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REVIEW

Indigenous knowledge in the Kithul (*Caryota urens* L.) industry of Sri Lanka and its scientific basis

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Abstract Exploitation of the kithul palm (*Caryota urens* L. Arecaceae) is an ancient industry in Sri Lanka, yet it is neither commercialized nor cultivated. Naturally established palms in the agroforestry systems or in the wild are used to produce food, beverage, timber, and traditional medicines. As kithul cultivation is not commercialized, the related production systems are not mechanized, products are not standardized, or value added. Each step related to kithul products has specific sets of methods learnt through experience, disseminated from one generation to the next. Diverse kithul products are used in diets, in industry and some of its products are integrated with Ayurvedic medicine. The scientific research findings corroborate some beneficial properties of kithul products such as floral sap, treacle, jaggery, toddy, vinegar and flour, claimed by ayurvedic physicians. Kithul products have many potential uses in the food industry, pharmaceuticals, bioremediation, energy production, and structural engineering. This review compiles the indigenous knowledge system behind the kithul industry in Sri Lanka and the scientific findings justifying the practices in the industry and properties of the products. We highlight the need to scientifically explore certain components in the industry such as the seasoning mixtures used for tapping the sap to develop more effective commercial products, develop innovative tapping and processing technology, and improved cultivars and establishment of plantations. We have also shown the scientific basis of the medicinal value of kithul-based products already used in local Ayurvedic medicine.

Keywords Agroforestry · Ayurveda · Ceylon · Floral sap · Flour · Jaggery · Medicinal uses · Treacle

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An introduction to the genus *Caryota* and the kithul palm (*Caryota urens* L.—Arecaceae)

Taxonomy, distribution and botanical features

Caryota is one of 189 genera in the plant family Arecaceae (Palms) consisting of ~ 2000 species distributed throughout the tropics and subtropics of the world. Arecaceae has six subfamilies and 16 tribes (Hahn 2002), and *Caryota* belongs to the subfamily Coryphoideae in the tribe Caryoteae, distributed in the subhumid and humid tropics from sea level to about 2200 m (Hahn 2002; Hahn and Sytsma 1999). There are three genera in the Tribe Caryoteae: *Arenga*

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with about 29 species (Mogea Johanis 2004), *Wallichia* with eight species (Henderson 2007), and *Caryota*. Species of *Caryota* grow in a wide diversity of habitats including riverbanks, the understorey of lowland forests, montane forests, secondary forests, limestone outcrops, and swamps. Thirteen species have been identified within *Caryota*, distributed in Sri Lanka, India, and southern China southwards throughout South-East Asia to northern Australia and Solomon Islands (Baker et al. 2009; Jeanson et al. 2011). Despite the diversity and wide distribution of *Caryota* spp., only *Caryota urens* L. (kithul) has been exploited for commercial purposes. It is a multipurpose palm found in Sri Lanka, India, Malaysia, Myanmar and Nepal and naturalised in Vietnam, Thailand and Papua New Guinea, with a west to east expansion suggested, based on phylogenetic analysis and geological evidence (Hahn and Sytsma 1999).

Kithul is a pleonanthic palm growing up to 20–25 m height with an unbranched and straight trunk. The fibrous leaf scars are noticeable on the trunk. Phyllotaxy is alternate and leaves or fronds make a crown on the top of the trunk (Fig. 1). About 30–40 graceful curvy leaves are produced in the crown. The mature leaves are about 6 m long, bipinnate, light to dark green with triangular pinnae having serrated margin and pointed tip. The bipinnate leaves, characteristic of the genus (Kubitzki 1998) look like a tail of a fish (Fig. 2), hence the English name of fishtail palm.

Kithul is a monoecious palm and being determinate, flowering occurs from the topmost axil and proceeds downwards, producing pendant unisexual florets in a spadix. The inflorescence is about 3 m long, axillary and branched (Fig. 1). Protandrous florets are borne spirally in triads of 2 male and 1 female flower. The fruit is a globose scarlet-red drupe, about 1 cm in diameter when mature, with a fleshy mesocarp and undifferentiated endocarp and one or two large hemispherical seeds (Kubitzki 1998).

Kithul is the name in Sinhala in Sri Lanka and in Tamil it is called Kundal Panai, Koondalpanai, Thippali, Tippili, and Konda-Panna. In English, it is called toddy palm, fishtail palm, Indian sago palm, sugar palm, wine palm, jaggery palm, and kitul palm. In India, different names are given in different languages; Sopari, Mari, Mada, and Dirgha (Orwa et al. 2009).

Products and uses

The Kithul tree has been used for millennia on the island of Sri Lanka and to a lesser extent in southern India but has still not been exploited to its full potential. It is of considerable economic value in Sri Lanka. It is used for food (pith as a source of starch), beverage, sustainable and healthier sugar alternatives, medicine, fodder, and wood. The sap is tapped from the emerging inflorescence for toddy, treacle and jaggery.

Among palms, *C. urens* and *Corypha utan* produce the highest sap yields among palms, of about 45 L per day (Nguyen et al. 2016). Because of high α-glycosidase inhibition activity, sap of *C. urens* has

Fig. 1 The upper part of kithul (*Caryota urens*) palm showing branched inflorescences (spadix) flowering from top of the tree downwards

Fig. 2 Bipinnate leaf of kithul palm characteristic of the genus *Caryota*

anti-diabetic properties (Ranasinghe et al. 2012a, b; Wimalasiri et al. 2016). A special caste of people who live in two major clusters in the vicinity of rainforests of Sri Lanka were assigned by the kings to tap the sap and make jaggery and treacle for the palace. This tradition continued during the colonial period and currently has become an income-generating venture for people living in the areas where the palm grows. Sri Lanka is the only country that exports considerable amounts of kithul products, particularly jaggery (Fig. 3) and treacle (Fig. 4), popular in Europe, Australia, North America and Asia. Jaggery and treacle are the main export products of kithul from Sri Lanka and their export value amounted to US$ 0.96 million and US$ 0.64 million, respectively, in 2022. Jaggery is becoming popular in Africa also in recent years (Fig. 3).

