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ORIGINAL ARTICLE

Kosuke Murai · Ryuichiro Kondo

Extractable sugar contents of trunks from fruiting and nonfruiting oil palms of different ages

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Abstract Oil palm trunks (OPTs) are a potential source of sugars for bioethanol production, and so we determined the glucose, fructose, and sucrose contents of hot water extracts from OPTs. Samples of OPTs were obtained from different regions of the trunk, from trunks of palms of different ages (31-, 19-, and 15-year-old), and from fruiting and nonfruiting palms. The extractable sugar contents of the whole OPT and the upper and lower regions of each OPT were calculated. Our results indicated that the upper parts of OPTs should be used for bioethanol production because they yield higher concentrations of sugars than the lower parts do. To produce a highly concentrated glucose solution for bioethanol production, OPTs should be harvested as soon as production of palm oil has been completed and when new male flowers have appeared. If these suggestions are followed, then the estimated ethanol concentration after fermentation is 3.2% and the estimated ethanol production per harvested area is 3.5 kl/ha.

Key words *Elaeis guineensis* · Oil palm trunk · Bioethanol · Starch · Fruiting

Introduction

In Southeast Asia, especially in Malaysia and Indonesia, oil palm (*Elaeis guineensis*) has been one of the most important commercial crops since the late 1950s. Recently, these countries have become the world's leading producers and exporters of palm oil. In 2006, Malaysia and Indonesia produced more than 15 million tons of palm oil.[1] Generally, the oil palm has an average economic life of 25 years.[2] During replanting, each hectare of oil palm estate generates approximately 80.4 tons of dry biomass, which consists of palm trunks (approximately 66 tons) and fronds (approximately 14.4 tons).[3] Replanting is necessary because older palms become too tall to harvest oil palm fruits economically,[4] and the yield of palm oil is so low that replacement with high-yielding young palms gives a much higher return.[5] Oil palm trunks (OPTs) are a waste product that is generated in the replanting process. At present, they are cut into pieces and left on the ground of oil palm estates to be degraded by bacteria and fungi[6] or are burned for quick disposal.[7]

There have been some investigations into utilization of waste OPTs. The production of laminated veneer lumber (LVL) or plywood from OPTs is a potentially profitable use.[6,8] Likewise, the production of pulp or paper from OPTs is technically feasible.[9,10]

Previously, we determined levels of alcohol–benzene extract, holocellulose, lignin, hot water extract, and hot water-extractable glucose in vertically and radially cut samples from three 25-year-old OPTs, designated OPT I, II, III. In that report, we showed that OPTs were a source of hot water-extractable glucose, which was derived from carbohydrates such as starch.[11] Our results showed that samples from higher up the trunk and from the inner regions of the trunk contained more hot water-extracted glucose than samples from the lower/outer regions of the trunk. Furthermore, the hot water-extractable glucose, fructose, and sucrose contents of OPT II samples taken from the region between 0.5 and 9.5 m along the trunk were estimated as 63, 13, and 11 kg, respectively.[11] These results indicated that waste OPTs could provide material for bioethanol production. However, there are large differences in hot water-extractable glucose contents even within the same region of each OPT. For example, hot water-extractable glucose contents based on meal from the higher, inner regions of OPT I and II were 10.8% and 36.2%, respectively.[11] To produce bioethanol economically, OPTs should be harvested when their starch content is at its highest.

Like oil palms, sago palms (*Metroxylon sagu*) contain starch in their trunks.[12] Sago palm could become an important source of commercial starch in tropical regions because it is one of the few tropical crops that can tolerate deep peat soils.[13] Therefore, the quantity and quality of starch in sago

K. Murai · R. Kondo (✉)
Department of Forest and Forest Products Sciences, Faculty of Agriculture, Kyushu University, 6-10-1 Hakozaki, Higashi-ku, Fukuoka 812-8581 Japan
Tel. +81-92-642-2811; Fax +81-92-642-2811
e-mail: ryukondo@agr.kyushu-u.ac.jp

palm is an important issue. It has been reported that starch content increased as the sago palms matured from *plawei* (mature vegetative growth) to *angau muda* (flowering) stage and decreased from *angau tua* (fruiting) to late *angau tua*.[14] There are also significant differences in granule size and amylase/amylopectin content of sago starch from sago palms of different growth stages.[15]

For economical bioethanol production, the concentration of ethanol after fermentation should be as high as possible. This decreases the costs of ethanol distillation, which is one of the most expensive steps in the bioethanol production process.[16] To achieve a high ethanol concentration after fermentation, it is essential to prepare a highly concentrated sugar solution. Thus, the objective of this study was to estimate the sugar composition of hot water extracts from OPTs of different growth stages. Sago palm is monocarpic, bearing fruits only once in its lifetime; in contrast, oil palm is polycarpic, bearing fruits several times. For this reason, we determined the composition of fruiting and nonfruiting palms, and palms of different ages. The results of this study can be used to determine the appropriate harvest time of OPTs to prepare highly concentrated sugar solutions for bioethanol production.

