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SAP FROM VARIOUS PALMS AS A RENEWABLE ENERGY SOURCE FOR BIOETHANOL PRODUCTION

Article Highlights

- Review with focus on an evaluation of various palm saps for bioethanol production
- Origin of sugar-rich palm saps and their chemical composition are reported
- Non-destructive tapping is the most sustainable method to collect sap from palms
- Ethanol production via acetic acid fermentation could improve carbon efficiency
- More sustainable bioethanol production from palm sap than from traditional crops

Abstract

Sap is a watery fluid that transports plant photosynthetic products towards various tissues to support growth. Tapping palms for their sap is reported to have originated from India approximately 4,000 years ago. Palm sap is rich in sugars with some inorganics and nutrients, which are attractive components for bioethanol production. Based on advances and current knowledge on the availability, collection, yield, and exploitation of various palm saps, this article evaluates their potential and sustainability as feedstocks for bioethanol production.

Keywords: palm sap, tapping, sugar, fermentation, bioethanol, sustainable.

Rapid depletions in and increasing prices of fossil fuels to meet continuously rising demands are of global concern [1]. Petroleum-based fuels lead to environmental pollution, which results in global warming, health hazards, and ecological imbalances [2]. The shift towards sustainable and environmentally-friendly energy sources has generated significant interest in developing biofuel production from plant biomass [3].

Bioethanol is one of the main commercial biofuels and is used as an attractive petrol substitute. It can be obtained from the conversion of natural biomass that contains sugars or starch via biological processes [1]. A recent report indicates that the total global bioethanol production in 2014 reached 93 billion liters with main contributions from corn ethanol in the USA (58%) and sugarcane ethanol in Brazil (25%) [4].

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Arable land areas for crops such as corn and sugarcane are limited. Agricultural expansion can result in deforestation, which is one of the main factors causing climate change [2]. Planting, maintaining, replanting, and growing such crops for ethanol production require various fossil energy inputs such as fertilizers, herbicides, insecticides, machinery, irrigation, and electricity, which can cause social and environmental impacts [5,6]. The use of available plants that do not require extensive maintenance and much fertilizer will be more appropriate for future bioethanol production. One such industrial plant is palm. It can grow abundantly with little care and can provide sugary sap as a feedstock for bioethanol production [7].

Palms are monocotyledonous angiosperms that belong to the Arecaceae family (also known as Palmae). They include six subfamilies, approximately 200 genera, and around 2,500-2,700 recognized species [8,9]. Geographically, most are native to tropical and subtropical regions from 44° north to 44° south [8]. Dowe (cited in [8]) indicated that palms prefer tropical regions (between 23.5° north and south) whereas only ~130 species grow naturally beyond this zone. Asia and the Pacific Islands show the highest palm biodiversity with approximately 1,385 species, followed by North and South America with ~1,147 species (Moore, 1973 cited in [9]), Madagascar with ~167 species, and mainland Africa with ~50 species (Dransfield and Beentje, 1995 cited in [8]). Even though palms have a low biodiversity in mainland Africa, they are spread widely throughout the continent [8].

Palm is an agro-industrial crop; oil is extracted from its seeds, mature leaves are used as thatching and building materials, young leaves are used as cigarette wrappers, young fruits are used as food, buds are used as an aromatic tea, leaflet midribs are used as broom material, stems are used for firewood, and roots are used medicinally [7,10-12]. However, little attention has been given to the sap that can be extracted from palms.

Palm sap is a sugar-rich exudate that can be obtained from wounding growing parts of a palm [13]. As reviewed by Francisco-Ortega and Zona [14], ~40 global palm species are used commonly to produce sap by local people. Coconut palm (*Cocos nucifera*), palmyra palm (*Borassus flabellifer*), sugar palm (*Arenga pinnata*), nipa palm (*Nypa fruticans*), kitul palm *(Caryota urens)*, oil palm *(Elaeis guineensis),* date palm (*Phoenix dactylifera*), wild date palm (*Phoenix sylvestris*), and raffia palms (*Raphia* spp.) were reported as major sugar-yielding palms in Asia and Africa [15]. Limited harvesting of these palms occurs for domestic utilization as a fresh beverage; in animal feed; and/or for the production of brown sugar, alcoholic beverages, and vinegar [5,14].

These saps contain a high amount of free sugars such as sucrose, glucose, and fructose that can be fermented to bioethanol much more easily than starchy or lignocellulosic materials [3]. Therefore, this review aims to evaluate the potential for use of sap from various palms for bioethanol production.

ORIGIN AND TRANSPORTATION OF SAP INSIDE PALM

Origin of sugary sap in palm

Many palm species (e.g., *Arenga* spp., *Caryota* spp., *Corypha* spp., and *Metroxylon* spp.) preserve their photosynthetic products from leaves as starch inside their stems [16]. During flowering and fruiting, starch is converted into sugars and enters the nutrient flow to be transported toward the growing parts of the plants [13]. The liquid that contains the nutrients and sugars constitutes the sap. Photosynthesis, starch hydrolysis, and sap flow require water that may be taken up from the environment through the roots of standing palms or from the tissues of felled palms [17].

In contrast, palm species such as *C. nucifera* and *N. fruticans* contain little starch in their stems [15,18]. To explain the sugar source in this case, Van Die and Tammes [13] proposed that soluble sugars from photosynthesis in the leaves are transported as the mobile phase of the sieve tube system throughout vegetative parts of the palms before they are used directly to form fruits or sap without starch accumulation. Ranasinghe *et al.* [19] found that soluble sugars are available in leaf and trunk tissues in sap- and nut-producing coconut palms (*C. nucifera*). Sugary sap appears to be the major reserve in this palm rather than starch.

Sap transportation in palm

Figures 1a and 1b compare the anatomy of a typical tree trunk and an oil palm trunk. Palms are monocotyledonous angiosperms and their anatomy differs from softwood and hardwood [21]. As shown in Figure 1a, a typical tree has concentric vascular tissues: xylem includes sapwood and heartwood parts, whereas phloem is only a narrow layer separated from xylem by a vascular cambium. In contrast, as

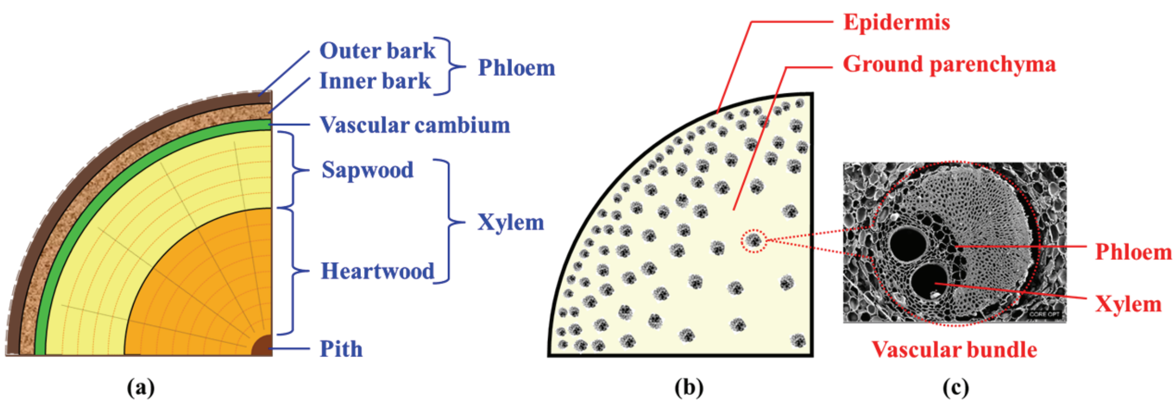

Figure 1. Structure of a) cross section of a typical tree trunk compared with b) cross section of an oil palm trunk and c) its vascular bundle [20].

shown in Figures 1b and 1c, xylem and phloem in palms are not concentric but are dispersed inside numerous vascular bundles. These vascular bundles are embedded in ground parenchyma, which is a storage tissue where starch, a sap source, can be detected [20].

According to Berg [21], water and dissolved minerals flow in xylem, whereas phloem is used to transport aqueous solutions of sugars and other nutrients either from the leaves to the consumption and storage sites or from the storage to the growing sites. Consequently, sap flow, which originates from leaves and/or storage sites, may be transported in the phloem to growing sites during flowering and fruiting.

An early study by Molisch (cited in [17]) found many plugged xylem vessels in the inflorescence stalk. This indicates that xylem vessels are unable to transport bleeding sap. Later reports proved that sap is released from phloem only in a sieve tube system [13].

