ritual dimensions to understand its importance and utilization within local communities.

Habitat and distribution of *Pandanus odorifer*

Pandanus odorifer (Forssk.) Kuntze naturally grows in coastal regions and can withstand salt sprays and strong winds (Rashmi *et al.* 2018). This coastal species is found in various regions (Figure 2) including India, Sri Lanka, the Maldives, southern China, the Ryukyu Islands (Japan), the Philippines, Taiwan, Vietnam, Laos, Cambodia, Thailand, Myanmar, Peninsular Malaysia, Indonesia, Singapore, Borneo, Papua New Guinea, and throughout the Pacific Ocean beaches, including Solomon Islands and Fiji (Callmander *et al.* 2021). Commonly found in coastal districts of Odisha, *Pandanus odorifer* thrives in diverse habitats such as seashores, riverbanks, wastelands, agricultural fields, ponds, canals, and roadsides (Figure 3). Notably, it flourishes along the Ganjam coast, particularly in the Kewda Belt, spanning approximately 675 km^2 from Rushikulya River to Bahuda River. This belt, 45 km long from north to south and 15 km wide from east to west along the Bay of Bengal, hosts around 80-85% of the Kewda canopy within a 10 km radius of the coastline. Flowering persists year-round, with peaks during the rainy season (June-September). Ganjam district alone shelters an estimated 3,00,000 to 4,00,000 trees, producing approximately 1,00,00,000 flowers daily, sustaining a rich habitat for various flora and fauna.

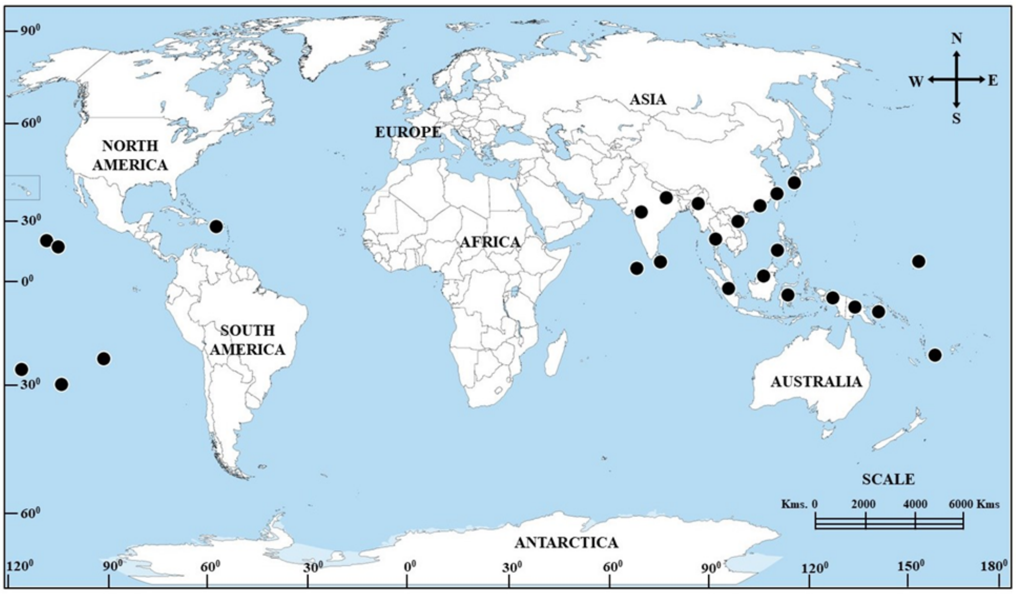

Figure 2. Worldwide distribution of *Pandanus odorifer*

Figure 3 a-f. Different habitats of *Pandanus odorifer* (Forssk.) Kuntze a. riverbanks, b. near canal, c. near pond, d. wastelands, e. roadsides, f. demarcation of crop fields

Botanical description

Pandanus odorifer (Forssk.) Kuntze (Syn.: *Pandanus odoratissimus* L.f., *P. fascicularis* Lam.), profusely branched, bushy dioecious shrub or small tree, up to 8 m tall, rarely erect. The stem is supported by numerous thick terete and stilt aerial roots (Figure 4). The leaves are glaucous green, ensiform, 1-1.5 m long, with caudate-acuminate tips and coriaceous texture. Marginal spines point forward, while those on the midrib may point forward or backward. The male flowers are borne on a spadix with numerous subsessile cylindric spikes enclosed in long white fragrant caudate-acuminate spathes. Female flowers feature a solitary spadix. The fruit is oblong or globose, forming a syncarpium that is 15 to 25 cm long (Saxena & Brahmam 1996; Adkar & Bhaskar 2014). The seeds are obovoid, ellipsoid, or oblong, measuring 6-20 mm in length, red-brown on the outside and whitish inside. Propagation is by seeds and vegetative method (Saxena & Brahmam 1996).