Kithul treacle is unique in that it is smooth and thick, without the cloying sweetness of sugar, contains many bioactives (polyphenols, amino acids, beta carotene, ascorbic acid etc.) and importantly has a low glycemic index (GI) of 27.84 as reported in a randomised clinical trial (EDB 2022). In the same trial kithul jaggery recorded a GI index of 31.34 and is recommended for diets of diabetic patients as a superior substitute for table sugar (GI = 65) by Sri Lankan

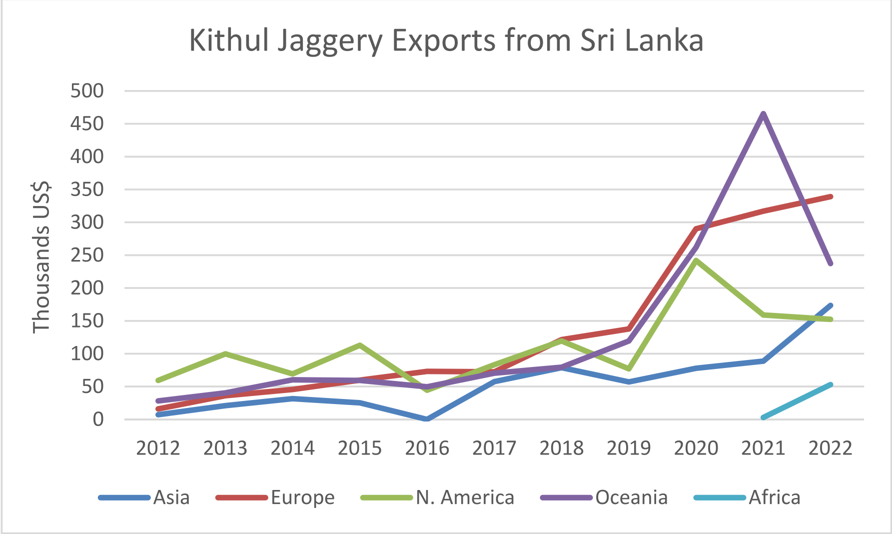

Fig. 3 Value of kithul jaggery exports to major markets from Sri Lanka (data courtesy Customs Department, Colombo, Sri Lanka)

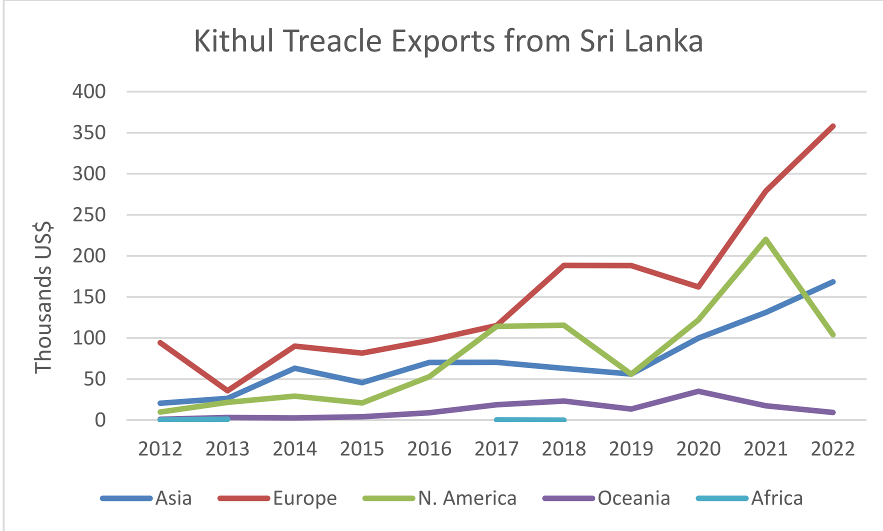

Fig. 4 Value of kithul treacle exports to major markets from Sri Lanka (data courtesy Customs Department, Colombo, Sri Lanka)

physicians and is becoming the 'superfood sweetener' (EDB 2022). Because of the unique taste and health benefits, the demand for kithul treacle and jaggery has steadily increased (EDB 2022). Kithul flour is gluten-free and has unique gelatinisation properties and because of its high digestibility and presence of a high proportion of resistant starch (Gunaratne et al. 2016a, b), it is included in convalescent food formulations; thus it has many health benefits compared to wheat alternatives such as tapioca and is therefore highly valued. There are many uses of kithul palm in local ayurveda medicine, some of the benefits of which have been proven by research (Gunaratne et al. 2016a, b; Wimalasiri et al. 2016EDB 2022).

Kithul production in Sri Lanka is very traditional and shrouded in folklore and relies on the skills passed through many generations. Indigenous cultural practices in the kithul industry are diverse and treacle is the main product. The experience-based cultural practices throughout the production process of treacle and other kithul products are documented in the present article based on interviews with members of established families in the industry in the remote areas where the kithul industry has a long history in Sri Lanka, as well as the authors' own life-time experience of living in the area and interacting with the people involved in the industry. The health benefits and uses of different products are also highlighted.

The main aim of this review on the kithul industry is to comprehensively examine and elucidate products, production process, knowledge utilized in production process and the diverse uses of kithul-derived products, ranging from floral sap and treacle to flour, toddy, vinegar, jaggery, leaf extract, immature fruits, seeds, roots, bark, timber, and their potential applications in the food and beverage industry, medicine, weed control, bioremediation, the construction industry, and as a biofuel.

Scientific methodology

To investigate the traditional knowledge and scientific basis underlying the kithul industry, a multi-faceted methodology was employed, incorporating both qualitative interviews and a literature review of published articles.

Qualitative interviews

The participants were selected purposively—individuals engaged in kithul tapping in Dellawa, Matara District in the Southern Province of Sri Lanka, representing a spectrum of experiences and practices inherited from their ancestors. Prior informed consent was obtained from all participants, ensuring ethical research practices and respect for cultural sensitivity. Face-to-face interviews were conducted to gather detailed information into each step of producing different beverages and foods from kithul, focusing on tapping methods, preparation techniques, and the application of seasoning mixtures.

Literature review

Rigorous searching and retrieval of relevant articles wase done from scientific databases, including PubMed, ScienceDirect, and other reputable platforms. The scientific facts gathered from peer-reviewed articles and scientific publications were related to the information on kithul palm, tapping methodologies, sap extraction, product processing, and the scientific basis of traditional practices.

Systematic review and thematic analysis of literature was done to extract scientific insights, methods, and ingredients associated with kithul industry processes. Cross-validation was done by comparative analysis of traditional knowledge obtained from interviews with scientifically validated information extracted from literature to identify similarities and gaps.

The knowledge synthesis was tried by integrating qualitative information and scientific findings to form a comprehensive understanding of the kithul industry, considering both traditional and evidence-based perspectives. This hybrid methodology, combining qualitative information from direct interviews with traditional practitioners and scientifically validated information from literature, aimed to provide a holistic understanding of the kithul industry, bridging the gap between indigenous knowledge and scientific understanding.