Material and methods

Sample preparation

This study was carried out in Ladang Tuan Mee, Sungei Buloh, Selangor, Malaysia. We harvested 31-year-old (A, B), 19-year-old (C, D), and 15-year-old (E, F) OPTs by cutting at the base of the trunk and then measured the height. OPTs A, C, E were from fruiting palms, and OPTs B, D, F were from nonfruiting palms. After harvesting, trunks were cut into discs and all discs were debarked. The diameter of each disc was measured and then the disc was cut into cubes (5 cm × 5 cm × 10 cm). The cubes were identified based on their location (northern or southern side of the trunk, and inner/outer region of the trunk; Fig. 1). Figure 2 shows the OPT sampling points. All OPT cubes were kept in the freezer before drying, and then were dried at 60°C for 2 days. The dried cubes were ground in a Wiley mill 1029-C (Yoshida Seisakusho, Tokyo) at a speed of 800 rpm for 1 min, and then in a crushing mill (A 11 basic analytical mill, IKA Japan, Nara) at a speed of 28 000 rpm for 1.5 min. After grinding, OPT meals were sieved through a 250-μm mesh sieve, which separated the meal into 250-μm pass and 250-μm over fractions. All separated OPT meals were weighed and then stored at room temperature in plastic bags until extraction experiments.

Determination of extractable sugars

To extract carbohydrate from OPT meal, 100 ml water, 1 g OPT meal, and 0.2% (v/v) alpha-amylase (Cleistase T10S, Amano Enzyme, Aichi) were autoclaved in a 200-ml Erlenmeyer flask at 121°C for 1 h. The hot water-extracted residues of OPT meal were removed by centrifugation at 1710 *g* for 10 min. Then, 2.7 ml supernatant was saccharified by adding 0.3 ml of 7 mg/ml glucoamylase (Gluczyme AF6, Amano Enzyme) solution, and the mixture was stirred at 100 rpm for 1 h at 55°C. After centrifugation at 20 600 *g* for 10 min, the mixture was filtered through a 0.45-μm membrane filter. The filtrate was then analyzed by high-performance liquid chromatography (HPLC) to quantify the amounts of extractable glucose, fructose, and sucrose. HPLC analyses were carried out on an HPLC instrument equipped with a Hitachi L-2130 pump and a Hitachi L-2490 RI detector fitted with a Shodex SUGAR SH1011 column (300 mm in length, inner diameter 8 mm; Showa Denko, Tokyo).

Results and discussion

Estimation of extractable sugar contents in OPTs

Table 1 shows the ratios of OPT meal weight (ROW), which compares the weight of 250-μm pass OPT meal to that of 250-μm over OPT meal. The center region of OPTs (sample numbers 2, 5, 8, 11, and 14) showed higher ROWs (typically ranging from 0.4 to 5.2) than those of samples from the northern and southern sides of the trunk. This is because

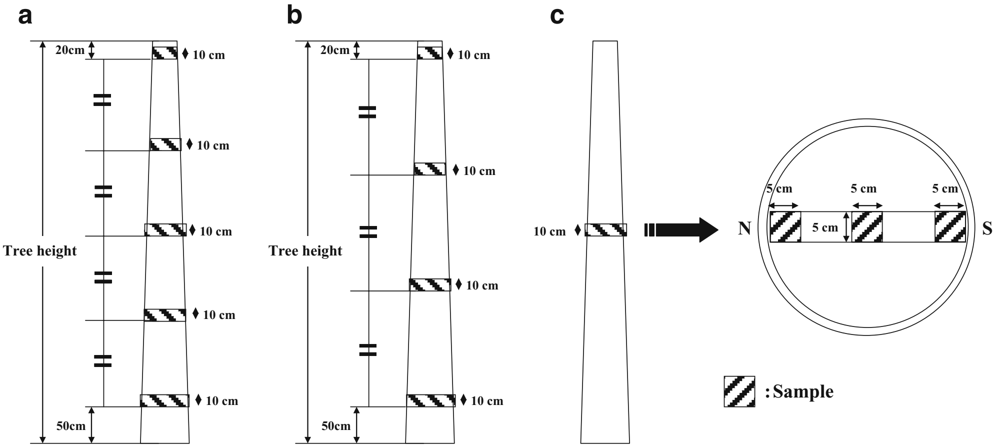

Fig. 1. Sampling method of oil palm trunks (OPTs). **a** Sampling of discs from 31- and 19-year-old OPTs (A–D). **b** Sampling of discs from 15-year-old OPT (E, F). **c** Sampling of cubes from disc