Phenology

The phenology of *Pandanus odorifer* in Odisha, India, reflects its adaptation to the tropical coastal climate of the region. The plant exhibits distinct seasonal cycles influenced by local environmental factors such as temperature, rainfall patterns, and photoperiod (Saxena & Brahmam 1996). Typically, *P. odorifer* begins its growth cycle with the onset of the monsoon season, benefiting from increased rainfall and humidity conducive to germination and initial growth. As the season progresses, the plant develops its characteristic long, narrow, rigid leaves and prop roots, which are well-suited for survival in diverse substrates ranging from sandy coastal soils to inland clayey or peaty soils. Flowering usually coincides with the peak of the rainy season or shortly thereafter, depending on local climatic variations. The aromatic inflorescences of *P. odorifer* attract essential pollinators, facilitating fruit set. Fruiting follows flowering, with the development of cone-like fruits containing edible seeds. These phenological patterns, closely tied to seasonal changes and local ecological dynamics, underscore the plant's ecological resilience and cultural importance in the region (Adkar & Bhaskar 2014).

Figure 4 a-f. Morphology of *Pandanus odorifer* (Forssk.) Kuntze a. whole plant, b. stem, c. leaves, d. roots, e. flower, f. fruit

Reproductive biology

Pandanus species, including *P. odorifer*, exhibit diverse reproductive strategies crucial for their ecological success. *P. odorifer* is dioecious with the female plant producing a non-scented fruit while the male produces a flower rich in volatiles. Fleming and Muchhala (2008) highlighted the genus' adaptation to wind-mediated pollination, complemented by interactions with insects, birds, and bats. Cox (1985, 1990) opined in favor of anemophily in *P. odorifer* because the pollen lacked pollen kitt and is easily carried off by wind, and because only the male inflorescences are visited by introduced honeybees. The plants utilize floral scents both to attract pollinators and as a defense mechanism against environmental stresses, with scent composition significantly influenced by external factors (Staudt & Bertin 1998; Gershenzon *et al.* 2000). A few nitidulid beetle species have been recorded as visitors to the male inflorescences of *P. odorifer* (Kato 2000). Recently, Miyamoto *et al.* (2024) opined in favor of insect pollination and stated that both male and female inflorescences are thermogenic at night when insect visitation occurs. Most known *Amystrops* species are associated with the inflorescences, suggesting a widespread, specialized *Pandanus-Amystrops* association.

Chemical composition

The methanol extract of *P. odorifer* leaves reportedly contains phytochemical constituents such as steroids, saponins, terpenoids, glycosides, tannins, and flavonoids (Londonkar & Kamble 2009). The leaves also contain pyridine alkaloids, including pandamarilactone-1 ($C_{18}H_{23}NO_4$), pandamarilactone-31 ($C_{19}H_{25}NO_4$), and pandamarilactone-32 ($C_{18}H_{21}NO_3$). The aroma compound 2-acetyl-1-pyrrolidine has been identified in the volatile oil of the leaves (Chilkwad *et al.* 2008; Kumar *et al.* 2010, Penu *et al.* 2020). Active principles isolated from the extract of the whole plant include 3-(4-(dimethylamino) cinnamoyl)-4-hydroxycoumarin, 3,3′-methylenebis(4-hydroxycoumarin), erythro-9,10-dihydroxyoctadecanoic acid, octadecanedioic acid, and dihydroagathic acid (Bharathidasan *et al.* 2012). Phytochemical analysis of *P. odorifer* root extracts led to the isolation of phenolic compounds, lignan-type compounds, and some benzofuran derivatives. Identified compounds include α-terpineol, β-carotene, β-sitosterol, benzyl benzoate, pinoresinol, germacrene-B, vitamin C, viridine, tangeterine, 5,8-hydroxy-7-methoxyflavone, and vanidine (Jong & Chau 1998; Adkar & Bhaskar 2014). Additionally, *P. odorifer* fruit extract is rich in antioxidant compounds such as caffeoylquinic acids (Zhang *et al.* 2013), vitamins C, E, and β-carotene (Englberger *et al.* 2006; Englberger *et al.* 2009), as well as isopentenyl, dimethylallyl acetates, and cinnamates (Vahirua-Lechat *et al.* 1996; Tanna *et al.* 2016). An examination of multiple reports (Nigam & Ahmed 1992; Maheshwari 1995; Naqvi & Mandal 1996; Bisht *et al.* 1997; Misra & Rao 1997) indicates that 2-phenylethyl methyl ether constitutes the primary component (65.6-75.4%) in natural Kewda oil, followed by terpinene-4-ol (11.7-20.9%), p-cymene (1.0-3.1%), and α-terpineol (1.2-2.9%) (Nigam & Ahmed 1992; Maheshwari 1995; Naqvi & Mandal 1996; Bisht *et al.* 1997; Misra & Rao 1997; Mishra *et al.* 2000).