Plant morphology as a selection criterion for tapping

Floral sap collected by tapping the inflorescence is used to produce treacle. Kithul palm takes 10–12 years to reach maturity. Being pleonanthic, kithul palm keeps producing inflorescences once mature. Tappers select the suitable palms for tapping using morphological markers. When the trunk is broader at the apex than at the base, yield potential is considered to be higher in such palms. This shape of palm is called “female type” while a cylindrical trunk that exhibits a similar diameter from top to bottom is called “male type” by the practitioners. According to them, the taller the palm, the greater the potential yield is. The palms in forests are taller since the palms grow in competition with other tree species and hence grow faster to bring the canopy above the other trees. Such palms are delayed in flowering and well-grown at the on-set of flowering. Such well-grown palms at maturity record a greater yield in a tapping cycle. The number of fronds in the tree crown is also considered a morphological marker for yield. The trees with higher frond number are considered high yielding by the practitioners. Further, if the gap between the adjacent fronds is comparatively longer, it’s also a good sign for a profitable tapping. Palms reach maturity faster when they grow in tea and coffee plantations in the humid and sub-humid areas and give a comparatively lower sap yield.

The topmost inflorescence is the first to emerge and is not usually tapped and left for seed production. These seeds are perceived as having the highest germination and seedling vigor although experimental evidence (Wickramasinghe et al 2008) does not support this belief. Nevertheless, this is a nature-friendly self-rule to sustain the plant populations since managed kithul plantations do not exist, and trees from the wild or those occurring naturally in home gardens or plantations of tea, coffee or spices are used for tapping. Unfortunately, the demand for toddy (the alcoholic drink made from kithul sap) from the first inflorescence is high among some villagers, particularly youth. Kithul trees play an important role in the agroforestry system, and smallholder farmers engage in kithul tapping as a secondary source of income. Seed germination takes more than two months and the highest seed germination and survival rates were recorded in dehulled seeds compared to gibberellic acid treatment, or mechanical and chemical (nitric acid) scarification (Wickramasinghe et al. 2008).

The process of tapping kithul inflorescence for sap

Kithul tapping for sap is an intricate process and shrouded in folklore with many rituals performed by the traditional practitioners. After selecting the tree to be tapped, the first step is getting access to the inflorescence, high up in the crown of the palm. “*Hera gehiima*” is preparing a ladder to climb up to the inflorescence. The ladder consists of two long poles that are set vertically, parallel to the trunk of the palm and securing them with vines at a 50–80 cm distance. *Bándura-wel* (*Nepenthes distillatoria*), *Pattikka-wel* (*Artabotrys zeylanicus*), *Korossa-wel* (*Tetracera sarmentosa*) or *Bambara-wel* (*Dalbergia pseudo-sissoo*) are used for binding poles. This set-up is durable for only about 3–6 months and requires repairs or complete replacement as the vines dry-up and start to crack. A single pole wrapped around the trunk is also used (Fig. 5). A kithul palm can produce up to 8–12 inflorescences and most of these are tapped over a period of about 10–15 years. With a determinate growth habit, inflorescences are produced from top axil to bottom, and once the last inflorescence produces its fruit the tree dies. Altogether around 40 fronds could be seen within the crown. After first tapping, fronds turn downward, and those fronds never return to the original upright position. Although the palms in the forests are available for tapping by anyone; with good mutual understanding people in the villages share this resource equitably. There is no way to accelerate flowering in palms. Yet, this is not a constraint since there is an abundance of inflorescences to tap as skilled tappers are in decline. Tapping needs continuous attention to detail, dedication and punctuality through the tapping cycle. This keeps the people, particularly youth away from kithul tapping despite the high demand for kithul products in the local and international markets.

Fig. 5 A kithul tapper ascending the ladder for collecting sap

Preparation of the inflorescence for tapping

The inflorescence of kithul must be prepared for tapping before the protective bract of the inflorescence called the prophyll opens naturally (Fig. 6a). Once an emerging inflorescence is visible, it is initially prepared by 'conditioning' it for tapping at the optimum time. *Aga iriima* (tip-damaging), *Arala demiima* (leaving the inflorescence) and *Mala agayiema* (evaluation) are the three stages in this process.

The best stage of maturity of the inflorescence for tip damaging is when three rings of sepal scars are visible at the base of its peduncle. For this, three oldest sepals are removed at the inflorescence tip and the still intact fourth sepal is slowly patted using fingers to loosen the tightly packed sepals inside the inflorescence. Then, leaving the inflorescence as it is for around ten days is called *Arala demiima*. During this period, the tightly packed and coiled rachillae of the inflorescence further loosen inside the fourth-youngest sepal. At this stage, the inflorescence is slightly shaken by hand, and it is repeated 2–3 times at a 3–4-day interval. At this point, rachillae are packed densely next to the youngest sepal.

At the evaluation (*Mala Agayiema*), a rachilla of the inflorescence is slowly bent and damaged, and the damaged ends carefully taken apart. The optimum maturity for the next stage of preparation is when sticky threads appear on these damaged surfaces, and they adhere to the two surfaces extending threads even up to about one inch (~ 2.5 cm) apart from one another. During the preparation of inflorescence, the fibrous hairs on the peduncle are removed using the blunt side of a knife (Fig. 6b) and the inflorescence is wrapped by a rattan (thin branch of *Calamus* spp.) in two stages: first wrapping from the base of the peduncle or *Ithi-Oluwa* to the distal end of the inflorescence (Fig. 6c) and then from the distal end to *Ithi-Oluwa* (Fig. 6d). Rattan is suitable for this purpose since it is waxy and repels moisture while allowing some degree of aeration. When material such as polythene is used to wrap

Fig. 6 Steps involved in kithul sap collection and treacle production. **a** Spadix at the right stage of maturity for tapping, **b** Removing spadix, **c** Loosing the inflorescence, **d** Leaving inflorescence for ten days (*Arala demiima*), **e** Cut surface of the inflorescence, **f** Removing the pot of sap, **g** Collected sap, **h** Boiling the sap

the inflorescence, it can induce fermentation within the inflorescence under the hot sun. Two wooden poles named *Olombo* are used to stabilise the inflorescence. Inflorescence is somewhat upright at this stage. Using a rope and the *Olombo,* the terminal part is dragged downwards and fixed (Fig. 7).