The sap of deciduous trees such as the maple tree (*Acer* spp.) can be tapped in early spring and has a lower sugar content (3-5%) compared with palm sap (10-20%) [13,15]. In contrast with palm, the sap in maple trees flows in the xylem. According to Essiamah and Eschrich (cited in [22]), starch accumulates in xylem parenchyma cells by late October. During the winter and early spring, this reserve is converted into dissolved sucrose, which is believed to protect the trees from frost damage. Consequently, xylem sap in maple trees can be exuded by drilling holes into the trunk. Because of differences in structure and sap transportation, palm sap tapping is very different.

METHODS FOR TAPPING PALM SAP

Tapping is a technique that is used to collect sap from palms. According to Johnson [9], tapping has a long history and is a pantropical activity. This practice is believed to have originated roughly 4,000 years ago in India (Ferguson, cited in [15]). Nowadays, sap extraction is very common and is technically advanced in Asia and the Pacific Islands. In Africa, simpler tapping practices are used on *E. guineensis*, *Hyphaene* spp., *Phoenix reclinata* and *Raphia* spp. to produce alcoholic beverages [14,15]. In contrast, it is an uncommon activity in Latin America [45].

Table 1 shows tapping methods for various palms. Palm species are tapped distinctively in different countries. In general, tapping methods are classified as destructive or non-destructive [14]. Destructive tapping triggers the death of the tapped palm, whereas the palm can survive when non-destructive tapping methods are used. Depending on the type of palm and the common local practice, tapping can be applied to various parts of the palm, such as the stem, the stalk or the inflorescence (a spadix surrounded by a spathe) [14,35,48].

Table 1. Distribution and tapping characteristics of various palms

Scientific name	Common name	Distribution	Tapped part	Tapping method	Tapping period[a] day	Age of first tapping yr	Years of tapping yr	Sap yield L per palm per day	Ref.
Acrocomia aculeata	Macaw palm Coyol palm	Tropical regions of the Americas (*e.g.*, Mexico, Caribbean countries, Paraguay, Argentina)	Terminal bud	Destructive	25	10-14	-	2	[23,24]
Arenga pinnata	Sugar palm	Humid areas of tropical South and Southeast Asia (*e.g.*, India, Sri Lanka, Guam, Papua New Guinea, Indonesia, Thailand, Vietnam)	Stalk	Non-destructive	30-60 (max. ~365)	5-12	2-5	12-15 (max. 33)	[11,25]
Arenga wightii	Wight's sago palm	India	Inflorescence (spadix)	Non-destructive	> 20	-	-	2	[8,26]
Attalea butyracea	Yagua palm	Dry to slightly humid lowlands of American (*e.g.*, Columbia)	Crown meristem of felled palm	Destructive	20-30	15-25	-	1-3.7	[27]
Borassus aethiopum	African fan palm	Tropical zone from West Africa through India and Southeast Asia to New Guinea and Australia	Palm heart (apical meristem)	Destructive	35-45	35	-	10	[28]
Borassus akeassii	-	Sub-Saharan Africa (*e.g.*, Senegal, Mali, Ivory Coast, Niger and Burkina Faso)	Stem below terminal bud	Non-destructive	Year-round	-	-	0.5-10 1.8-4.1	[29] [30]

Table 1. Continued

Scientific name	Common name	Distribution	Tapped part	Tapping method	Tapping period[a] day	Age of first tapping yr	Years of tapping yr	Sap yield L per palm per day	Ref.
Borassus flabellifer	Palmyra palm Lontar palm	Tropical countries in Asia (*e.g.*, Nepal, Sri Lanka, India, Malaysia, Indonesia, Phillipines, Vietnam)	Inflorescence (spadix)	Non-destructive	90-180	20-30	30	6-10	[15,31, 32]
Caryota mitis	Clustering fishtail palm	India, Brunei, Malaysia, Myanmar; Indonesia, Thailand, Vietnam	Inflorescence	Non-destructive	-	-	-	-	[8,9]
Caryota urens	Kitul palm	Humid areas of South Asia (*e.g.*, India, Sri Lanka, Malaysia, Indonesia, Philippines)	Stalk (peduncle)	Non-destructive	60-90	10-20	3-5	45	[33,34]
Cocos nucifera	Coconut palm	Common to tropical lands	Inflorescence (spadix)	Non-destructive	40-45	7	20	1.7-4.3	[15,35-37]
Corypha umbraculifera	Talipot palm	Tropical rainforest of South and Southeast Asia (*e.g.*, Sri Lanka, India, Myanmar, Thailand, Cambodia)	Inflorescence	Non-destructive	90-120	30-70	-	20	[8,38]
Corypha utan	Buri palm	Wide distribution in dry and open areas of Asia (*e.g.*, India, Srilanka, Bangladesh, Malaysia, Indonesia, Philippines, Australia)	Inflorescence	Non-destructive	132	30-70	-	Max. 45	[8,16, 17,38]
Elaeis guineensis	Oil palm	Tropical rain forest regions of Africa, Southeast Asia, South and Central America (*e.g.*, Nigeria, Ivory Coast, Cameroon, Madagascar, Angola, Malaysia, Indonesia, Colombia)	Terminal bud	Destructive	14-120	> 10	-	4	[17,39]
			Felled trunk	Destructive	-	25-30	-	-	[12,40]
			Inflorescence (spadix)	Non-destructive	-	6-10	10-15	5	[14,15, 17,41]
Hyphaene coriacea	Lala palm	Arid parts of Africa (*e.g.*, Madagascar, South Africa)	Terminal bud	Destructive	-	-	-	-	[14,15, 42]
Hyphaene petersiana	Real fan palm Ivory palm	Subtropical, low-lying regions of South Central Africa	Terminal bud	Destructive	35-60	-	-	1	[43]
Hyphaene thebaica	Doum palm	Egypt and other dry regions	Apical meristem	Destructive	14-25	-	-	Up to 4	[15]
Jubaea chilensis	Chilean palm	South America (*e.g.*, Chile)	Apical meristem of uprooted palm	Destructive	42-56	5-15	-	8	[15,44]
			Apical meristem	Non-destructive	-	-	-	-	[44,45]
Mauritia flexuosa	Buriti palm	Near swamps and other wet areas in tropical South America (*e.g.*, Trinidad, Colombia, Venezuela, Guyana, Suriname, French Guinea, Brazil, Ecuador, Peru, Bolivia)	Terminal bud	Destructive	-	-	-	-	[14,15]
			Inflorescence	Non-destructive	-	-	-	-	[15]
Metroxylon sagu	Sago palm	Humid tropical lowlands, up to an altitude of 700 m (*e.g.*, Papua New Guinea, Melanesia, Indonesia, Malaysia, Thailand)	Stalk	Non-destructive	> 75	9-12	-	2-10	[16,46]

Table 1. Continued

Scientific name	Common name	Distribution	Tapped part	Tapping method	Tapping period[a] day	Age of first tapping yr	Years of tapping yr	Sap yield L per palm per day	Ref.
Nypa fruticans	Nipa palm	Soft mud and slow-moving tidal areas such as coastlines, estuaries, mangrove forests (*e.g.*, India, Sri Lanka, Bangladesh, Burma, Thailand, Cambodia, Malaysia, Indonesia, Philippines, Vietnam, Nigeria)	Stalk (cut off inflorescence)	Non-destructive	60-340	5	50	1.3	[5,47-49]
Phoenix canariensis	Canary Island date palm	Canary Islands	Apical meristem	Non-destructive	-	-	-	-	[14,44]
Phoenix dactylifera	Date palm	Arid and semiarid regions of western Asia and North Africa (*e.g.*, Egypt, Iran, Saudi Arabia, United Arab Emirates, Pakistan, Algeria, Iraq, Sudan, Oman, Libya)	Growing point of palm (terminal bud)	Non-destructive	90-120	-	25	8-10 5-15	[2,10, 17] [50,51]
Phoenix reclinata	Senegal date palm	Tropical Africa, the Arabian Peninsula, Madagascar and the Comoro Islands	Terminal bud	Destructive	30-60	-	-	-	[14,15, 52]
			Inflorescence	Non-destructive	-	-	-	-	[52]
Phoenix sylvestris	Wild date palm	Arid and desert areas of northern Africa, the Middle East and Southern Asia (*e.g.*, Arabian Peninsula, Iran, Pakistan, Bangladesh, India)	Stem below terminal bud	Non-destructive	152	5-7	20-25	1.2-2.5	[10,15, 53,54]
Pseudophoenix ekmanii	Dominican cherry palm	Dominican Republic	Crown meristem	Destructive	-	-	-	-	[55]
Pseudophoenix vinifera	Cacheo	Dominican Republic, Haiti	Crown meristem	Destructive	-	-	-	-	[8,55]
Raphia farinifera	-	Wet areas of Madagascar	Terminal bud	Destructive	-	-	-	2	[15]
Raphia hookeri	Raffia palm	Swampy areas in forest regions of Africa (*e.g.*, Nigeria, Madagascar, Ghana, Cameroon, Gabon, Congo)	Terminal bud	Destructive	60	7-10	-	2	[15,56]
	Wine palm		Inflorescence	Non-destructive	-	-	-	-	[14,57]
Raphia vinifera	Bamboo palm	Tropical Africa (e.*g*., Cameroon)	-	Destructive	-	-	-	-	[54]

[a]Tapping period for each terminal bud/spathe/stalk

Destructive tapping of stem

Figures 2a–d show examples of destructive tapping. The techniques can be conducted either by cutting the stem completely (a and b) or by making holes on standing palms (c). Because these methods attack the meristem, which is the embryonic tissue and source of growth for the palm, they result in the death of tapped stems.