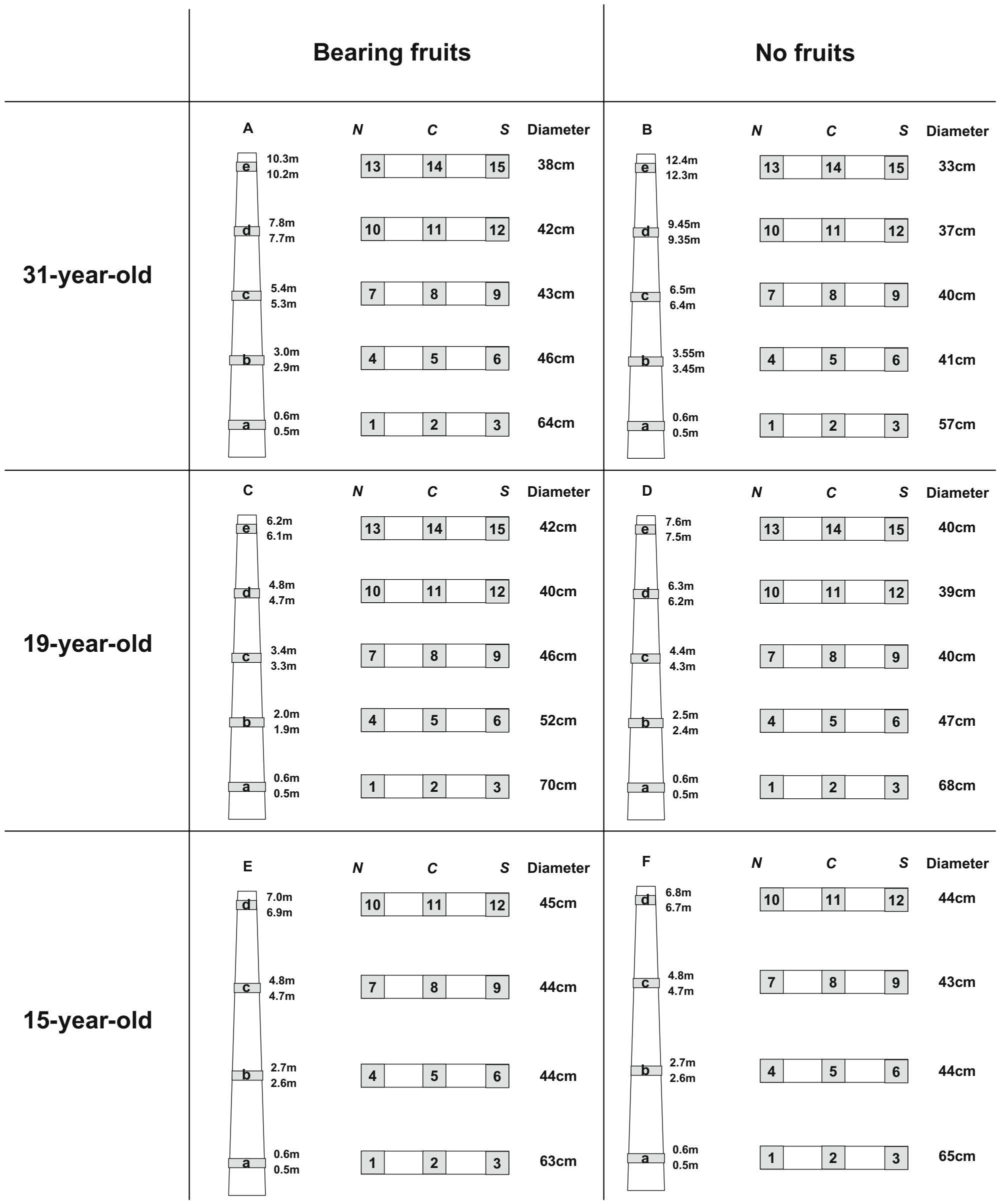

Fig. 2. The layout of sampling points of the 31-year-old (*A*, *B*), 19-year-old (*C*, *D*), and 15-year-old (*E*, *F*) OPTs. OPTs *A*, *C*, *E* were from fruiting palms, and OPTs *B*, *D*, *F* were from nonfruiting palms. *N*, north; *C*, center; and *S*, south

Table 1. Ratios of oil palm trunk (OPT) meal weight (250-μm pass OPT meal weight / 250-μm over OPT meal weight)

Sample number	A	B	C	D	E	F
1	0.63	0.93	0.81	0.90	0.65	0.71
2	1.54	1.59	1.73	1.21	2.04	1.00
3	0.65	0.69	0.88	0.98	0.81	0.57
4	0.49	0.79	0.68	0.63	1.02	0.54
5	1.45	0.80	1.87	1.02	4.87	1.27
6	0.47	0.54	0.60	0.78	1.33	0.50
7	0.43	0.45	0.64	0.67	1.60	0.54
8	0.47	1.10	1.64	1.06	3.42	1.15
9	0.37	0.46	0.60	1.01	2.43	0.66
10	0.54	0.63	0.62	1.00	1.89	1.17
11	0.40	1.30	1.25	2.28	5.24	3.83
12	0.77	0.62	0.54	1.10	2.19	1.26
13	1.68	0.86	1.09	1.05	–	–
14	3.51	2.41	2.49	1.84	–	–
15	1.15	0.91	1.17	0.85	–	–

the outer region near the bark contains abundant vascular bundles,[17] whereas the center region is composed of parenchymatous tissues.[17,18] Vascular bundles have lower starch contents than that of parenchyma cells, but instead contain other fundamental structural components, such as cellulose and lignin. This results in the rigid structure of vascular bundles and explains why it was difficult to grind outer OPT to a fine meal. OPT E had the highest ROW of all OPT samples.