Application of the seasoning mixture

After preparing the inflorescence, a seasoning mixture must be applied to the peduncle to get a continuous flow of the sap and to increase flow rate of sap. A groove with a depth of ¼" (~6 mm) is made along

Fig. 7 An inflorescence of kithul prepared for tapping. It is dragged downwards and fixed using two poles (*Olombo*) and rope

the dorsal surface of the peduncle and the seasoning pulp is filled in the groove. The inflorescences that are allowed to open naturally are not responsive to the seasoning.

Three types of immature leaves among *Habarala* (*Alocasia mycorrhizas*), *Walla Patta* (*Gyrinops walla), Mandoran* (*Cynometra zeylanica*), *Bándura* (*Nepenthes distillatoria*), and *Kekatiya (Aponogeton crispus)* are used along with a few other ingredients: bird-chili (*Capsicum frutescence)* paste, ginger tubers (*Zingiber officinale)*, garlic cloves (*Allium sativum)*, and pepper powder (*Piper nigrum*). Carbon layers of sediment from wooden poles in the mantel above wooden hearths of traditional firewood-based kitchens are also used in the mixture. These ingredients are partially dried in a pan and ground into a powder. The paste or dough is mixed with a pinch of salt, sieved fly ash, and limestone powder. Before applying the seasoning mixture, sieved ash is applied all over the inflorescence as a disinfectant. Thereafter, the seasoning mixture is filled into the prepared grove of the peduncle in the early morning and is left to dry.

In the evening, the groove with the seasoning mixture is covered with Jackfruit leaves (*Artocarpus heterophyllus*), *Pinna* (*Clerodendrum infortunatum*) or *Keppetiya* (*Croton laccifer*). *Gadimba* (*Trema orientalis*) stem peels are used for wrapping the inflorescence, and *Kollankola* (*Pogostemon heyneanus*) is used for seasoning mixtures for the first three inflorescences. A spathe of areca nut (*Areca catechu*) is placed over the laid leaves on the seasoning mixture in the inflorescence and tightly bound with rattan (*Calamus rotang)*. Coconut (*Cocos nucifera*) fibre ropes are not suitable for this purpose since they are more hygroscopic and increase the chances of microbial growth during the rainy seasons.

Tapping for floral sap, and sap yields

A thin and sharp knife is used for tapping of kithul inflorescence, and that knife is not used for any other purposes. The sharp edge of the knife is used to remove a very thin layer of inflorescence from the distal end at each cutting (Fig. 5e). The economic life of the inflorescence depends on the thickness of the slice removed at each cutting. The thinner the removed part at a time, longer will be the economic life of the inflorescence. It is important to make sure that only the sharp edge of the blade touches the inflorescence and not the blade of the knife.

Two pots are simultaneously prepared for use, one after another for sap collection. Pots are thoroughly washed and dried on the firewood kitchen mantel; the smoke sterilizing the pots. Floral sap can be kept only for 10–12 h without starting to ferment. Fermentation is faster under high temperatures. *Ankenda* (*Acronychia pedunculata*) leaves or stem peels of Hal (*Vateria copallifera*) or *Mandoran* (*Vatica paludosa*) are added to the pot before collecting the sap. This prevents the fermentation of the sap while in the pot. Usually, the tapping is performed two times a day; morning and evening. A third tapping maybe performed around noon. Nevertheless, the pot is changed only in the morning and evening, but not at noon. The palms located in remote areas are tapped only twice a day. Whatever the tapping frequency, a maximum of 25–30 bottles per half-day or 50–60 bottles (~40 L) per day can be collected from an average palm. However, if the sap flow is greater, less the treacle yield is. There is no noteworthy difference in the sap yield between inflorescences of the same tree, but there is a high variation between different trees depending on their location, growth and other morphological characters as already described. The cut edge of the inflorescence and collected sap is shown in Fig. 8.

Fig. 8 Tapped kithul inflorescence cut at the peduncle and collected sap in clay pot

The economic yield of an inflorescence lasts for about three months and depends on the physical length of the inflorescence, which is mostly decided by the genetic factors of the palm. Continued tapping up to the proximal end of the peduncle (*Ithi-Oluwa*) is challenging. If the inflorescence sap flows well, reaching the distal end of the peduncle and rachis, the continuation of tapping along the rest of the inflorescence is naturally promising. The peduncle is harder than the inflorescence with rachis, and the treacle produced by the peduncle sap is tastier, thicker and darker than the treacle produced by tapping the inflorescence at the distal end. The best quality treacle is produced when the peduncle is about two inches (~5 cm) in diameter. Commercially available recommended seasoning mixtures increase the sap flow rate, but the treacle produced from such sap is not rich with sugars and the treacle is not thick. Excessive increase of sap flow rate makes the palm exhausted, reducing the sap yield of successive inflorescences. The ratio between floral sap volume and final treacle yield in the palms treated with commercially available seasoning mixtures is around 20:1, while it is 6:1 in the palms treated with herbal seasoning mixtures produced by the tappers. This calls for research to identify the components in seasoning mixtures that make the treacle yield higher in floral sap of kithul.

If the sap collection is significantly greater in a palm than the average, the flowering of the next inflorescence will be delayed. If an inflorescence fails in tapping, the next floral initiation would be earlier than the palms in which tapping was successful. These phenomena mark the natural balancing of palm productivity.

Quantity and quality determinants of sap and treacle

Location of the palm

Other than proper tapping practices, kithul palm doesn't need much attention or special management practices. Most of the palms grow as orphan plants in other plantations, in abandoned lands or in humid forest. The palms growing in cleared land grow slower, and their sap yield is less than those found in the forests. In general, eight bottles of sap are required to produce one bottle of treacle from the palms growing in tea plantations. Forest palms are comparatively taller, and the treacle yield is higher; four bottles of sap producing one bottle of treacle if the seasoning mixture is made as described. Palms found on or amongst the rocky outcrops yield less sap, and it requires around six bottles of sap to produce one bottle of treacle. No effect of water availability in the land has been evident for palm growth or treacle yield in the wet zone in Sri Lanka. The topography of the land where the palms are found does not affect the sap yield either, and the tappers don't consider it when selecting the palms for tapping.

Other factors influencing sap yield

Delay in preparing the emerged inflorescence for initial tapping reduces the potential sap yield drastically. Use of a blunt knife for tapping can close the sieve tube elements, reducing or blocking the sap flow. Swaying in the wind wrings the trunk of the palm, adversely affecting sap flow. Unlike some palms such as *Butia capitata*, *Phoenix canariensis*, *Phoenix dactylifera* and *Sabal palmetto* that tolerate wind (Duryea and Kampf 2007), the trunk of kithul palm wrings in different directions in wind, adversely affecting sap flow.