A detailed procedure for tapping is as follows: first, based on the experience of the tappers, mature palms are selected carefully before they are cut or uprooted. To facilitate the harvest, felled palms are placed horizontally on the ground and defoliated. Then, a cavity is made by cutting the terminal bud (apical meristem) of the stem (Figure 2a). This cavity is covered with thin materials (*e.g.*, wood pieces, plastic sheets) to protect the sap accumulated therein (Figure 2b) from flies, mosquitoes, and bees [23,24]. Finally, sap is collected from the cavity daily until its exhaustion.

Using this process, *Acrocomia aculeata* in Honduras [24] and *Attalea butyracea* in Colombia [27] provided 2 and 1 L sap per palm per day, respect-

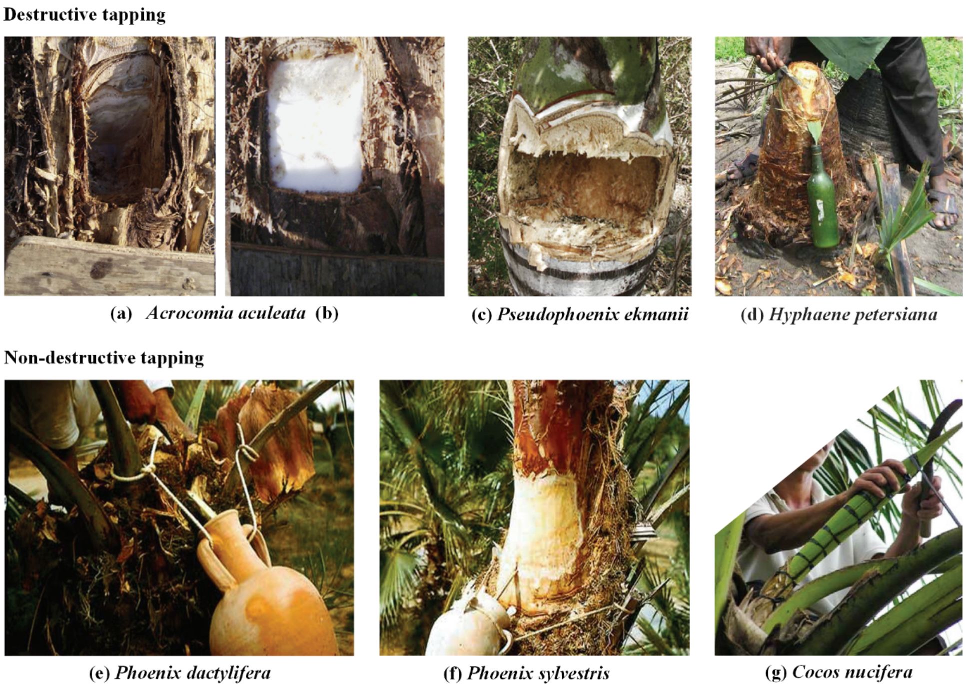

Figure 2. Illustrations of destructive tapping of: a), b) felled Acrocomia aculeata [23], c) standing Pseudophoenix ekmanii [55], d) standing Hyphaene petersiana [43], and non-destructive tapping of: e) Phoenix dactylifera [10], f) Phoenix sylvestris [10] and g) Cocos nucifera [37].

ively, for approximately 25 days. Similarly, an average of 4 L sap/day was obtained from a felled *E. guineensis* palm for two months in West Africa [17]. Using a similar method, *Jubaea chilensis* in Chile produced 400 L sap/palm over 6-8 weeks during the summer season [15,44].

Recent studies proposed felling of old oil palms (*E. guineensis*) to extract sap. Old palms with poor oil productivity were cut to replant new ones. Yamada *et al.* [12] found that the felled trunks contained a significant quantity of sugar-rich sap (approximately 70 wt%) that could be obtained mechanically.

When tapping living palms without cutting, a large hole is made in the growing part of the stem (as shown in Figure 2c). *Pseudophoenix ekmanii*, a small palm species, can be tapped using this approach. According to Namoff *et al.* [55], less than 4% of tapped palms could survive the treatment. In north-western Guinea, tapping a standing palm of *Borassus aethiopum* can yield 10 L sap/day for 35-45 days, which results in its death [28]. A few species, such as *E. guineensis* and *Raphia hookeri*, can be tapped on living palms [15].

Tapping standing stems of *Hyphaene petersiana* can be conducted by cutting the tip of the stem to expose the meristem (Figure 2d). After 3 days, the cut stem surface is trimmed and a V-shaped leaf is inserted to collect sap several times per day [43]. This method is also applied to *Hyphaene coriacea* [42] and *Hyphaene thebaica* [15].

Most palms with single-stemmed growth die when destructive tapping is applied. However, several clustering palms that usually grow many clumping stems can survive the tapping [14]. For example, a cut stem of *P. reclinata* [15] or a standing stem of *H. coriacea* [42], *H. petersiana* [43], and *H. thebaica* [15] would die after tapping, but their clumps with other stems can outlast. Occasionally, some remaining stumps from dead stems of *Hyphaene* spp. regenerate new stems and coppices [42,43].

Although destructive methods are relatively easy, rapid, and do not require tappers to climb tall palms like *A. butyracea* and *J. chilensis*, recent studies indicate that destructive methods are unsustainable for most tapped palms because they cause a rapid decline in their population [45]. In Chile, this unsustainable method is believed to have caused *J. chilensis* to be on the brink of extinction [44]. Similarly, this approach has been reported to have induced a decline in population of *A. aculeata* in Central America [24], *B. aethiopum* in the Republic of Guinea [28], and *Beccariophoenix madagascariensis* in Madagascar (Dransfield and Beentje, cited in [14]).

Non-destructive tapping of stem

The non-destructive tapping of stem is practiced in the upper parts of the living stem. Whereas destructive tapping is made by cutting a large hole to reach the meristem, non-destructive tapping is accomplished by cutting out thin scraps of tissue to achieve repeated tapping without killing the palm [14].

Sap extraction can vary for each palm species. Figure 2e shows an example of the method applied to *P. dactylifera*. Tapping starts by removing some leaves around the top of the stem. The stem is shaved into a cone shape, but the terminal bud and some fronds are left intact to allow for palm survival. A canal is cut around the base of the cone where a spout is attached to guide the sap flow from the cone towards a container [10]. The cone is covered to prevent it from drying out in the sun, and is recut to remove the dry surface and allow continued sap flow. Using this method, a palm can yield 8-10 L sap/day for 3-4 months. The palm can regrow an apical meristem and may be tapped again 3-4 times every 5 years [10]. *Phoenix canariensis* in the Canary Islands is tapped using a similar approach. A slight difference is that part of the crown (top of the stem) is cut out to form a bowl-shaped hollow to accumulate exudate [14].

Figure 2f shows a variant method for non-destructive tapping of stem. Only leaves around the tapping position are removed and the palm is tapped from the side of the stem. Shaving for many years forms zigzag scars on the palm trunk [53]. This method has been applied to *P. sylvestris* in South Asia [53] and to *P. dactylifera* [10], which can be tapped every year for 20-25 years [10,54].

Sap of *Borassus akeassii* in Burkina Faso is extracted from a hollow incised at the base of a main leaf. This species can be tapped throughout the year with a yield of 0.5-10 L sap/day [29].

As shown in Table 1, non-destructive tapping of stem is common in Africa and Asia. Although this method necessitates more skill and is more labor-intensive because it requires a tapper to climb the palm, this practice is more sustainable than destructive tapping.

Non-destructive tapping of stalk

The method includes pretreatment followed by tapping. In the pretreatment, stalk is beaten regularly to stimulate sap flow, whereas the actual tapping step involves regular cutting of the pretreated stalk to continue sap flow [48].