Protecting agricultural landscapes

Landscape refers to the visual aspects of an area of land, often encompassing its physical features and human elements. These landscapes are frequently characterized by subsistence agriculture and a direct reliance on local ecological resources, such as fuelwood or crops for personal consumption (Tallis *et al.* 2008; Egoh *et al.* 2012; Pereponova 2023). Bio-fencing, also known as green fencing or boundary planting, is an ancient agricultural practice adopted by farmers to safeguard their cultivated fields from human and animal encroachment. This method is prevalent in India, where live fences serve to demarcate crop fields, pastures, households, and farm boundaries, creating a network of plant cover across rural landscapes. These live fences not only occur in diverse biophysical settings, including different elevations, ecological life zones, and soil types, but they also reflect distinct cultural and land use histories, particularly in areas with significant agricultural production such as vegetable plantations, pastures, and home gardens (Saucer 1979; Budowski 1987; Panda *et al.* 2018). In regions where land conversion to agriculture has been extensive, live fences often represent the primary form of remaining tree cover in the landscape. One example of a plant commonly used for bio-fencing is *P. odorifer*, whose entire plant forms a green wall (Figure 5). Farmers opt for this plant due to its cost-effectiveness and effectiveness in protecting against herbivores, due to its spiny leaves and dense growth. Furthermore, the leaves of *P. odorifer* possess unpalatable qualities, making them undesirable for herbivores. This combination of physical deterrents and unappealing taste makes it an ideal choice for bio-fencing purposes.

Economic and environmental benefits

The branches, roots, and leaves of *P. odorifer* hold significant economic value. The branches serve as pillars in small cattle huts. The trunks of aged plants are used in thatched house construction (Little & Skolmen 1989). Besides, the leaves of *Pandanus* are tough and have spines thus employed as fences for crops to protect from cattle. Additionally, Kewda leaves find application in crafting durable nets, mattresses, hats, flower baskets, money purses, handbags, and file folders (Maharana & Lenka 1993; Shiva & Jafri 1998). Dried branches and leaves are commonly used as fuel in rural areas. The trunk and branches are used as fuel wood where other fuel wood is scarce. From an environmental perspective, *P. odorifer* proves to be eco-friendly. Its soil-binding properties are crucial in preventing soil erosion in agricultural fields and stabilizing dunes along the coastline (Panda *et al.* 2007; Pattanaik *et al.* 2008; Aparna & Rajasekhar 2015). This stabilizes dunes, reducing the impact of winds and thereby protecting the coastline. *P. odorifer* emerges as an essential coastal bioresource, significantly contributing to both the socio-economy and ecology of the region.

Figure 5. *Pandanus odorifer* (Forssk.) Kuntze bio-fencing to safeguard cultivated fields from human and animal encroachment

Cultural significance

During Mahashivaratri, the revered celebration dedicated to Lord Shiva, the ritualistic offering of *P. odorifer* flowers, commonly known as Ketaki flowers, holds profound symbolism deeply rooted in Hindu mythology and tradition. This practice's significance can be traced back to ancient texts like the Shiva Purana (Shastri 1970), where a celestial dispute between Lord Shiva and Lord Brahma is recounted. Central to this tale is the Ketaki flower, which, though playing a pivotal role, does so deceitfully, resulting in a curse upon both Brahma and the flower. Despite its checkered past, devotees continue the tradition of offering Ketaki flowers to Lord Shiva during Mahashivaratri, viewing it as an act of repentance and reconciliation (Figure 6a). This ritual serves as a poignant symbol of devotees' acknowledgment of past misdeeds and their earnest quest for forgiveness and divine grace. Through the acceptance of Ketaki flowers during Mahashivaratri, believers express a profound belief in redemption and spiritual growth, underscoring the transformative power of devotion and the eternal compassion of Lord Shiva.