Pathogens or insects have not been reported as serious concerns in kithul palm. This could be due to the fact that there are no plantations of kithul, and trees grow far apart in agroforestry systems or in the forests. However, red cardinal beetles (*Pyrochroa serraticornis*) feed on the inflorescence and deposit eggs in the soft areas of the inflorescence. Larvae feed on the inflorescence and proceed to the trunk. At the time tapping is stopped, the remaining peduncle must be covered by polythene to prevent red cardinal beetle attack. If this beetle infects in the middle of the tapping cycle, inserting table salt into the bore is sometimes effective. Kithul seeds are a favourite food of the Asian palm civet (*Paradoxurus hermaphroditus*) that has a habit of licking the cut surface of inflorescence. This can adversely affect the sap flow. Monkeys shake the inflorescence as a habit and it stops the sap flow permanently, the same as by the wind. Elephants are fond of kithul fronds and trunk, but don't eat stems rich in flour. Elephants destroy the palms in the forest at a very young age, foraging on the young fronds and tender stems. According to traditional tappers, during the rainy season, the emergence and growth of roots and the resulting distribution of sap to feed the growing roots reduces the sap flow to the inflorescence. This can result even in complete stoppage of sap flow, particularly in low yielding palms. However, the sap yield is higher immediately after the rainy season than during the dry season. The physiology of sap flow after and before the rainy season has been documented by Wu et al. (2018) in other palm species in China. Sometimes, in the rainy season, the rattan wrapped around the base of the peduncle is removed and the peduncle is heated using a flame produced by a coconut spathe to increase the sap flow rate. After this operation, the inflorescence is wrapped again. This is not practiced in the dry seasons. Lightning strike is an occupational hazard for tappers during the rainy season and has to be avoided.

Kithul floral sap and its use in treacle production

Kithul floral sap (*Thelijja* in Sinhalese) is considered a healthy drink, especially to alleviate malnutrition and traditionally hepatitis. The effect of anti-oxidative compounds in kithul sap could be the reason for it's use in traditional treatment of hepatitis (Azam et al. 2016).

The sap collected early in the tapping cycle usually has a somewhat stringent taste and is unsuitable for treacle production.I It is traditionally retained to ward off the dangers from evil spirits and for blessings. Treacle is made by straining the sap and boiling it slowly in a traditional three stone firewood stove while removing the bubbling supernatant (Fig. 9) which would make treacle astringent if not removed. After volatilization of excess water, the boiling sound, according to villagers, changes to "*Bos-bos*" from "*Churu-churu*" since concentrated treacle traps the air bubbles inside before evaporating and bursting out at the liquid surface. This is the right time to stop boiling and to remove the pot of treacle out of the hearth (Fig. 9a).

To prevent fermentation of treacle, a piece of bark of *Hal* (*Vateria copallifera*) tree is added at the end of the process. A stock of peels of *Hal* is kept in the mantel above the firewood stove, for use in treacle production. *Ankenda* (*Acronychia pedunculata*) leaves prevent sap fermentation, but it is not used in treacle to prevent fermentation. Treacle never gets contaminated with pests or worms if the boiling

Fig. 9 Treacle production using three-stone firewood stove to concentrate kithul sap **a**, and treacle in arecanut (*Areca catechu*) spathe used to package treacle **b**

process has been optimized. Poorly processed treacle can get contaminated and will also ferment quickly. Treacle that is stored for long has sugar crystallizing over the bottom surface of the container, resulting in increased viscosity and deterioration of taste. There are no methods to stop crystallization. In overboiled treacle, crystallization is quicker, even within a few days after treacle production. As these crystals appear as sand they are known as *Weli-hakuru* ("sand jaggery" in translation). It could be mixed with the sap again during a new cycle of treacle production, particularly when the sap is of low quality. According to the tappers' perception, treacle produced by applying commercially available seasoning mixtures have shorter shelf life and the taste is inferior. Good-quality treacle with optimum viscosity and sweetness has an attractive golden colour. Once fermented, treacle can be further boiled to maintain the sweetness, but the original sweet smell will not be retained.

The spathe of arecanut (*Areca catechu*), also called 'betel nut' is the best choice of villagers for packing treacle (Fig. 9b) and this package is usually hung closer to the mantel for long-term storage. However, with the high demand for treacle in the market, the storage requirements are minimal.

Antidiabetic properties of kithul sap and treacle have been attributed to their alpha-glucosidase inhibition activity (Ranasinghe et al. 2012a, b). The major amino acids in treacle are glutamate, serine, asparagine, arginine and aspartate (Somasiri et al. 2010). The flavor enhancer glutamate present in treacle gives it a unique pleasant odor (Somasiri et al. 2012). High concentration of arginine (50 mg/100 g of treacle), considered to be the natural Viagra, could be the reason for folkloric claims of sexual arousal after consumption of kithul products. Additionally, reproduction enhancing amino acids histidine and tyrosine present in kithul products including treacle would enhance this effect. Furthermore, antioxidant properties of both methionine and cysteine and antirheumatic properties of cysteine enrich the medicinal value of treacle (Somasiri et al. 2012). Treacle contains 0.3% protein, 7.9% fat, 80% carbohydrate of which 33% comprise of digestible carbohydrates: glucose, maltose and starch (Gunasekara 2018).

The glycemic index reflects how quickly ingested food causes blood sugar increment. It is a rating system from 0 to 100, and the higher the rate the faster it increases blood sugar.

Glycemic index (GI) can be converted to glycemic load by multiplying GI value and dietary carbohydrate content per serving. Glycemic load is associated with non-communicable diseases namely type 2 diabetes, cancers, and cardiovascular diseases (Foster-Powell et al. 2002). The preferable level of glycemic load for human health is between 10 and 20 per serving (Foster-Powell, et al. 2002). Treacle is reported to have a lower glycemic index (35) and a medium glycemic load (18) (Gunasekara 2018), while the glycemic index for rice is 69 (Venn, and Green 2007) and that for bread is 100 (Capriles and Arêas 2013). The peak reduction of blood glucose in treacle was just 16% compared to that of table sugar (Gunasekara 2018).

Hydroxylmethylfurfural is a toxic compound found in bee honey produced as a result of breakdown of fructose in the presence of acid, but it has not been found in treacle (Ranaweera 2015).

Kithul flour

Kithul flour production and its health benefits

Kithul flour is extracted from the crown of the stem pith. Palms that are used for tapping and juvenile palms are not used for flour production, since the pith is not rich in sugars. Only the palms that have started flowering and attained maturity are suitable for this purpose. By making a deep cut at the base of the trunk with an axe and observing the dried blade for powdery appearance is a simple test to ensure that the palm is suitable for flour extraction.