This method is applied mostly to *N. fruticans* [48]. Figure 3 shows the traditional process for sap collection from this palm. First, a stalk that carries flowers or fruits is selected and cleaned. Then, tappers bend or pat the stalk manually, then, kick and beat it using a wooden mallet a certain number of times daily over several weeks to several months [7,48]. The manner, frequency, and period of pretreatment may vary according to country.

After pretreatment, the stalk is cut and sap is gathered in a pot. The sieve tubes in the surface of the cut stalk may close as the palm heals itself naturally [13]. Therefore, the wound is renewed by cutting a thin slice off the stalk using a sharp knife to maintain the sap flow until the stalk is too short for tapping. In Papua New Guinea, a palm stalk with an average length of 1.7 m can be tapped for ~100 days with a mean sap yield of 1.3 L/day [48]. Because *N. fruticans* flowers regularly, it can be tapped many times for up to 50 years [5].

In a similar manner, *A. pinnata* and *Metroxylon sagu* can be tapped on their stalks, which are beaten with a mallet for 2-3 weeks prior to cutting for sap extraction. A stalk of *A. pinnata* can be tapped for 1-2 months with an average sap yield of 12-15 L per stalk per day [11], whereas the sap yield of *M. sagu* changes from 10 to 2 L/stalk/day after 2.5 months [46].

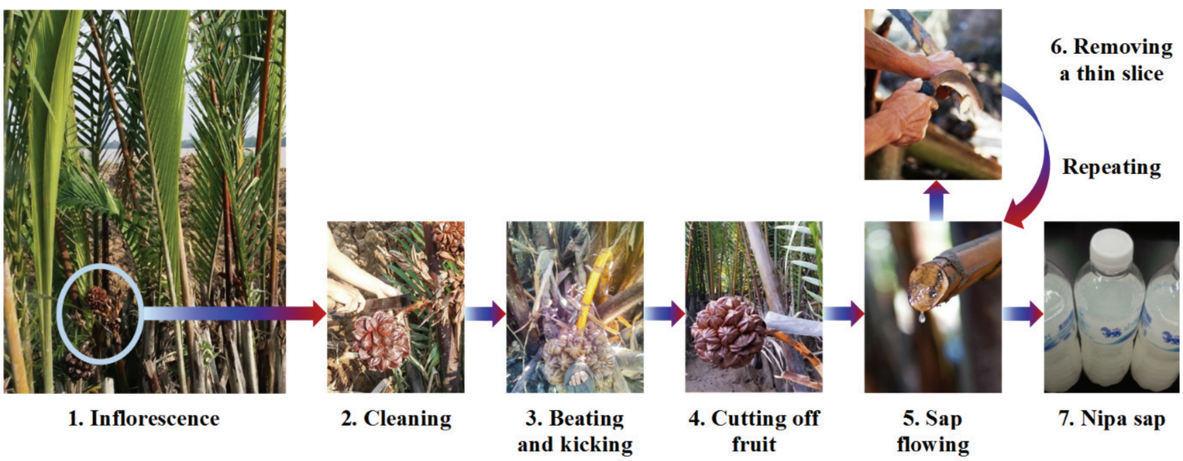

Figure 3. Traditional tapping process for sap production from nipa palm (photos 5 and 6 cited from [58]).

Non-destructive tapping of inflorescence

Tapping on spadix (unopened inflorescence) uses a method similar to that applied for stalk. However, the pretreatment step for spadix is relatively quicker than that for stalk.

Figure 2g shows a tapped spadix of *C. nucifera*. The tapped spadix is bound tightly around from the base to the apex with a rope to prevent it from bursting. Before slicing the apex, it is beaten using a wooden mallet for several days as opposed to several weeks or months for non-destructive tapping of stalk. According to Arivalagan *et al.* [35], this palm produces 12-14 spadices every year and one spadix can produce 1.5 L sap/day. With a tapping period of 40-45 days for each spadix, several spadices on one palm can be tapped simultaneously. Thus, the palm can yield sap year-round for up to 20 years.

Likewise, *B. flabellifer*, with several tapped spadices can provide 6-10 L sap/day for a few months every year [31,32]. It is also a perennial plant that can flower for 12-20 years and can live for more than 100 years [32]. Recently, Arunavathi *et al.* [31] proposed a tool to tap this palm. It consists of a funnel that covers the cut spadix to gather bleeding sap and convey it inside a tube to the base of the palm. This tool provides a 30% higher sap yield. It protects the sap from insects, and reduces the climbing of tall palms from twice to once a day.

Non-destructive tapping of inflorescence without pretreatment was reported for *E. guineensis* and *R. hookeri* [14,17,57]. Tappers in Africa often cut the inflorescence directly to produce sap. In Senegal, *E. guineensis* can yield approximately 5 L sap/palm/day [15]. According to Parbey *et al.* [39], this practice is more advanced and sustainable than the destructive method because the palm can be exploited annually for 10-15 years.

As described in Table 1, most palm species in tropical areas of Asia and the Pacific Islands are tapped using non-destructive methods. Although they are labor-intensive [34], the palms can survive and generate new inflorescences or stalks for the next tapping. Hence, this practice is supposed to be a sustainable and economic approach for palm populations compared with destructive tapping [9,45].

Because the anatomy and physiology of palm species are similar in different continents, many authors believed that the non-destructive tapping approach in given regions can be adopted for palm species in other areas [9,14,27,28,45]. For example, non-destructive tapping of *P. canariensis* in the Canary Islands was successfully applied to *J. chilensis* in Chile. The palms survived and could be tapped again every 5 years [44]. Thus, technology transfer may promote sustainable tapping of palms in different areas of the world.

Factors that affect sap yield

Sap production varies according to different factors such as tapping time, tapping method, sex and age of the palm, weather, and environment (water, soil, and sunlight) [15,25,34].

Tapping time

Sap yield can reach a maximum just before or during flowering and fruiting [13]. Pethiyagoda (cited in [15]) suggested that a rapid increase in respiratory rate occurs during this period. This phenomenon may accelerate conversions of reserves into nutrients and the transfer rate of sap flow to growing points.

Tapping method

The pretreatment of inflorescences or stalks is essential to achieve a high sap yield. Phloem sap is transported in living sieve tubes that also contain protoplasmic filaments or P-protein to maintain their vital functions [13]. These components may increase the resistance to sap flow and may plug the sieve tube system. Pretreating the inflorescence or stalk is thought to remove slime and P-protein from the transport system and prevent their re-formation. In addition, Van Die and Tammes [13] revealed that a negative pressure, which may exist in the xylem system, can act as an obstacle to phloem sap flow. The suction of sap in phloem to adjacent xylem vessels could be restricted by plugged xylem vessel formation, which may be enhanced by the wounding of stalks or spadices.

Some strategies have been used to improve sap yield. For example, tappers believe that scorching felled stems of species such as *H. petersiana* [43] and *R. hookeri* [15] may increase sap yield. A paste made from various ingredients is sometimes coated on the cut surface of spadix to stimulate sap flow from coconut palm (*C. nucifera*) [35] and kitul palm (*C. urens*) [34].

Flower sex

Some palms generate male and female flowers in one inflorescence (e.g., coconut palm (*C. nucifera*) [36] and kitul palm (*C. urens*) [34]), whereas others produce separate male and female inflorescences in a monoecious palm (e.g., *A. pinnata* [11] and *E. guineensis* [15]) or different dioecious palms (*e.g.*, *B. flabellifer* [31] and *P. dactylifera* [2]). When male and female inflorescences are separated, the sex of the inflorescences can affect sap production. For example, sap from *A. pinnata* is produced mainly from male inflorescences, which provide better sap quality and require less labor [11]. Male and female inflorescences of *E. guineensis* and *B. flabellifer* can be tapped [15,31]. However, their sap yield, tapping duration, and sap quality may not be similar. In India, female *B. flabellifer* is reported to give a higher sap yield [32]. Borin (cited in [31]) also showed that the tapping duration of the female palms was 5-6 months compared with 3 months for male palms, but the sugar concentration in the sap from female palms was lower than that from the male ones (116 and 132 g/L, respectively).

Palm age

Middle-aged palms have been reported to give the best sap yield as evidenced from *A. aculeata* in Honduras [24], *B. flabellifer*, and *P. dactylifera* in Bangladesh [51]. Chowdhury *et al.* [53] showed that sap yield varied for 5-7-, 7-14-, and more than 28-year-old wild date palms (*P. sylvestris*) to be 3.6-4.5, 5.7-7.5, and 3.6-4.5 L sap/palm for 3 nights, respectively.