Tables 2–7 show the composition of extractable sugars in the OPTs. The highest yield of hot water-extractable glucose (85%) was obtained from the 250-μm pass OPT E-11 meal (Table 6). This E-11 region had the highest ROW (5.2) of all the samples (Table 1). The high ROW value indicated that the sample consisted of parenchymatous tissues, and consequently, contained a high proportion of hot water-extractable glucose. Only small amounts fructose and

Table 2. Extractable sugar composition and estimated extractable sugar contents in the meal of OPT A (31-year-old, fruiting)

Sample number	Direction	Size	Sugar composition[c] (%)			Estimated sugar contents[d] (%)			
			Glucose	Fructose	Sucrose	Glucose	Fructose	Sucrose	Total
1	north	pass[a]	3.4 ± 0.1	1.6 ± 0.0	1.0 ± 0.0	2.5	1.5	0.5	4.6
		over[b]	2.0 ± 0.2	1.5 ± 0.1	0.3 ± 0.0				
2	center	pass[a]	6.4 ± 0.0	1.0 ± 0.0	1.3 ± 0.0	4.9	1.0	1.1	7.0
		over[b]	2.6 ± 0.0	1.0 ± 0.0	0.8 ± 0.4				
3	south	pass[a]	5.4 ± 0.0	2.0 ± 0.0	2.4 ± 0.0	3.7	2.0	1.6	7.3
		over[b]	2.6 ± 0.1	1.9 ± 0.0	1.1 ± 0.1				
4	north	pass[a]	5.5 ± 0.1	2.1 ± 0.0	0.5 ± 0.0	3.4	2.2	0.4	5.9
		over[b]	2.3 ± 0.2	2.2 ± 0.0	0.3 ± 0.0				
5	center	pass[a]	6.1 ± 0.0	2.1 ± 0.0	2.5 ± 0.0	5.0	2.0	2.0	9.0
		over[b]	3.5 ± 0.2	2.0 ± 0.1	1.1 ± 0.0				
6	south	pass[a]	4.9 ± 0.0	1.3 ± 0.0	0.3 ± 0.0	3.1	1.4	0.2	4.7
		over[b]	2.3 ± 0.0	1.4 ± 0.0	0.2 ± 0.0				
7	north	pass[a]	6.7 ± 0.2	2.8 ± 0.1	1.0 ± 0.3	3.9	2.8	0.6	7.3
		over[b]	2.7 ± 0.1	2.7 ± 0.0	0.5 ± 0.0				
8	center	pass[a]	7.7 ± 0.1	2.2 ± 0.1	2.7 ± 0.0	5.0	1.9	2.3	9.2
		over[b]	3.7 ± 0.2	1.8 ± 0.0	2.0 ± 0.5				
9	south	pass[a]	12.4 ± 0.2	2.1 ± 0.0	0.7 ± 0.0	5.0	2.0	0.4	7.4
		over[b]	2.3 ± 0.1	1.9 ± 0.0	0.3 ± 0.0				
10	north	pass[a]	23.8 ± 0.2	1.3 ± 0.0	0.7 ± 0.0	10.8	1.8	0.6	13.2
		over[b]	3.8 ± 0.2	2.1 ± 0.1	0.5 ± 0.0				
11	center	pass[a]	6.4 ± 0.1	2.1 ± 0.0	1.6 ± 0.0	4.6	2.1	1.7	8.4
		over[b]	3.9 ± 0.2	2.0 ± 0.0	1.7 ± 0.0				
12	south	pass[a]	28.9 ± 0.4	4.0 ± 0.2	0.7 ± 0.0	15.2	4.0	0.7	19.9
		over[b]	4.8 ± 0.1	4.1 ± 0.2	0.6 ± 0.0				
13	north	pass[a]	47.9 ± 0.1	2.5 ± 0.0	0.4 ± 0.0	32.2	3.1	0.4	35.8
		over[b]	5.8 ± 0.0	4.1 ± 0.0	0.5 ± 0.0				
14	center	pass[a]	76.4 ± 0.4	2.5 ± 0.0	0.5 ± 0.0	62.3	3.0	0.7	65.9
		over[b]	12.6 ± 0.9	4.8 ± 0.1	1.2 ± 0.1				
15	south	pass[a]	53.1 ± 1.1	3.0 ± 0.1	0.7 ± 0.1	32.9	3.8	0.8	37.5
		over[b]	9.7 ± 2.2	4.7 ± 0.1	0.9 ± 0.3				

[a] 250-µm pass
[b] 250-µm over
[c] Sugar composition values were expressed as a percentage of dry weight of OPT meal ± SD ($n = 2$)
[d] Extractable sugar contents were estimated as a percentage of dry weight of each region of OPT