The process of flour extraction is manual and is very simple. The pith is cut into smaller pieces and crushed in a mortar. The pulp obtained after crushing is mixed with water, and the debris, especially the woody parts, are removed. The mixture is allowed to settle, and the upper layer of clear water is carefully removed, retaining the sediment. Finally, the sediment is strained using a muslin cloth.

Kithul flour porridge (*kithul kenda*) is a valuable food for convalescing patients. Additionally, it is prescribed by Ayurveda physicians to treat general weakness, hypertension, gastric ulcer, migraine and headaches, rheumatism, and snake and insect bite poisoning (Kuhanneya et al. 2016; Mariyan and Ajay 2012). The scientific basis of the effectiveness in these treatments is based on the scavenging activity induced by free radicals, ion chelating capacity, and electron donating capacity in kithul flour (Ranasinghe et al. 2012a, b; Wimalasiri et al. 2016). Antioxidant properties and Oxygen Radical Absorbance Capacity (ORAC) value of boiled kithul flour were greater than those of powdered kithul flour supporting potent medicinal claims (Wimalasiri et al. 2016). Rheumatoid arthritis is an inflammatory and autoimmune disease caused by reactive oxygen species (Hirao, et al. 2012). Rutin is one of the polyphenolic compounds found in kithul extract that exhibits different pharmacological functions, including anti-oxidative, neuroprotective, anti-diabetic, anti-inflammatory, antiadipogenic, and hormone therapeutic functions (Selloum et al. 2003). Polyphenols, umbelliferone and rutin present as phytochemicals in kithul flour inhibit rheumatoid arthritis by blocking TNF-alpha, and the presence of these antioxidants and their inhibitory activities have been demonstrated by molecular docking of phytophenols in kithul flour (Sujitha and Kripa 2020). Polyphenol and flavonoid contents in kithul flour increase at the boiling temperature compared to the powdered form by around four-fold (Wimalasiri et al. 2016). The texture, color, rheology, and interfacial flocculation of kithul flour significantly change at the gelatinization temperature (73–81 °C). Gelatinization temperature of kithul flour is very narrow compared to that of wheat (62–88 °C) (Ranaweera and Gunatilake 2022). These properties can be altered by mixing kithul flour with other food ingredients according to consumer preference. According to Wijesinghe et al. (2015), kithul flour is relatively high in calcium (70.1 mg/100 g), potassium (59.5 mg/100 g), magnesium (66.6 mg/100 g) and iron (14.0 mg/100 g). According to them, out of 66.82% of total starch in kithul flour, 28.4% is amylose and 71.3% is amylopectin. Kithul flour is very low in proteins and lipids and 42.5% of its starch is resistant starch (RS) (Gunaratne, et al. 2016a, b). The RS content of kithul flour is around 66% of its total starch according to Sudheesh et al. (2019) and it could be further increased by physical and chemical modifications under *in-vitro* conditions.

Antimicrobial and antioxidant properties in bioactive ingredients of kithul have been reported by Ananth et al. (2013). Antioxidant and polyphenolic contents of kithul flour vary with the extraction and production protocols (Kuhanneya et al. 2016). Antioxidant properties of kithul flour associated with health care in traditional medicine for diabetes have been proven in an *in-vitro* assay (Wimalasiri et al. 2016).

Kithul starch in the food industry and in biopolymers

A cinnamon flavoured instant porridge powder has been developed using enzyme hydrolysed kithul flour having low gelatinisation and viscosity properties

(Kuhanneya et al. 2016). This porridge is superior to traditional porridges due to sweetness without added sugar and enhanced bioactive properties and is less viscous. Vindika and Wijesekara (2021) found that incorporating kithul flour to hulled mungbean flour resulted in products with better organoleptic properties than mungbean flour alone, and food gels developed by mixing these two ingredients can be a potential functional food. Wijesinghe et al. (2020) used modified kithul flour as a stabiliser for ice cream, and in sensory research it was proven to be better than commercial ice cream. Its value as a stabiliser was further confirmed in the successful development of drinking yoghurt (Wijesinghe et al. 2018).

With more people looking for vegetarian food, modified kithul flour can be of immense value as the product is even cheaper to produce. Similarly, incorporation of 75% kithul flour in rice crackers significantly increased α-amylase inhibition percentage demonstrating health benefits in this gluten-free food (Ranaweera and Gunatilake 2022). Reduction of the gel formation ability of kithul flour has been achieved by gamma irradiation (Sudheesh, et al. 2019). Kithul flour has been integrated into biscuit production with high consumer preference and health benefits (Ranaweera and Gunathilake 2022).

In addition to various food uses, kithul flour has been successfully incorporated into low density polyethylene and the product was found to be readily biodegradable through soil burial research (Samarasekara et al. 2012). Kithul starch has high crystallinity and surface homogeneity properties that can be converted to a better mechanical barrier by treating with γ—irradiation (Sudheesh et al. 2021). These properties of kithul flour make it a good wrapping product for the food industry (Wijesinghe et al. 2015).

Kithul toddy

If the treacle yield is less in the sap collected from a given palm, such type of sap tends to ferment quickly. Toddy is an alcoholic drink produced by fermenting the sap of palms in Sri Lanka. It is produced in large quantities from coconut (*Cocos nucifera*), palmyra palm (*Borassus flabellifer*) and kithul palm. *Salfi-Rasa* is a traditional drink made from floral sap of kithul in the Bastar region of Chhattisgarh State in Central India (Kumar et al. 2012). Usually, the palms that give 2–3 bottles of relatively low floral sap yield for a tapping time are used for toddy production. A spoon of already prepared toddy is used to inoculate the fresh floral sap for toddy production. Initial inoculum (*Mandi*) can also be prepared using floral sap as the initial material. For this, some rice grains are ground and added to the pot prepared for sap collection with a few slices of *Habarala* (*Alocasia mycorrhizas*) stalks and a few pieces of kithul palm leaves. The pot is set to the tapping inflorescence and each time the inflorescence is tapped, the supernatant of the sap is thrown away. This must be repeated for three days and finally, a good quality inoculum can be collected from the bottom of the pot.