Utilizing fibers: Eco-friendly solutions for sustainable industries

In recent times, there has been a significant shift in research focus towards the development of eco-friendly and sustainable materials derived from renewable natural resources. Natural fibers represent one such material category that is environmentally safe, biodegradable, and cost-effective. These fibers are sourced from various parts of plants, including the stem, bast, leaves, and roots (Demircan *et al.* 2020; Ilaiya Perumal & Sarala 2020). Natural fibers are preferred over synthetic ones for reinforcing polymer-based composite materials. Currently, natural fiber-reinforced polymer composites find applications across a wide range of industries, including automotive, aerospace, construction, military, and industrial sectors (Brailson Mansingh *et al.* 2021). For instance, the prop roots of the *P. odorifer* plant possess high-quality fibers that penetrate deeply into the ground, resulting in improved fiber strength and quantity. These strong fibers are used to manufacture ropes, baskets, and painting brushes (Sahu *et al.* 2013). The root is also used in the thatching of houses and fencing of boundaries (Figure 6b-e). Additionally, local communities often utilize the roots as toothbrushes (Sahu & Mishra 2007). By harnessing the natural fibers from *P. odorifer*, industries can reduce their reliance on synthetic materials and contribute to the promotion of sustainable practices.

Figure 6a-f. a. The ritualistic offering of *Pandanus odorifer* (Forssk.) Kuntze flower during Mahashivaratri, the revered celebration dedicated to Lord Shiva, b. processed roots, c. selling of root in market, d use of roots for thatching of roof, e. use of root in repairing boundary wall, f. burning of *P. odorifer* plant

Nutritional significance of fruits

Pandanus odorifer fruits, popularly called "Kia Panasa" in Odisha, are consumed in various parts of Odisha (Noor & Satapathy 2020). They are a staple food in Micronesia, Tuvalu, and Kiribati (Miller *et al.* 1956; Englberger 2003). A 100 g portion of the edible pericarp is mainly comprised of water (80 g) and carbohydrates (17 g). There are also significant levels of beta-carotene (19 to 19,000 µg) and vitamin C (5 mg), along with small amounts of protein (1.3 mg), fat (0.7 mg), and fiber (3.5 g) (Englberger 2003; Englberger 2006; Englberger 2006a). The edible flesh of deeper yellow and orange-colored varieties contains higher levels of provitamin A carotenoids. The fruit of these varieties has considerable potential for alleviating vitamin A deficiency (Englberger 2003).

Traditional uses and therapeutic applications

Pandanus odorifer is a plant of significant medicinal importance. In traditional Ayurvedic and Siddha medicine, various parts of *P. odorifer*, including flowers, leaves, fruits, and roots, are utilized either individually or in combination with other ingredients to address a diverse array of ailments (Table 1). The leaves of *P. odorifer* are particularly valued for their effectiveness in treating edema, tumors, leprosy, spasms, inflammation, scabies, leukoderma, pain, wounds, ulcers, colic, skin diseases, and rheumatoid arthritis (Warrier 1997; Chatterjee & Pakrashi 2001; Panda *et al.* 2008; Rajeswari *et al.* 2011; Adkar & Bhaskar 2014; Shim 2019). Tablets prepared from leaf extracts are orally administered to alleviate pain, inflammation, and epilepsy in traditional medical practices (Panda *et al.* 2009). The male flowers find application in the treatment of skin and heart-related infections (Adkar & Bhaskar 2014). Additionally, the roots are utilized for their antidiabetic, antidote, abortifacient, hemorrhoidal, and dermatological (for skin diseases, leprosy, scabies, and syphilis) properties (Jain 1991; Meilleur *et al.* 1997). The fruit exhibits efficacy in treating ailments such as vat, kapha, urinary discharge, and leprosy, and also serves as a male aphrodisiac, possessing notable analgesic, anti-pyretic, cytotoxic, and anti-inflammatory activities (Adkar & Bhaskar 2014; Hossain *et al.* 2020). Furthermore, the oil derived from *P. odorifer* is recommended for its efficacy in managing rheumatoid arthritis, skin diseases, earaches, headaches, arthritis, debility, depurative purposes, giddiness, as a laxative, for leprosy, and for alleviating spasms (Adkar & Bhaskar 2014).