Table 3. Extractable sugar composition and estimated extractable sugar contents in the meal of OPT B (31-year-old, nonfruiting)

Sample number	Direction	Size	Sugar composition[c] (%)			Estimated sugar contents[d] (%)			
			Glucose	Fructose	Sucrose	Glucose	Fructose	Sucrose	Total
1	north	pass[a]	6.0 ± 0.0	2.4 ± 0.0	1.0 ± 0.1	3.6	1.5	0.6	5.7
		over[b]	1.4 ± 0.1	0.6 ± 0.0	0.2 ± 0.0				
2	center	pass[a]	2.9 ± 0.0	1.2 ± 0.0	2.2 ± 0.0	2.7	1.3	1.7	5.6
		over[b]	2.2 ± 0.1	1.3 ± 0.0	0.8 ± 0.0				
3	south	pass[a]	3.6 ± 0.0	1.7 ± 0.0	1.6 ± 0.1	2.3	1.0	0.8	4.0
		over[b]	1.4 ± 0.1	0.5 ± 0.1	0.2 ± 0.0				
4	north	pass[a]	6.6 ± 0.0	1.8 ± 0.0	2.2 ± 0.0	3.9	1.2	1.2	6.2
		over[b]	1.8 ± 0.1	0.7 ± 0.1	0.3 ± 0.0				
5	center	pass[a]	14.2 ± 0.3	3.5 ± 0.1	2.0 ± 0.1	8.2	2.6	1.2	12.0
		over[b]	3.3 ± 1.9	1.9 ± 1.6	0.5 ± 0.4				
6	south	pass[a]	11.1 ± 0.0	1.3 ± 0.0	1.0 ± 0.0	6.0	1.7	0.7	8.3
		over[b]	3.2 ± 1.9	1.9 ± 1.6	0.5 ± 0.3				
7	north	pass[a]	10.0 ± 0.1	2.2 ± 0.0	1.3 ± 0.0	4.8	1.6	0.5	6.9
		over[b]	2.5 ± 0.0	1.3 ± 0.0	0.2 ± 0.0				
8	center	pass[a]	9.4 ± 0.4	4.1 ± 0.1	3.5 ± 0.0	8.1	4.1	3.2	15.5
		over[b]	6.7 ± 0.3	4.2 ± 0.0	2.9 ± 0.0				
9	south	pass[a]	15.0 ± 0.1	2.7 ± 0.0	1.9 ± 0.0	6.7	2.4	0.9	10.1
		over[b]	2.9 ± 0.0	2.3 ± 0.1	0.5 ± 0.1				
10	north	pass[a]	36.3 ± 0.2	2.2 ± 0.0	0.6 ± 0.0	16.3	2.8	0.5	19.5
		over[b]	3.6 ± 0.1	3.2 ± 0.1	0.4 ± 0.1				
11	center	pass[a]	48.3 ± 0.3	2.5 ± 0.0	2.3 ± 0.0	32.9	3.3	2.7	38.8
		over[b]	12.8 ± 0.9	4.3 ± 0.0	3.2 ± 0.0				
12	south	pass[a]	34.5 ± 0.9	3.3 ± 0.0	1.3 ± 0.0	16.6	4.2	1.4	22.2
		over[b]	5.5 ± 0.3	4.8 ± 0.1	1.5 ± 0.0				
13	north	pass[a]	63.2 ± 0.5	1.8 ± 0.0	0.4 ± 0.0	33.4	2.4	0.4	36.2
		over[b]	7.8 ± 0.3	2.9 ± 0.4	0.3 ± 0.1				
14	center	pass[a]	69.3 ± 0.4	1.0 ± 0.0	0.5 ± 0.0	54.1	1.2	0.5	55.8
		over[b]	17.7 ± 1.8	1.6 ± 0.1	0.4 ± 0.0				
15	south	pass[a]	69.0 ± 2.2	1.4 ± 0.4	0.3 ± 0.0	36.8	1.8	0.4	39.1
		over[b]	7.4 ± 1.0	2.3 ± 0.1	0.5 ± 0.0				

[a] 250-µm pass
[b] 250-µm over
[c] Sugar composition values were expressed as a percentage of dry weight of OPT meal ± SD ($n = 2$)
[d] Extractable sugar contents were estimated as a percentage of dry weight of each region of OPT

Table 4. Extractable sugar composition and estimated extractable sugar contents in the meal of OPT C (19-year-old, fruiting)