At the initial stage of toddy production, *Lactobacilli* and *Leuconostoc* bacteria and yeast strains, *Candida tropicalis* and *Pichia membranifaciens* are prominent in the collected floral sap. *Saccharomyces cerevisiae* concentration increases with time reducing pH from 7 down to 4 (Jayathilake and Wijeyaratne 1999). *Leuconostoc* and *Hanseniaspora* have been identified as the most abundant bacteria and yeast genera, respectively in the early stage of toddy fermentation. The *Saccharomyces* population increased one day after inoculation. Additionally, fungal genera, *Torulaspora, Lachancea* and *Starmerella* can be found throughout the fermentation process at different concentrations (Das and Tamang 2021).

Two yeast strains of *Candida tropicalis* found in kithul toddy have the potential for use in cell-based protein production (Wijeyaratne and Jayathilake 2000). The major sugar in unfermented floral sap is sucrose, and glucose and fructose are traceable. Toddy contains cysteic acid, thiamin and riboflavin.

Toddy is ready for consumption 12 h after floral sap inoculation. Extra inoculum must be removed to stop further fermentation of toddy. *Kudametta* (*Fimbristylis dichotoma*) leaves stop toddy fermentation even in the presence of sufficient inoculum. Antimicrobial activity of *kudametta* is due to the presence of terpenoids, flavonoids and phenolic compounds and is also a good insecticide (Abdullah et al. 2021).

According to the traditional tappers, toddy is a potential allergen, and therefore shouldn't be consumed continuously. However, other than a report about occupational contact dermatitis occurring in toddy tappers (Srinivas et al. 1987), allergic problems of toddy consumption have not been reported. The positive effect in memory enhancement by hydroalcoholic extract of kithul has been demonstrated in an

Alzheimer's model study using mice (Muralidharan et al. 2019).

Vinegar

Over fermentation of toddy produces vinegar. The term "*Vini Aigre*" means "Sour wine" which implies the production of vinegar originated from over fermentation of alcohol (Jayathissa 1983). Traditional vinegar production is a simple process where bird chilli and pepper are added to toddy and left for some time for vinegar production. Fully fermented vinegar is used as inoculum for the production of new batches of vinegar from toddy. Vinegar production is not done in a commercial scale in the kithul industry. Ethanol is used for commercial vinegar production by bacterial oxidation under aerobic conditions to yield 4–5% of acetic acid.

Jaggery

Jaggery is produced by further evaporation of treacle. Condensed treacle is poured into cleaned coconut shells. After leaving for drying, the jaggery is separated from the coconut shell and wrapped in a piece of dried banana leaf (Fig. 10). As a norm, jaggery is not produced from treacle produced at the initial stage of tapping. The jaggery production starts in the middle of the tapping cycle if only the tapping is well established. The best quality jaggery should dissolve amidst the fingers due to body temperature. Alpha amylase and alpha-glucosidase enzyme inhibitors, which help control blood sugar levels in individuals with diabetes, are present in jaggery (Gunasekara 2018).

Fig. 10 Jaggary is produced by further drying of kithul treacle in coconut shells. Usually, two blocks are wrapped in dried banana leaves as the final product

Leaf extract

Crude ethanol extract of kithul leaves contains a considerable amount of natural antioxidants to treat diseases caused by free radical oxidative stress (Uddin et al. 2016). The presence of phytosterols, flavonoids, tannins, carbohydrates, and phenolic compounds in leaf extracts of kithul has been reported by Patel et al. (2015). These compounds have analgesic and anti-inflammatory activities (Patel and Saluja 2012). Antioxidant properties, and antimicrobial activity on the bacterial strains of *Bacillus subtilis, Staphylococcus aureus, Escherichia coli* and *Pseudomonas aeruginosa*, antifungal activity on fungal species of *Rhizopus sp., Aspergillus niger, Penicillium sp*. and *Fusarium,* and larvicidal activities on *Aedes aegypti* mosquito larvae of leaf extract of kithul have been demonstrated in *in-vitro* culture (Vanaja and Kavitha 2017). Anti-inflammatory activity of kithul leaf extract has also been demonstrated by the inhibition of protein denaturation method (Vanaja and Kavitha 2017). Haematological, biochemical and histopathological tests proved the nontoxic properties of hydroalcohol extract of kithul leaves (Balaji and Ganesan 2020). Further, rutin and umbelliferone from kithul leaf extract exhibited remarkable inhibition of nitrous oxide, a common product in inflammatory diseases (Balaji and Ganesan 2021). Kithul leaf metabolites have chemopreventive drug properties due to its ability to induce phase II cytoprotective enzyme NAD(P)H:quinone oxidoreductase 1 (NQO1) (El-Akad et al. 2021). Kithul immature leaf extract has shown antibacterial properties against several bacterial strains (De Zoysa et al. 2022).

In addition to its medicinal properties, the leaf extract of kithul has performed well in corrosion inhibition of metals (Saratha 2018). Kithul leaf plays a role in the dietary diversity of elephants in Sri Lanka, both wild and in captivity.

Properties of immature kithul fruits

Kithul extracts prepared from immature fruits have shown potential antibacterial activity against bacterial strains *Staphylococcus aureus* (ATCC 25923), *Streptococcus pyogenes* (clinical isolate), *E. coli* (ATCC 25922), and *Pseudomonas aeruginosa* (ATCC 10662) (De Zoysa et al. 2022). Kithul fruit metabolites have shown chemopreventive drug properties (El-Akad, et al. 2021).

Potential uses of kithul seeds in medicine, weed control, bioremediation of contaminated soils and as a biofuel

A significant antiangiogenic effect of kithul seed extract has been shown in the Zebra fish model (Bafna et al. 2015). The extract from kithul seed and seed pericarp inhibited the germination of three important weed species in rice, *Echinochloa crus-galli*, *Ischaemum rugosum* and *Ipomoea aquatica* demonstrating its potential use as a bioweedicide (Fonseka et al. 2017).

The hepatoprotective effect of extracts prepared from kithul flowers that contained flavonoids, tannins, triterpenoids and phenolics has been described by Dhanya (2020). In addition to these compounds, Charles et al. (2011) have demonstrated the presence of saponins and serpentine in floral tissues of kithul as well as the relatively high content of iron, zinc, manganese, potassium, calcium and magnesium. Kithul inflorescence waste biomass is a potential biosorbent for bioremediation of hexavalent chromium contaminated media (Rangabhashiyam and Selvaraju 2015). GC–MS ethyl acetate extract of kithul inflorescence yielded twenty-six different compounds (Nancy et al. 2021) and their functions are yet to be revealed.