Promoting sustainable cultivation and ethical harvesting practices for *Pandanus odorifer* can create livelihood opportunities for local communities, ensuring a steady supply of plant material for traditional medicine while preserving natural habitats. This approach supports both economic stability and environmental conservation. Establishing community-owned enterprises for the production and processing of *P. odorifer* products can economically empower indigenous populations by enhancing local knowledge on cultivation, processing, and marketing. Developing value-added products like oils, extracts, and herbal formulations derived from *P. odorifer* can boost market potential and create niche markets that respect traditional practices. Protecting and documenting the traditional knowledge associated with *P. odorifer* preserves cultural heritage and ensures communities benefit from their intellectual property. Sharing benefits from the commercial use of traditional medicine can further improve socio-economic outcomes. Integrating *P. odorifer* into mainstream healthcare systems can provide affordable healthcare, particularly in rural areas, supporting the continued practice of traditional medicine and preserving biodiversity (Warrier 1997; Bodeker & Kronenberg 2002; Panda 2004).

Table 1. Traditional medicinal uses of *P. odorifer*

Parts used	Disorder treated	Traditional medicine	Country	Reference
Flower	Syphilis, tumor, skin diseases, leukoderma, leprosy, generating perspiration, earache, bronchitis, blood diseases, asthma, urinary tract illnesses, headache, rheumatism, constipation, diabetes.	Siddha Medicine, Ayurveda	Sri Lanka, India	Warrier *et al.* 2005, Raina *et al.* 2004, Ilanchezhian and Joseph 2006, Khare 2011, Sathasivampillai *et al.* 2015, 2016, 2017, 2018.
Leaf	Brain diseases, heart diseases, leukoderma, scabies, skin diseases, smallpox, tumor, leprosy, syphilis, headache, rheumatism.	Ayurveda	Sri Lanka, India	Warrier *et al.* 2005, Raina *et al.* 2004
Root	Constipation, urinary tract illnesses, diabetes, syphilis, fever, thyroid disorders.	Ayurveda	India, Taiwan	Nadkarni 1996, Jong and Chau 1998, Ilanchezhian and Joseph 2006, Khare 2011.
Fruit	Vat, kapha, urinary discharge, leprosy, male aphrodisiac, analgesic, anti-pyretic, cytotoxic, anti-inflammatory activities	Ayurveda	India, Bangladesh	Adkar and Bhaskar 2014, Hossain *et al.* 2020

Modernizing traditional methods of application in the field of medicine

Natural products and traditional medicines, such as Traditional Chinese Medicine, Ayurveda, Kampo, Traditional Korean Medicine, and Unani, have evolved into well-regulated systems, deeply rooted in cultural heritage. These practices are increasingly integrated with modern science, particularly through the fields of ethnobotany and ethnopharmacognosy, which guide researchers in discovering new molecules from diverse sources. The flora of the tropics, with its rich biodiversity, plays a crucial role in providing new leads for drug development. Natural products, which have evolved over millions of years, offer unique chemical diversity and drug-like properties, making them invaluable resources for creating new therapeutic agents (Fabricant & Farnsworth 2001; Suntar 2020; Pirintsos *et al.* 2022; Chaachouay & Zidane 2024). Modernizing traditional methods of application in the field of medicine involves a synergistic approach that blends centuries-old herbal wisdom with contemporary scientific advancements. The phytochemical constituents of plants like *Pandanus odorifer*, renowned for their aromatic and therapeutic properties, can be validated and enhanced through scientific research and advanced extraction techniques. Innovative technologies such as Supercritical Fluid Extraction, Microwave-Assisted Extraction, High-Performance Liquid Chromatography, Gas Chromatography, Nuclear Magnetic Resonance Spectroscopy, and Crystallography, have enabled the precise determination of active compounds, leading to the development of novel therapeutic drugs. This approach not only preserves and respects indigenous knowledge but also bridges the gap between traditional and modern medicine, offering more holistic and personalized treatment options. By integrating these traditional methods into mainstream healthcare, a wide spectrum of health concerns can be addressed, promoting overall well-being. The convergence of ancient practices with modern methodologies fosters a comprehensive approach to healthcare, ensuring that the wisdom of the past is leveraged alongside the advancements of the present to enhance therapeutic efficacy and patient outcomes. (Galm & Shen 2007; Yuan *et al.* 2016; Ponphaiboon *et al.* 2023).