Sample number	Direction	Size	Sugar composition[c] (%)			Estimated sugar contents[d] (%)			
			Glucose	Fructose	Sucrose	Glucose	Fructose	Sucrose	Total
1	north	pass[a]	6.7 ± 0.2	2.6 ± 0.1	0.3 ± 0.0	4.4	1.8	0.4	6.6
		over[b]	2.5 ± 0.1	1.2 ± 0.1	0.5 ± 0.0				
2	center	pass[a]	3.5 ± 0.1	2.0 ± 0.0	0.5 ± 0.0	3.1	1.8	0.4	5.3
		over[b]	2.4 ± 0.0	1.3 ± 0.0	0.3 ± 0.0				
3	south	pass[a]	7.5 ± 0.1	3.3 ± 0.1	2.0 ± 0.0	5.6	2.6	1.8	10.1
		over[b]	4.0 ± 0.0	2.0 ± 0.0	1.6 ± 0.0				
4	north	pass[a]	13.0 ± 0.4	2.9 ± 0.1	2.0 ± 0.1	7.3	2.3	1.6	11.2
		over[b]	3.5 ± 0.1	1.9 ± 0.0	1.4 ± 0.1				
5	center	pass[a]	8.7 ± 0.4	4.5 ± 0.2	2.0 ± 0.1	7.7	4.2	1.6	13.5
		over[b]	5.9 ± 0.1	3.7 ± 0.0	0.7 ± 0.0				
6	south	pass[a]	12.5 ± 0.1	2.9 ± 0.0	1.2 ± 0.2	8.6	3.1	1.2	12.9
		over[b]	6.2 ± 0.2	3.3 ± 0.0	1.1 ± 0.0				
7	north	pass[a]	30.8 ± 0.5	3.6 ± 0.1	2.5 ± 0.1	16.7	3.8	2.2	22.7
		over[b]	7.7 ± 0.8	3.9 ± 0.3	2.1 ± 0.5				
8	center	pass[a]	12.8 ± 0.2	5.4 ± 0.0	3.6 ± 0.1	11.0	5.1	3.4	19.5
		over[b]	8.0 ± 0.2	4.7 ± 0.1	3.0 ± 0.1				
9	south	pass[a]	19.5 ± 0.5	4.0 ± 0.1	2.6 ± 0.0	10.8	3.8	2.1	16.7
		over[b]	5.7 ± 0.1	3.7 ± 0.1	1.8 ± 0.0				
10	north	pass[a]	38.2 ± 0.1	4.5 ± 0.0	0.5 ± 0.0	19.1	4.9	1.6	25.5
		over[b]	7.2 ± 0.2	5.1 ± 0.2	2.2 ± 0.5				
11	center	pass[a]	27.7 ± 0.7	7.0 ± 0.2	3.4 ± 0.2	21.5	6.7	2.9	31.1
		over[b]	13.7 ± 0.5	6.4 ± 0.2	2.3 ± 0.6				
12	south	pass[a]	22.8 ± 0.2	3.2 ± 0.1	1.7 ± 0.0	13.0	3.5	1.4	17.8
		over[b]	7.7 ± 0.2	3.6 ± 0.1	1.2 ± 0.2				
13	north	pass[a]	69.2 ± 1.7	1.1 ± 0.0	0.5 ± 0.4	39.7	1.7	0.5	41.9
		over[b]	7.5 ± 0.3	2.4 ± 0.0	0.6 ± 0.2				
14	center	pass[a]	59.5 ± 0.7	0.5 ± 0.0	2.9 ± 0.5	46.5	0.6	2.2	49.3
		over[b]	14.0 ± 0.9	0.9 ± 0.0	0.6 ± 0.0				
15	south	pass[a]	70.1 ± 0.3	1.3 ± 0.0	0.4 ± 0.2	41.2	2.1	0.8	44.2
		over[b]	7.5 ± 0.2	3.1 ± 0.2	1.3 ± 0.1				

[a] 250-µm pass
[b] 250-µm over
[c] Sugar composition values were expressed as a percentage of dry weight of OPT meal ± SD ($n = 2$)
[d] Extractable sugar contents were estimated as a percentage of dry weight of each region of OPT

Table 5. Extractable sugar composition and estimated extractable sugar contents in the meal of OPT D (19-year-old, nonfruiting)