Weather and environment

Weather affects sap production. Hinchy (cited in [7]) revealed that *N. fruticans* produced a higher sap yield in cloudy weather, but its sugar content was lower. During the night, more sap was bled, which accounted for 70-80% of the daily total sap yield [48]. In Burkina Faso, the sap yield from *B. akeassii* during dry, cold months reached ~4.1 L per palm per day, but decreased significantly to 1.8 L per palm per day in the hot period [30]. Tapping of *C. urens* provided sap of the best quality in the dry season, and of the highest quantity in the rainy season [34]. In Tunisia, the sap yield of *P. dactylifera* increased from 5-10 L/palm/day during winter to 10-15 L per palm per day in the spring [50]. The sap quality (*e.g.*, sugar content, kinds of sugars, and pH) also changed between the two periods.

Comparison of sap yield from various palms

As shown in Table 1, *C. urens* gave the highest sap yield per palm compared with other palms. An inflorescence of this palm was recorded to yield 5.3-9.4 L sap daily for 3 months and a palm with a few inflorescences gave 45 L per palm per day. Tapping can be maintained for roughly 9 months per year for 3-5 years [34]. *Corypha utan* can also produce up to 45 L sap/palm daily. However, this monocarpic palm, which will die after flowering and fruiting, could be tapped only for a short period [16].

N. fruticans has the longest tapping time (50 years) compared with other palms, and it requires only 5 years to reach maturity before the first sap collection. The stalk of this palm can be tapped for up to 340 days/yr [49], which is close to the maximum tapping period found for *A. pinnata* (365 days) [11]. Therefore, *N. fruticans* may be a sustainable palm for sap collection.

COMPOSITION OF PALM SAP

Sugars

Table 2 reports the chemical composition of palm saps compared with sugarcane juice. Sucrose, glucose, and fructose are the main components of most palm saps. Sucrose is the primary sugar of sap tapped from various palm species. However, glucose is the dominant sugar for sap squeezed from felled trunks of *E. guineensis* because sucrose, starch, cellulose, and/or hemicellulose may be hydrolyzed into glucose and other sugars by microbes in that particular sample [12]. Sucrose is commonly regarded as the main transport form of carbohydrates in many plants [13,19]. Phloem sap of palm species contains this sugar. Gibbs (cited in [13]) reported that all bleeding saps of *A. pinnata*, *C. nucifera*, *C. utan*, and *N. fruticans* consist of sucrose and almost no reducing sugars.

Table 2. Chemical composition of various palm saps compared with sugarcane juice

Palm/Sugarcane	Tapped part	pH	Sap composition, g/L							Ref.
			Total sugars	Sucrose	Glucose	Fructose	Ethanol	Organic acids	Inorganics	
Oil palm	Trunk	5.0	98.1	6.5	85.2	4.1	-	1.0	1.0	[59]
(*Elaeis guineensis*)	Trunk	-	93.9	0.0	89.3	4.6	-	-	-	[40]
	Trunk	-	54.9	9.9	41.8	3.3	-	-	3.6	[60]
	Inflorescence (fresh sap)	6.6	116.1	105.9	4.9	5.3	-	-	-	[41]
	Inflorescence (1 day old sap)	3.7	10.6	3.1	3.6	3.9	-	-	-	[41]
Coyol palm	Stem (fresh sap)	7.3	116.3	113.6	0.0	2.7	0.0	0.0	-	[23]
(*Acrocomia aculeata*)	Stem (old sap)	4.3	79.9	25.4	21.5	33.0	5.9	3.4	-	[23]

Table 2. Continued

Palm/Sugarcane	Tapped part	pH	Sap composition, g/L							Ref.
			Total sugars	Sucrose	Glucose	Fructose	Ethanol	Organic acids	Inorganics	
Coconut palm (*Cocos nucifera*)	Spadix	6.4	130.6	77.3	36.6	16.7	-	-	2.6	[61]
Palmyra palm (*Borassus flabellifer)*	Female inflorescence	7.3	116.0	-	-	-	0.0	-	-	[62]
	Male inflorescence	7.2	132.0	-	-	-	0.0	-	-	[62]
Date palm (*Phoenix dactylifera*)	Stem	6.8	124.8	99.3	8.0	9.4	-	-	3.5	[63]
Nipa palm (*Nypa fruticans)*	Stalk (old sap)	4.4	142.1	78.4	32.3	31.4	1.7	2.1	6.3	[47]
	Stalk (fresh sap)	6.9	144.2	105.1	23.7	15.5	1.0	4.1	5.2	[64]
	Stalk (1 day old sap)	5.9	144.5	74.9	43.9	25.7	3.2	7.5	5.4	[64]
Sugarcane (*Saccharum officinarum*)	Stem	-	150.3	148.3	1.0	1.0	0.0	0.0	4.1	[65]

Other sugars may also be detected in small amounts, such as maltose and raffinose in palmyra sap [31]; myo-inositol in date palm sap [63]; raffinose in oil palm sap [41]; and xylose, galactoses, and rhamnose in oil palm trunk sap [59]. Because sap quality depends on tapping conditions, the total sugar content in fresh sap may range from 10 to 20% [15]. Compared with sugarcane juice, in general, palm sap shows similar main and total sugar contents. For example, the total sugar content (sucrose, glucose, and fructose) in the sap of *N. fruticans* and sugarcane juice was 14.0 and 14.6 wt%, respectively [65].

Minor organic compounds

Palm sap can contain various minor organic compounds that depend on nutrients for the growth of palms or fermentation products after tapping [13]. Nur Aimi *et al.* [66] used gas chromatography-mass spectrometry and showed that fresh sap of *N. fruticans* contained ethanol, diacetyl, and esters as volatile compounds. After the simultaneous fermentation of sap, 1-propanol, 2-methylpropanol, 3-methylbutanol, acetoin, acetic acid, and formic acid were also detected in addition to the compounds in the fresh sap. The volatile compounds may be important odorants of fresh and fermented sap.

Salvi and Katewa [67] determined that sap of *P. sylvestris* was rich in lipids, proteins, fibers, and 13 types of vitamins. Many kinds of vitamins (niacin, thiamin, riboflavin, ascorbic acid, and vitamin A) existed in saps of *B. flabellifer*, *C. nucifera*, and *P. sylvestris* [62].

Inorganic compounds

Various minerals were detected in palm sap. Barh and Mazumdar [62] indicated that inorganic elements such as Ca, Mg, Fe, Na, K, Zn, Cu, and P are present in all saps of *B. flabellifer*, *C. nucifera*, and *P. sylvestris*. Nguyen *et al.* [47] found that *N. fruticans* contained several inorganics that are also present in different palm saps and even in sugarcane juice.

The inorganic content in palm sap may be affected by soils, water sources, and fertilizers [5]. The sap of *N. fruticans*, which grows near brackish water or seawater, has particularly high contents of Na and Cl, most probably from the seawater salt [47].

Yeasts and bacteria

Some yeasts and bacteria exist in palm sap. According to Ziadi *et al.* [50], these microorganisms could derive from autochthonous palm microflora and/or contamination during tapping. Additionally, the nutrient-rich palm sap environment can support their growth. As reviewed by Santiago-Urbina and Ruíz-Terán [68], the microflora of palm sap includes yeasts (10^4-10^7 CFU/mL), lactic acid bacteria (10^7-10^9 CFU/mL), acetic acid bacteria (10^5-10^8 CFU/mL), aerobic mesophilic bacteria (10^6-10^9 CFU/mL), and coliforms (10^3-10^7 CFU/mL). The study indicated that *Saccharomyces cerevisiae* and *Zymomonas mobilis* are the main microorganisms responsible for ethanol fermentation during palm sap storage.

Palm sap preservation

Because of rapid fermentation by various microorganisms in the sap, the quality of palm sap can change continuously during tapping and storage. Sucrose can be hydrolyzed spontaneously to glucose and fructose, and further fermentation of these sugars may occur simultaneously to yield different products such as ethanol, lactic acid, and acetic acid [41,50]. Tamunaidu and Saka [64] indicated that the extensive decrease in sucrose content in 1-day-old nipa sap was partially compensated by an increase in reducing sugars, ethanol, lactic acid, and acetic acid contents, as shown in Table 2.

Normally, the pH of fresh palm sap ranges from neutral to slightly alkaline [13]. However, fermentation products such as organic acids, including lactic and acetic acids, can decrease the palm sap pH. For example, the pH of oil palm sap decreased from 6.6 to 3.7 after a day of harvesting, whereas the total sugar content was reduced approximately 11-fold from 116 to 11 g/L [41]. Furthermore, sap appearance changed from clear to milky-white by rapid microorganism growth during storage [50].

Suitable conservation techniques have been tested to preserve the chemical composition and properties of fresh sap. For example, the tapped area and container have been covered to reduce environmental contaminants and to avoid the acceleration of fermentation by sunlight heat [63]. The sap can also be collected from containers twice a day rather than once a day [15]. Another strategy is to rinse the container with water [57] and sterilize it using smoke or alcohol [11,49].