The effluent waste samples discharged by various industries have been bioremediated by removing Pb II ions using nitric acid-activated carbon extracted from kithul seeds (Ravulapalli and Kunta 2018). Kithul seeds inherit a high adsorption capacity and it can be significantly increased by alkali treatment with 0.1 M NaOH to bioremediate Cu(II) contaminated aqueous solutions successfully (Rao and Khatoon 2016). The authors showed that the alkali-treated kithul seeds can be effectively regenerated for reuse up to three times using 0.1 N HCl. Ultrasonic-assisted kithul seeds also performed well as an absorbent of Cu(II) (Saravanan et al. 2016). The authors showed that the removal of Cu(II) ions onto the seeds is exothermic and has an impulsive nature of absorption. Kithul seeds are also used as a biosorbent of Cr(VI) for the bioremediation of contaminated solutions (Suganya et al. 2016). Furthermore, kithul seeds have been successfully utilized to bioremediate Zn(II) contaminated in a batch adsorption test (Saravanan et al. 2018). These results show that waste kithul seeds are an exceptional source for bioremediation and is currently underutilized.

Each inflorescence of kithul produces hundreds or even thousands of seeds that are available in abundance. Products of pyrolysis of the dried seed of kithul has high energy and therefore it is a good biofuel (Kothandaraman and Somasundaram 2021). The bio-diesel production was 82% in seed extract of kithul after KOH catalyst treatment (Srinivasan et al. 2018). Thus, in addition to its role in agroforestry systems and sustainable food production, kithul palm also has potential to contribute to reducing fossil fuel use.

Kithul roots and bark

Roots, bark, and the bud of kithul palm have also been used to treat rheumatic swellings, *hemicrania continua*, tooth ailments and snake bites in traditional medicine (Srivastav et al. 2015).

Kithul timber

The mature trunk has a timber value as the wood is strong after completion of flowering. Timber from the base of stem, up to about three meters is used as hardwood for producing mortar and pestles, strengthening the wooden structure of clay walls, preparing handrails for staircases, manufacturing rollers for tea factories, constructing doors and door frames, traditional carvings and producing traditional drums. Nowadays, wood is integrated with many other structural materials to produce new products with different properties for diverse utilities.

A low-cost material with epoxy bio-composites was made using kithul fibre and coconut husk biochar particles exhibiting high toughness (Jayabalakrishnan et al. 2021; Prabhu et al. 2022). The physical properties of kithul wood are ideal for the production of brake pads with physical properties similar to metal (Krishnan et al. 2019). Reinforced kithul fibre could be used in automobiles, and domestic appliances as well as in defense products (Arun Prakash et al. 2020). The microwave shielding materials have been produced by a combination of kithul wood with zinc and silver nanoparticles and cobalt nanowire (Merizgui et al. 2021).

A hybrid form of glass-*Caryota urens* product in epoxy resin matrix was found to improve the end product's toughness and hydrophobicity, reducing water absorption (Raju et al. 2021). Spadix fibres are used after reinforcement for automotive and structural applications (Yamuna et al. 2019). A new type of polyester composites reinforced with kithul fibres have been produced to bear the highest load and withstand bending ability (Shetty et al. 2018). In addition to improved strength and other qualities, these products are more environmentally friendly than the original petroleum-based products.

Insecticidal properties

Silver nanoparticles synthesized from kithul have shown higher mortality rates in larvae of dengue causing mosquito vector, *Aedes egypt* (Al Aboody 2020).

Knowledge gap and future research needs

The kithul industry, with its unique products derived from the sap of kithul palm trees, faces several challenges that hinder its growth and sustainability. The industry lacks innovative sap extraction methods and advanced processing techniques for maintaining product quality. Consequently, global market trends and opportunities for kithul products need further analysis. Additionally, quality standards and certifications (e.g., organic, fair trade) are yet to be established. Moreover, the entire value chain, from cultivation to processing, requires optimization for increased efficiency. Simultaneously, the impact of climate change on kithul palm trees needs comprehensive research. Furthermore, exploring modern technologies, such as IoT and precision agriculture, can enhance farm management. Consequently, the implementation of technology for data-driven decision-making is essential in various stages of the kithul production process.

Conclusion

Kithul is a major constituent in agroforestry in Sri Lanka. Floral sap, treacle, flour, jaggery, and vinegar are the main kithul products processed with indigenous knowledge. So far, the function of components used in the seasoning mixture prepared for kithul tapping have not been scientifically investigated. On the other hand, research confirmed the medicinal properties of kithul products used in traditional ayurveda medicine. These include low glycemic index, moderate glycemic load, antioxidant, anti-inflammatory, antibacterial, antiviral, anti-angiogenic, and memory enhancing ability. The physical properties of kithul starch make it ideal for production of food wrappers. Kithul leaves, seed pericarp, whole seed, fruits, flowers, floral peduncle and leaves are also used traditionally but there are other untapped commercial uses for these parts of the palm. Kithul seeds can be used for industrial purposes such as production of insecticides and weedicides, for bioremediation of Pb(II), Cu(II), Cr(VI) and Zn(II) and as a biofuel. The seed extract is antiangiogenic. Kithul leaf is a source of natural antioxidants and leaf extract demonstrated antioxidative, antibacterial, antifungal, anti-inflammatory, larvicidal, and analgesic properties. Kithul flowers are used as a hair growth promoter and showed hepatoprotective properties. Kithul inflorescence with the peduncle is a good bio sorbent to remediate Cr(VI) contaminated wastes. Kithul wood is reinforced with many compatible materials for different applications in structural engineering. Still, there are many areas in the kithul industry which need scientific interventions and commercialization after consumer preferred value addition.

Kithul is a significant component in agroforestry in Sri Lanka, contributing to various products processed with indigenous knowledge. Despite its diverse uses, certain aspects remain scientifically unexplored, such as the components in the seasoning mixture for kithul tapping. Conversely, scientific research validated the medicinal properties of kithul products, aligning with traditional Ayurveda medicine. The untapped commercial potential of various parts of the kithul palm, such as seeds for industrial purposes and leaves for antioxidative and medicinal properties, opens avenues for further exploration. While current applications, such as Kithul wood in structural engineering, showcase versatility, there is a pressing need for scientific interventions and consumer-driven value addition in the kithul industry. Bridging indigenous knowledge with scientific findings offers an opportunity for sustainable exploitation, including the identification of components in seasoning mixtures to enhance the floral sap yield in kithul. Considering this, a final call for collaborative research between traditional wisdom and scientific advancements emerges, emphasizing the imperative for a holistic approach to ensure the continued prosperity of the kithul industry in Sri Lanka.

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Declarations

Competing interests The authors declare no competing interests.

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