Sample number	Direction	Size	Sugar composition[c] (%)			Estimated sugar contents[d] (%)			
			Glucose	Fructose	Sucrose	Glucose	Fructose	Sucrose	Total
1	north	pass[a]	4.5 ± 0.1	0.6 ± 0.0	0.4 ± 0.0	3.1	0.6	0.3	4.0
		over[b]	1.8 ± 0.0	0.6 ± 0.0	0.1 ± 0.0				
2	center	pass[a]	2.8 ± 0.0	1.0 ± 0.0	0.2 ± 0.0	2.3	0.8	0.2	3.2
		over[b]	1.7 ± 0.2	0.5 ± 0.0	0.1 ± 0.1				
3	south	pass[a]	3.9 ± 0.1	1.7 ± 0.0	0.6 ± 0.0	2.9	1.3	0.3	4.5
		over[b]	2.0 ± 0.0	0.9 ± 0.1	nd[e]				
4	north	pass[a]	12.5 ± 0.6	2.5 ± 0.2	1.2 ± 0.6	6.5	2.1	0.7	9.3
		over[b]	2.7 ± 0.0	1.9 ± 0.1	0.4 ± 0.0				
5	center	pass[a]	5.8 ± 0.2	1.8 ± 0.1	4.1 ± 0.1	4.2	1.4	3.0	8.6
		over[b]	2.6 ± 0.2	0.9 ± 0.0	1.9 ± 0.2				
6	south	pass[a]	9.9 ± 0.2	3.2 ± 0.1	nd[e]	7.0	2.8	0.0	9.8
		over[b]	4.7 ± 0.3	2.4 ± 0.3	nd[e]				
7	north	pass[a]	44.5 ± 0.9	2.4 ± 0.0	2.3 ± 0.1	21.3	2.9	0.9	25.1
		over[b]	5.7 ± 0.1	3.2 ± 0.1	nd[e]				
8	center	pass[a]	40.1 ± 0.5	7.4 ± 0.1	3.7 ± 0.3	26.2	7.7	3.9	37.8
		over[b]	11.4 ± 0.3	8.1 ± 0.1	4.1 ± 0.1				
9	south	pass[a]	32.7 ± 0.2	1.5 ± 0.1	2.0 ± 0.2	18.1	1.6	1.3	21.0
		over[b]	3.5 ± 0.0	1.7 ± 0.1	0.5 ± 0.0				
10	north	pass[a]	48.8 ± 0.3	1.3 ± 0.0	1.3 ± 0.2	26.5	1.8	0.8	29.0
		over[b]	4.1 ± 0.1	2.2 ± 0.2	0.3 ± 0.0				
11	center	pass[a]	71.4 ± 0.1	0.8 ± 0.0	1.6 ± 0.1	53.2	1.4	1.6	56.1
		over[b]	11.6 ± 0.6	2.5 ± 0.2	1.5 ± 0.6				
12	south	pass[a]	54.7 ± 0.1	1.9 ± 0.0	1.5 ± 0.1	32.5	3.0	1.5	37.0
		over[b]	8.1 ± 0.2	4.1 ± 0.1	1.5 ± 0.0				
13	north	pass[a]	46.0 ± 0.2	0.8 ± 0.0	2.3 ± 0.1	25.6	1.0	1.4	27.9
		over[b]	4.1 ± 0.1	1.2 ± 0.1	0.4 ± 0.0				
14	center	pass[a]	70.8 ± 0.2	1.0 ± 0.0	1.9 ± 0.2	51.7	1.9	2.0	55.6
		over[b]	16.5 ± 1.6	3.6 ± 0.1	2.1 ± 0.3				
15	south	pass[a]	52.4 ± 0.3	0.4 ± 0.0	2.2 ± 0.1	26.1	0.6	1.3	28.0
		over[b]	3.9 ± 0.0	0.7 ± 0.0	0.6 ± 0.2				

[a] 250-µm pass
[b] 250-µm over
[c] Sugar composition values were expressed as a percentage of dry weight of OPT meal ± SD ($n = 2$)
[d] Extractable sugar contents were estimated as a percentage of dry weight of each region of OPT
[e] Not detected

Table 6. Extractable sugar composition and estimated extractable sugar contents in the meal of OPT E (15-year-old, fruiting)

Sample number	Direction	Size	Sugar composition[c] (%)			Estimated sugar contents[d] (%)			
			Glucose	Fructose	Sucrose	Glucose	Fructose	Sucrose	Total
1	north	pass[a]	7.8 ± 0.2	3.0 ± 0.1	0.5 ± 0.1	4.2	1.6	0.5	6.3
		over[b]	1.9 ± 0.3	0.6 ± 0.1	0.5 ± 0.1				
2	center	pass[a]	15.1 ± 0.8	7.0 ± 0.2	0.4 ± 0.5	11.9	5.7	0.4	17.9
		over[b]	5.4 ± 0.9	2.9 ± 0.4	0.4 ± 0.0				
3	south	pass[a]	5.8 ± 0.4	1.1 ± 0.1	0.0 ± 0.0	3.8	0.7	0.0	4.6
		over[b]	2.2 ± 0.2	0.4 ± 0.1	0.0 ± 0.0				
4	north	pass[a]	49.6 ± 0.6	1.8 ± 0.1	1.1 ± 0.6	27.6	1.9	2.0	31.5
		over[b]	5.2 ± 0.3	2.0 ± 0.1	2.8 ± 0.3				
5	center	pass[a]	72.4 ± 2.9	1.0 ± 0.0	8.4 ± 0.8	61.6	1.5	7.8	70.9
		over[b]	9.1 ± 0.5	3.4 ± 0.1	5.2 ± 0.2				
6	south	pass[a]	68.4 ± 0.2	1.2 ± 0.0	0.4 ± 0.1	41.4	1.9	0.2	43.5
		over[b]	5.4 ± 0.4	2.8 ± 0.2	0.1 ± 0.0				
7	north	pass[a]	73.1 ± 1.3	1.2 ± 0.0	2.2 ± 0.0	47.6	1.7	1.4	50.6
		over[b]	6.9 ± 0.0	2.4 ± 0.1	0.1 ± 0.0				
8	center	pass[a]	49.5 ± 0.7	4.3 ± 0.1	1.0 ± 0.0	42.2	5.0	0.9	48.1
		over[b]	17.2 ± 0.3	7.5 ± 0.2	0.8 ± 0.0				
9	south	pass[a]	72.5 ± 0.0	1.4 ± 0.0	2.4 ± 0.0	52.2	1.6	1.8	55.6
		over[b]	3.2 ± 0.1	2.2 ± 0.3	0.3 ± 0.1				
10	north	pass[a]	74.0 ± 1.1	1.0 ± 0.1	1.8 ± 0.2	49.6	1.0	1.2	51.7
		over[b]	3.3 ± 0.0	0.9 ± 1.2	0.2 ± 0.2				
11	center	pass[a]	85.0 ± 1.1	1.1 ± 0.0	0.4 ± 0.1	74.6	1.3	0.4	76.3
		over[b]	19.8 ± 3.6	2.7 ± 0.4	0.2 ± 0.0				
12	south	pass[a]	82.5 ± 0.4	0.7 ± 0.0	0.7 ± 0.0	57.8	1.0	0.5	59.3
		over[b]	3.9 ± 0.2	1.7 ± 0.1	0.1 ± 0.0				