To slow the fermentation of fresh sap, the inner part of the container can be coated with lime [51]. Tannin-rich bark or leaves of many plant species can also be used as preservatives (*e.g.*, *Launaea coromandelica* bark, *Schleichera oleosa* bark, *Shorea* spp. bark, *Vateria* spp. bark, *Vatica chinensis* bark, *Anacardium occidentale* leaves, and *Acronychia laurifolia* leaves) [15,33]. In addition, some industrial chemicals such as sodium metabisulphite [57], sodium azide [63] or chlorine [7] can prevent the proliferation of microorganisms for a certain period of time.

However, these agents cannot preserve palm sap during long storage periods and may yield an undesirable smell and taste. To be more effective, locals often boil palm sap to a viscous form or solid sugar. In this process, microorganisms can be exterminated by heat and the high sugar concentration of the obtained product can inhibit their growth [69]. Thermal treatment was also proposed by Tamunaidu and Saka [64] where sap of *N. fruticans* was heated at 100 °C for 10 min and then kept in tightly stoppered bottles prior to storing. Similarly, sap of *R. hookeri* pasteurized in green bottles at 75 °C for 45 min was stable for 24 months [57].

Keeping the sap in a cooler box with dried ice or freezing can also contribute to its preservation [66]. Hebbar *et al.* [35] developed a chiller that contained ice cubes or gel ice packets around a container. The instrument was connected with the cut spadix of *C. nucifera* and carefully covered. The bleeding sap was maintained at 2-3 °C for 10-12 h before collection.

TRADITIONAL USES OF PALM SAP

Fresh sap as beverage

Nowadays, tapping palms for sap is a common practice to generate important income for locals in various tropical areas. The sugars, odorants, proteins, fats, fibers, vitamins, and minerals in the sap are attractive components for human consumption. Fresh sap, which is sweet, odorous, clear or translucent, with neutral pH, is a popular beverage in many local communities [2,34]. However, this tapped nectar should be consumed within a day, before it ferments spontaneously to alcohols and acids [52,63].

Animal feed

A variety of animal species consume palm sap. According to Everett [34], tappers in Sri Lanka sometimes set traps to protect their sap containers from monkeys. To fatten animals for meat production, palm sap was investigated as a main diet ingredient for pigs in Cambodia [70] and in certain islands of Indonesia [71]. During the dry season, as other fodders become scarce, farmers can rear pigs using the sap and leftovers after sugar preparation. Besides pigs, other animals such as ducks, poultry, dogs, and cattle have been reported to be fed using palm sap [15,70].

Syrup and sugar production

In rural communities, syrup and jaggery (brown sugar) are typical products derived from palm sap [45,52]. Both are prepared from fresh sap by boiling in a large pot. The pot can be placed on a wood-burning stove for a few hours until the sap becomes viscous and golden-brown [34]. The resulting syrup looks like honey and is poured into bottles and sealed for sale [45]. Alternatively, brown sugar production requires further heating of the syrup until sugar crystals start to form [11]. Then, the thick syrup is cooled and shaped in molds to provide solid sugar.

Alcoholic beverage production

Palm sap can be fermented to alcoholic beverages, which are popular products in some tropical regions of the world [14]. They are known locally as palm wine or toddy [68] and are rich in nutrients [52]. The beverage is produced from the spontaneous fermentation of palm sap within several days and it becomes alcoholic after a few hours of tapping. During this process, sugars are transformed to ethanol and a small quantity of acids by yeasts, lactic acid bacteria, and acetic acid bacteria [2]. As a consequence, the liquid pH changes from neutral to acidic. Unique odorants of the drink are also developed during this fermentation period [52]. The product may be further distilled to obtain a stronger alcoholic drink [11,34].

Vinegar production

Further fermentation of the alcoholic beverage by acetic acid bacteria can produce vinegar. It is commonly consumed in many countries of Asia and the Pacific Islands [14]. In the Philippines, sap of *A. pinnata*, *C. nucifera*, and *N. fruticans* is used for vinegar production [72]. The process includes alcoholic fermentation by yeasts and acetic acid fermentation by *Acetobacter* spp. Production may take 1-2 months. The product is then bottled and sold.

Limitations in the traditional uses of palm sap

According to Dalibard [71], tapping practices for traditional use have declined because the trade in fresh sap is limited to close geographical locations because of its instability (Romera, cited in [15]).

Fuelwood wastage for concentrating sap is the main limitation in syrup and sugar production. For example, sugar preparation from the sap of *B. flabellifer* in several areas resulted in a fuelwood shortage and led to forest-cutting [71]. In addition, farmers should process the freshly tapped sap immediately to avoid fermentation [15]. As a result, wood collection and boiling stages occupy almost all their time [70]. Sugar production from sap of *A. pinnata* is not favored in certain Indonesian provinces because of its saturation in local markets and the high investment required in equipment, fuelwood, and labor [11].

Alcoholic beverages, a popular product from palm sap, are prohibited in Muslim communities [11]. They are also discouraged in many places because of potential dangers from alcohol abuse and addiction [10].

For these reasons, many tapped palms are regarded as underutilized sugar-yielding palms [5,71]. Hence, the shift in use of palm sap from traditional products to bioethanol may create new interests in existing underutilized palms and may even enhance local economies.

METHODS FOR BIOETHANOL PRODUCTION FROM PALM SAP

Alcoholic fermentation of palm sap for bioethanol production

Like traditional sugar crops, palm sap can be processed for bioethanol production via direct alcoholic fermentation by microorganisms. The process is similar to the spontaneous fermentation that occurs during alcoholic beverage production, which includes sucrose hydrolysis into monosugars (glucose and fructose) and their fermentation into ethanol [3]. One microorganism can complete both stages with a maximum yield of 0.51 g ethanol/g sugar [1]. During these bioreactions, 1 mol of hexose can be converted theoretically into 2 mol of ethanol and 2 mol of CO_2, according to: $C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$.

Table 3 reports batch alcoholic fermentation of palm saps for bioethanol production compared with sugarcane juice. In a general trend, it shows that palm sap provides a slightly higher efficiency when *S. cerevisiae* is used for fermentation. Although various microbes, including yeasts, fungi, and bacteria can produce ethanol as the major product, *S. cerevisiae* is the preferred biocatalyst for palm sap. The yeast can provide a high ethanol yield and productivity, with a high tolerance to ethanol and substrate [2]. For example, nipa sap (140 g/L sugars) can be converted directly to 69 g/L ethanol by *S. cerevisiae* with reasonable yield (0.49 g ethanol/g sugars) and high productivity (2.2 g/L/h) [5]. The fermentation is conducted at low temperature (28-32 °C), which may not require energy for heating the broth. Yeast can grow within a broad pH range from 2.5 to 8.0 [76]. Hence, initial pH adjustment and pH control during batch fermentation may be neglected.

Recently, Natarajan *et al.* [75] investigated the yeast *Lachancea fermentati* that was isolated from nipa sap for fermentation. Under optimal conditions at 30 °C and pH 5.4, and for a fermentation time of 20 h, 110 g/L sugars in nipa sap produced 46 g/L ethanol, which corresponds to a conversion efficiency of 82% and a high ethanol productivity (2.3 g/(L/h)).

Besides yeasts, the bacterium *Z. mobilis* was also studied for alcoholic fermentation. This bacterium is claimed to exhibit a higher ethanol yield and productivity, and a higher substrate uptake compared with *S. cerevisiae* [3]. Sap of palmyra (*B. flabellifer*) has been fermented by *Z. mobilis* and 59 g/L of ethanol were obtained from 206 g/L of sugars, with a yield of 0.30 g ethanol/g sugars [73]. Although *Z. mobilis* is a facultative anaerobe, high oxygen concentrations influence its performance negatively [77], whereas *S.*

Table 3. Batch alcoholic fermentation of various palm saps, sugarcane juice and sucrose for bioethanol production