Traditional techniques in kewda perfumery: preserving centuries-old craftsmanship

India boasts a rich perfumery tradition dating back over 5000 years to the ancient civilization of the Indus Valley. Excavations at sites such as Harappa and Mohenjo-Daro have unearthed artifacts resembling present-day Deg and Bhabka traditional distillation units, indicating the early use of water distillation techniques. During ancient times, Indian perfumes and aromatic substances such as Sandalwood, Kashmiri saffron, Assami Black agar, Himalayan Kasturi, various floral Attars, and essential herbal oils were highly sought-after commodities in trade. The perfume industry gained significant momentum during the reign of King Harshabardhana (606 to 647 AD), as evidenced by historical records. Indian fragrances found their way to Europe through Egypt, often referred to as Arabian perfumes, showcasing India's influence on global trade during that era. Cities like Kanauj, Kumbakonam, Pataliputra, Pandharpur, Poona, and Bangalore emerged as prominent centers for essential oil industries in ancient India. King Harshabardhana even imposed a business tax on perfume products, indicating the flourishing trade of aromatic substances during his reign. The Mughal emperors further enriched India's perfumery tradition with their love for exotic fragrances, as documented in Ain-e-Akbari (1547-1605) by Abul Fazl. During the Mughal period, cities like Lucknow, Aligarh, Jaunpur, Ghazipur, Delhi, and Jaipur became renowned hubs for perfume and floral extracts (Roy 1991; Saran 2005; Eraly 2007; Dwivedi 2011).

Pandanus odorifer, is an economically significant aromatic plant valued for its essential oil. This oil, extracted primarily from male flowers, is in high demand across various industries including aromatherapy, cosmetics, and food flavoring due to its distinctive fragrance. The key aromatic compound in this oil is phenylethyl methyl ether (Nasim *et al.* 2021). The Kewda perfume industry, a significant cottage industry in the coastal Ganjam district of Odisha, traces its origins back approximately 200 years. It commenced in the outskirts of Berhampur, Ganjam District, by Muslim immigrants from the Punjab province of undivided India (Dutta *et al.* 1987). Kewda Attar, a renowned fragrance in India since ancient times, primarily originates from this region, with approximately 90% of Kewda essence sourced from Ganjam District (Rout *et al.* 2011). Kewda attar, water, and oil (rooh) are integral perfumery products in India. The process of preparing these products involves collecting Kewra flowers in the early morning using plucking sticks, followed by distillation in distilleries to extract the perfumery components. Kewra Attar is produced by removing the outer green spiny parts and pointed tips of the spathe of the flowers. Subsequently, 1000 flowers are added to 60 liters of water and heated. The steam, along with Kewda oil vapors, is passed through sandalwood oil kept in a receiver, where the Kewda aroma is gradually absorbed, resulting in Kewda Attar. It typically contains 3-5% Kewda oil blended with sandalwood oil and is utilized in various applications such as scenting clothes, bouquets, lotions, cosmetics, soaps, hair oils, tobacco products, Pan Masala, and Agarbati (incense sticks). Kewda attar and water are used for flavouring various foods, sweets, syrups, and soft drinks. They are popular in north India, especially on festive occasions. Kewra water is obtained through a similar distillation process with water, yielding approximately 10-18 liters from 1000 flowers. It contains about 0.02% Kewda oil and is utilized for flavoring sweets, syrups, soft drinks, and other food preparations, as well as in natural packaged food items. The essential oil from Kewda flowers, known as Kewda rooh, is obtained through hydro-distillation, where flowers are repeatedly distilled without a base oil in the receiver vessel. Approximately 30 grams of pure oil can be extracted from 1000 flowers (Kusuma *et al.* 2012). Kewda rooh is valued for its stimulant and antispasmodic properties, often administered for headaches and rheumatism. Additionally, there is considerable potential for export to Arabian countries and the Middle East (Sahu & Misra 2007).