Feedstock	Tapped part	Microorganism	Nutrient supplement	*t* °C	Initial pH adjustment	Time h	Initial sugar g/L	Sugar utilization, %	Bioethanol				Ref.
									Concentration g/L	Productivity g $L^{-1}h^{-1}$	Yield, g/g of total sugars	Conversion efficiency[a], %	
Oil palm (*Elaeis guineensis*)	Trunk	*Saccharomyces cerevisiae*	No	30	No	24	57	86	19	0.8	0.38	75	[60]
		S. cerevisiae Kyokai No. 7	No	30	6.0	24	62	100	30	1.3	-	94	[59]
		S. cerevisiae ATCC 24860	No	30	4.0	24	94	100	48	2.0	0.50	99	[40]
Palmyra palm (*Borassus flabellifer)*	Inflorescence	Zymomonas mobilis NRRL B-14234	Yes	30	No	60	206	-	60	1.0	0.30	60	[73]
		S. cerevisiae Y18	Yes	32	No	48	150	-	70	1.5	-	92	[74]
Nipa palm (*Nypa fruticans)*	Stalk	*Lachancea fermentati*	Yes	30	5.4	20	111	96	46	2.3	-	82	[75]
		S. cerevisiae NBRC, Japan	Yes	28	No	28	131	99	55	2.0	0.42	85	[65]
		S. cerevisiae NBRC, Japan	Yes	28	No	32	140	100	69	2.2	0.49	97	[5]
		S. cerevisiae NBRC, Japan	No	28	No	48	140	100	68	1.4	0.49	96	[5]
Sugarcane (*Saccharum officinarum*)	Stem	*S. cerevisiae* NBRC, Japan	No	28	No	48	140	100	62	1.3	0.44	87	[5]
Sucrose	-	*S. cerevisiae* NBRC, Japan	No	28	No	32	140	-	-	~0.0	~0.00	1	[5]

[a]*Based on theoretical maximum yield of bioethanol*

cerevisiae can tolerate aerobic conditions [1]. Because maintaining anoxia is difficult practically, *S. cerevisiae* remains the preferred microorganism for alcoholic fermentation.

Bioethanol production *via* acetic acid fermentation

As described above, ethanol yield from the alcoholic fermentation is limited partly because of the formation of CO_2 as a by-product. Hence, an advanced bioethanol production process via acetic acid fermentation and subsequent catalytic hydrogenolysis was developed recently by Saka *et al.* [78,79], as described in the following reactions:

$$C_6H_{12}O_6 \longrightarrow 3CH_3COOH \xrightarrow[3H_2O]{6H_2} 3C_2H_5OH$$

According to this equation, all carbon atoms in hexose can be converted to bioethanol without CO_2

release. Therefore, theoretically the acetic acid fermentation method can provide a 50% higher ethanol yield compared with traditional alcoholic fermentation. Although this process was developed for lignocellulosic biomass, nipa sap has also been investigated as a sugary feedstock [47].

The sap as hydrolyzed by either oxalic acid or invertase was fermented anaerobically at 60 °C by *Moorella thermoacetica* (formerly *Clostridium thermoaceticum*) at pH 7.0 and in N_2. After pretreatment of sap, all sugars and organic acids were converted to acetic acid with a conversion efficiency of 0.98 g acetic acid/g sugar. The obtained acetic acid can be hydrogenated into bioethanol. As demonstrated by Kawamoto *et al.* [80,81], aqueous acetic acid solutions were converted to ethanol at 92.8-98.2 mol% using Ru-Sn/TiO_2 (4 wt.% Ru and 4 wt.% Sn on TiO_2) catalyst. As a result, 0.70–0.74 g ethanol/g sugar could be obtained from nipa sap, which is much higher compared with the yield from alcoholic fermentation. This advanced process can promisingly produce bioethanol from palm sap with a higher carbon utilization efficiency compared with conventional alcoholic fermentation. In addition, if organic acids such as lactic and/or acetic acids are present in the palm sap, they can also be converted into ethanol in this process [47,82].

POTENTIAL FOR BIOETHANOL PRODUCTION FROM SAP OF VARIOUS PALM SPECIES

Ethanol yield from sap of different palms

Ethanol yield depends on many parameters such as the environment and cultivation techniques applied to the palm (*e.g.*, seed quality, palm density, and nutrient supplement), ratio of productive palms, tapping techniques and duration, sugar content of the sap, fermentation method, and yield [5,15,25]. Table 4 summarizes the potential for bioethanol production from several palm saps compared with traditional crops.

Table 4. Potential of bioethanol production from palm saps compared with other crops

Crops	Average crop yield, t/(ha/yr)	Estimated sap yield, L/(ha/yr)	Estimated bioethanol yield, L/(ha/yr)	Estimated area	Maximum estimated bioethanol production, ML/yr	Ref.
			Sugar crops			
Sugarcane (*Saccharum officinarum*)	65.0	-	4,550	20 Mha all over the world	91,000	[6]
Sugarbeet (*Beta vulgaris*)	46.0	-	5,060	5.4 Mha all over the world	27,000	[6]
			Starch crops			
Corn (*Zea mays*)	4.9	-	1,960	145 Mha all over the world	284,000	[6]
Rice (*Oryza sativa*)	4.2	-	1,806	150 Mha all over the world	271,000	[6]
Wheat (*Triticum* spp.)	2.8	-	602	215 Mha all over the world	205,000	[6]
			Palms			
Nipa palm (*Nypa fruticans*)	-	50,000-100,000	4,550-9,100	700,000 ha in Indonesia 500,000 ha in Papua New Guinea 20,000 ha in Malaysia 8,000 ha in Philippines	5,590-11,180	[5]
	-	40,000-160,000	3,590-22,370	Indonesia (Sungsang)	-	[83]
	-	169,000	11,000	Papua New Guinea	-	[48]
Oil palm (*Elaeis guineensis*), sap from inflorescence	-	-	7,800	57,400 ha in Ghana (336,000 ha available)	448	[39]

Table 4. Continued

Crops	Average crop yield, t/(ha/yr)	Estimated sap yield, L/(ha/yr)	Estimated bioethanol yield, L/(ha/yr)	Estimated area	Maximum estimated bioethanol production, ML/yr	Ref.
			Palms			
Oil palm (*Elaeis guineensis*), sap from felled trunk	-	-	8,700-9,400	150,000 and 182,000 ha of felled oil palm in Malaysia and Indonesia, respectively	3,000	[12]
Coconut palm (*Cocos nucifera*)	-	239,000	19,000	4,097 coconut palms (total 2260 ha in Tuvalu)	0.4	[36]
Sugar palm (*Arenga pinnata*)	- -	- -	7,184 8,094	2,350 ha in Batang Toru, Indonesia 10,500 ha in Tomohon, Indonesia	-	[25]

The evaluations were made based on alcoholic fermentation. Average crop yields and estimated plantation areas were taken into consideration for each crop. When the cultivated areas are disregarded, theoretically, starch crops appear to provide the highest ethanol production in ML/yr compared with sugar crops and palm saps because they are cultivated in large areas from 145 Mha for corn to 215 Mha for wheat. When the plantation areas are taken into consideration, the palms show the highest ethanol yield estimated in L/(ha/yr).

In more detail, the estimated ethanol yields from saps of *N. fruticans*, *E. guineensis*, *C. nucifera* and *A. pinnata* are 4,550–9,100, 7,800, 19,000, and 7,184–-8,094 L/ha/yr, respectively. In general, these ethanol yields are higher than those from starch and sugar crops (from 602 L/(ha/yr) for wheat to 5,060 L/(ha/yr) for sugarbeet). Therefore, palm sap can serve as a good feedstock for ethanol production. Palm saps that are investigated most for this purpose include those from *N. fruticans*, *C. nucifera*, *E. guineensis*, and *A. pinnata*.

N. fruticans, an underutilized palm, was assessed recently for bioethanol yield by several authors. A detailed study for ethanol production from *N. fruticans* was conducted by Tamunaidu *et al.* [5]. If a sap yield of 0.5–1.0 L per palm per day is assumed, with a tapping period of 100 day/yr, and with a population of 1,000 palm/ha, then an annual sap yield of 50,000–-100,000 L/(ha/yr) could be achieved from this palm. In alcoholic fermentation, sap with a minimum sugar content of 15 wt.% was converted to ethanol with a yield of ~0.48 g ethanol/g sugars. Consequently, the annual ethanol yield was estimated to be 4,550–9,100 L/(ha/yr). Using this result for 1.23 Mha of *N. fruticans* plantations in Indonesia, Papua New Guinea, Malaysia and the Philippines (cited in [5]), the annual ethanol production may reach 5,590–11,180 ML/yr. Similarly, Hidayat [83] investigated natural nipa palm in Indonesia to give an annual ethanol yield that ranges from 3,590 to 22,370 L/(ha/yr). In the Philippines, Halos (cited in [7]) reported that the ethanol yield from nipa palm was 6,480–10,224 L/(ha/yr) and could be increased to 18,165 L/(ha/yr) under improved management. In Papua New Guinea, Päivöke [48] estimated that the ethanol yield of nipa sap could reach 11,000 L/(ha/yr).

C. nucifera shows a high potential for ethanol yield (Table 4). This pantropical palm was recorded to yield ethanol quantities of 5,000 L/(ha/yr) (del Rosario, cited in [7]). Recently, its potential for bioethanol was explored by Hemstock [36]. In Tuvalu, coconut palms are spread over 2,260 ha with an average density of 211 palm/ha. However, only 4,097 of the 476,412 coconut palms (less than 1%) were tapped throughout the year by locals to provide more than 5 ML/yr of sap. With an ethanol yield of 8 vol.%, the sap could be processed theoretically to an ethanol production of 0.4 ML/yr, which could be equivalent to 31% petroleum consumption in this area. Otherwise, assuming that all palms are tapped with an average sap yield of 3.1 L per palm per day, ethanol production could reach 19,000 L/(ha/yr).

E. guineensis, which can be tapped from the stem or spadix, is also promising for bioethanol production. According to Parbey *et al.* [39], tapping oil palm non-destructively could yield ethanol at 7,800 L/(ha/yr). The authors suppose that this ethanol source could replace 10-20% of the gasoline demand in Ghana. The use of old oil palm trunks (~25 years old) for ethanol production was assessed by Yamada *et al.* [12]. The authors assumed that 4% of cultivated palm areas become too old for oil production and should be cut annually for replantation. The estimated ethanol yield could reach 8,700-9,400 L/(ha/yr) and a promising ethanol production of 3,000 ML/yr could be achieved from 3.74 Mha in Malaysia and 4.54 Mha in Indonesia.

An investigation was conducted by van de Staaij *et al.* on bioethanol production from *A. pinnata* [25]. From data collected from different villages in Indonesia, the average ethanol yields for Batang Toru and Tomohon areas were calculated to be 7,184 and 8,094 L/(ha/yr), respectively. The authors also proposed two management modes of sugar palm for bioethanol production. Conservatively, 100 sugar palms intercropped with other crops could give an ethanol yield of 4,780 L/(ha/yr). Conversely, monoculture mode with 1,089 palm/ha may produce ethanol at up to 52,000 L/(ha/yr).

Sustainability of using palm sap for bioethanol production

Palm saps show interesting characteristics for sustainable bioethanol production.

Palm is available and is abundant locally

Most tapped palms commonly grow wildly or semi-wildly throughout tropical and sub-tropical areas [8,9]. Some high-value palms (*e.g.*, coconut, oil, date, and palmyra palms) exist already [9,10,12]. Hence, palm may be tapped immediately without investment for cultivation [15]. The following palms have been reported as locally abundant: *A. pinnata* [11], *A. butyracea* [27], *M. flexuosa* [8], *N. fruticans* [7] and *P. sylvestris* [10]. In Latin America, for example, products from palms are consumed mostly by local markets without international trade [45]. Sugar sources may therefore be abundant for bioethanol production [71].

Palms live longer compared with corn and sugarcane and can be tapped for several years

As summarized in Table 1, palms can yield sap for many years: 30 years for *B. flabellifer*, 20 years for *C. nucifera*, 50 years for *N. fruticans*, and 25 years for *P. sylvestris*. Logging and replanting, which are necessary for the harvest of sugar and starch crops, can therefore be reduced for tapped palms. Moreover, some palms (*e.g.*, *A. pinnata*, *B. akeassii*, *C. nucifera* and *N. fruticans*) produce sap daily almost all year long as opposed to seasonal production of sugars from sugarcane [25,29,35,48]. Hence, the sugar source for ethanol production plants would not be interrupted.

Palms can grow in abandoned areas rather than on agricultural lands

Many palms can adapt to harsh lands that are unsuitable for other crops, such as sugarcane and corn. Roughly 90% of palm species occur in tropical forests [8]. Palms may exist in ecosystems that are humid (*e.g.*, *A. pinnata*, *Corypha umbraculifera*, *E. guineensis*, and *M. sagu*), swampy (*e.g.*, *M. flexuosa* and *R. hookeri*), arid (*e.g.*, *C. utan*, *H. coriacea*, and *P. sylvestris*), deserts (*e.g.*, *P. dactylifera*), mountainous (*e.g.*, *P. reclinata*), grasslands (*e.g.*, *B. aethiopum, B. flabellifer* and *H. petersiana*), and contain brackish water (*e.g.*, *N. fruticans*) [8]. Consequently, the development of some palm ecosystems for tapping can restrict competition with food crops for agricultural land [7].

Palms require little care and investment for their growth

Since palms are able to grow wild in harsh lands, they require little care and minimal fertilizers for their survival and growth. For example, *A. pinnata* can adapt to different soil types, requires almost no maintenance, and rarely suffers from serious diseases [11]. *J. chilensis* can grow in dry and poor-nutrient soils without fertilizers, pesticides or irrigation, according to González *et al.* [44]. Similarly, Tamunaidu *et al.* [5] reported that the utilization of fertilizers, herbicides, insecticides, water, machinery, electricity or fuel for sugarcane fields is very limited or unnecessary for *N. fruticans*.

Tapping palm can produce sap directly without waste

Harvesting of traditional energy crops often produces large volumes of biomass wastes such as straw, leaves and bagasse [1,7]. Sugar extraction from sugarcane involves extra investment in equipment and energy for compression of stem [7]. Thus, direct tapping of palms for bioethanol production may become more convenient than conventional crops.

Palm sap can be converted easily to bioethanol compared with starch or lignocellulosic feedstocks

In alcoholic fermentation, free sugars in palm sap can be converted directly into ethanol without complex pretreatment and hydrolysis that occurs for starch or lignocellulosic feedstocks [3]. Moreover, fermentation of lignocellulosic materials requires an external supply of nutrients to maintain microorganism activity [84]. In contrast, palm saps contain inorganics, amino acids, and vitamins, which can play a role as nutrients during fermentation [59,85]. Nipa sap and oil palm trunk sap were shown to produce ethanol without nutrient supplements [5,59]. Thus, using palm sap instead of lignocellulosics could reduce nutrient costs, although additional fermentation time may be required to achieve a high ethanol yield [5].

Bioethanol production can be a form of sap preservation

As discussed previously, fresh sap is unstable. However, ethanol production reduces the pH of the fermented sap. Additionally, ethanol inhibits the proliferation of contaminating microorganisms. Therefore, bioethanol production can constitute a method to preserve and utilize sap efficiently.

Bioethanol production from palm sap can promote local economies and ecosystems

Tapping palm for bioethanol production can generate work and income for local farmers and encourage them to maintain the local palm population rather than replacing it with other industrial crops.

Tapping palm sap for bioethanol production may compete with other palm products. For example, tapping female flowers sacrifices fruit formation. Tapping may also reduce fruit yield from the palm [10]. When *A. pinnata* is tapped for sap, its starch content may be reduced [11]. Conversely, tapping *C. nucifera* can stimulate fruit production. Mathes (cited in [15]) revealed that after tapping, coconut palm yielded a 2-3 times higher fruit production than untapped coconut palms.

Sap and other palm products should be considered to achieve sustainable bioethanol production. Palms that yield sap as the main product are suitable for ethanol production. For example, tapping *P. sylvestris* makes best use of the plant because its fruit is of low attraction for humans [53]. For *C. nucifera*, although the economic value of its sap was evaluated to be higher than that of its fruit [15], both products can be exploited to diversify the economic output of the palm [8]. Tapping *E. guineensis* (inflorescence or felled trunk) is recommended for old palms that reach the end of their lifespan for oil extraction [12,39]. Integration of sap with other products may provide a better palm management [15].

CONCLUDING REMARKS

To date, palm sap has been used in traditional ways without many industrial applications. However, this work reports that palm saps can yield as high as 22,370 L ethanol/(ha/yr), which is much greater than that derived from traditional crops such as corn or sugarcane. Because palms do not require much fertilizer or particular care, and since they are able to live long and can be tapped for up to 50 years, their utilization would be more environmentally benign compared with corn and sugarcane. Sustainable bioethanol production from palm sap could be achieved with the proper integration of sap exploitation alongside existing palm industries and plantations.

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PREGLEDNI RAD

BILJNI SOK RAZLIČITIH PALMI KAO OBNOVLJIVI IZVOR ENERGIJE ZA PROIZVODNJU BIOETANOLA

Biljni sok je vodena tečnost koja transportuje biljne fotosintetske proizvode prema različitim tkivima neophodne za rast. Zasecanje palmi radi sakupljanja njihovog soka je nastalo u Indije pre oko 4.000 godina. Sok palme je bogat šećerima sa nekim neorganskim i hranljivim materijama, koje su atraktivne sirovine za proizvodnju bioetanola. Na osnovu naprednih i sadašnjih znanja o dostupnosti, prikupljanju, prinosu i eksploataciji raznih sokova različitih palmi, ovaj rad ocenjuje njihov potencijal i održivost kao sirovina za proizvodnju bioetanola.

Ključne reči: palmin sok, zasecanje, šećer, fermentacija, bioetanol, održiv razvoj.