The ecological impact of burning *Pandanus odorifer* on biodiversity

Pandanus odorifer is recognized as a vital species extensively utilized by communities for their economic needs (Pattanaik *et al.* 2008). Groves of *P. odorifer* are considered significant vegetative formations, particularly in association with human settlements. However, the burning of *P. odorifer*, a crucial component of various ecosystems, poses substantial threats to biodiversity (Figure 4f). As a keystone species, Pandanus provides habitat and sustenance for a diverse array of organisms, including birds, insects, snakes, and small mammals (Bachan & Nasser 2015; Gurmeet & Amrita 2015; Solomon Raju 2020). The destruction of *Pandanus* disrupts these intricate ecosystems, resulting in a loss of biodiversity. Moreover, *Pandanus* plays a critical role in stabilizing coastal dunes, offering protection against erosion and storm surges (Tongway & Ludwig 2011). Its absence renders different habitats susceptible to environmental degradation, diminishing resilience to climate change impacts. Preserving *P. odorifer* is imperative for the species it directly supports and for the overall health and resilience of different ecosystems.

Contribution of spatiotemporal evolution and traditional knowledge in achieving sustainability goals

The spatiotemporal evolution and traditional knowledge of *Pandanus odorifer* significantly contribute to achieving sustainability goals by integrating ecological, economic, and cultural dimensions. Its wide geographical distribution and ecological adaptability inform strategies to mitigate the impacts of climate change and habitat loss, aiding biodiversity conservation and climate change adaptation (Stone 1970; Bellwood & Hughes 2001). Traditional knowledge provides deep insights into sustainable practices such as bio-fencing, soil conservation, and medicinal uses, honed over generations. These practices support local economies, cultural heritage, and sustainable resource management, fostering a harmonious relationship with nature. Integrating scientific research with traditional wisdom enhances ecosystem management and strengthens community resilience, promoting sustainable use of natural resources. This holistic approach aligns with global sustainability targets, including the UN Sustainable Development Goals (SDGs) related to life on land (SDG 15), climate action (SDG 13), sustainable communities (SDG 11), food security through sustainable agriculture (SDG 2), health benefits through ethnobotanical practices (SDG 3), and responsible consumption and production (SDG 12) (Kanie *et al.* 2019; Vijge *et al.* 2020). Thus, the spatiotemporal evolution and traditional knowledge of *P. odorifer* play a vital role in advancing sustainability efforts, enhancing ecosystem resilience, and fostering sustainable development in communities dependent on this valuable species.

Limitations of the study

This study on *Pandanus odorifer* encounters some limitations. One significant limitation is the phenological observations, which were restricted to a limited geographical area. This restriction potentially overlooks variations in different environmental conditions and regions. Additionally, the sustainability assessments might not fully capture the complex interactions between the species and its ecosystem, especially in the context of climate change and human activities.

Conclusion

The goal of this paper is to explore the drivers of ecosystem services provided by *Pandanus odorifer*. The present communication delves into the diverse importance of *P. odorifer* across various domains, spanning botany, ecology, traditional medicine, perfumery, and economic sustainability. The plant's thriving presence in diverse ecosystems exhibits remarkable adaptability and ecological significance. *P. odorifer* serves multiple crucial roles, from acting as a protective barrier in agricultural bio-fencing to serving as a valuable source of essential oils for the perfumery industry. Its versatility is deeply rooted in human culture and livelihoods, reflecting its profound integration into various aspects of daily life. Moreover, the plant's nutritional value and therapeutic applications underscore its holistic importance to communities across different regions. Its multifaceted contributions underscore its pivotal role in sustaining and enriching human life. However, in some areas, it is found that people are burning the plants, which creates a negative impact on the environment and ecosystem. In this context, raising awareness among people is necessary for the proper maintenance of biodiversity. In conclusion, this study underscores the fundamental role played by *P. odorifer* in numerous aspects of human existence, ranging from its ecological contributions to its cultural and economic significance. By amalgamating traditional knowledge with scientific understanding, we emphasize the imperative of preserving indigenous practices and biodiversity for sustainable development. Moving forward, continued research and conservation efforts are essential to safeguard this invaluable plant species and unlock its full potential for the well-being of present and future generations.

Declarations

List of abbreviations: The article does not contain abbreviations.

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