[a] 250-µm pass
[b] 250-µm over
[c] Sugar composition values were expressed as a percentage of dry weight of OPT meal ± SD ($n = 2$)
[d] Extractable sugar contents were estimated as a percentage of dry weight of each region of OPT

Table 7. Extractable sugar composition and estimated extractable sugar contents in the meal of OPT F (15-year-old, nonfruiting)

Sample number	Direction	Size	Sugar composition[c] (%)			Estimated sugar contents[d] (%)			
			Glucose	Fructose	Sucrose	Glucose	Fructose	Sucrose	Total
1	north	pass[a]	5.3 ± 0.1	0.3 ± 0.0	nd[e]	2.9	0.2	0.0	3.1
		over[b]	1.3 ± 0.1	0.0 ± 0.0	nd[e]				
2	center	pass[a]	7.6 ± 0.0	3.9 ± 0.0	0.9 ± 0.0	7.6	4.2	0.8	12.7
		over[b]	7.7 ± 0.5	4.6 ± 0.3	0.8 ± 0.1				
3	south	pass[a]	8.1 ± 0.1	3.6 ± 0.0	0.9 ± 0.0	6.1	3.1	0.6	9.7
		over[b]	4.9 ± 0.1	2.8 ± 0.1	0.4 ± 0.6				
4	north	pass[a]	5.9 ± 0.2	2.6 ± 0.1	0.6 ± 0.0	4.5	2.5	0.4	7.4
		over[b]	3.8 ± 0.1	2.4 ± 0.0	0.3 ± 0.0				
5	center	pass[a]	7.4 ± 0.0	2.0 ± 0.0	2.2 ± 0.0	5.7	2.2	2.3	10.1
		over[b]	3.5 ± 0.1	2.4 ± 0.0	2.3 ± 0.1				
6	south	pass[a]	12.5 ± 0.0	4.3 ± 0.0	1.5 ± 0.0	9.0	4.7	0.9	14.6
		over[b]	7.3 ± 0.4	4.9 ± 0.3	0.6 ± 0.0				
7	north	pass[a]	19.0 ± 0.2	1.1 ± 0.0	0.8 ± 0.1	8.0	1.3	0.5	9.8
		over[b]	2.1 ± 0.1	1.4 ± 0.1	0.3 ± 0.0				
8	center	pass[a]	45.1 ± 1.2	4.0 ± 0.0	0.6 ± 0.1	28.9	4.9	0.6	34.5
		over[b]	10.3 ± 2.1	6.0 ± 0.3	0.7 ± 0.0				
9	south	pass[a]	31.7 ± 0.6	0.2 ± 0.0	0.5 ± 0.0	14.4	0.7	0.7	15.7
		over[b]	3.0 ± 0.1	0.9 ± 0.0	0.8 ± 0.1				
10	north	pass[a]	61.5 ± 0.3	0.0 ± 0.0	1.0 ± 0.2	34.3	0.2	0.6	35.2
		over[b]	2.6 ± 0.2	0.5 ± 0.0	0.1 ± 0.0				
11	center	pass[a]	75.7 ± 1.4	0.6 ± 0.0	1.3 ± 0.0	61.1	0.8	1.1	63.0
		over[b]	5.4 ± 0.1	1.5 ± 0.0	0.2 ± 0.0				
12	south	pass[a]	58.0 ± 0.0	0.7 ± 0.1	2.3 ± 0.6	34.0	0.9	1.4	36.3
		over[b]	3.9 ± 0.1	1.1 ± 0.1	0.3 ± 0.0				

[a] 250-µm pass
[b] 250-µm over
[c] Sugar composition values were expressed as a percentage of dry weight of OPT meal ± SD ($n = 2$)
[d] Extractable sugar contents were estimated as a percentage of dry weight of each region of OPT
[e] Not detected

Table 8. Estimated extractable glucose, fructose, and sucrose contents of the whole and the upper and lower regions of OPT A-F and II[11]

OPT			A	B	C	D	E	F	II
Whole	Weight (kg)	OPT	533.1	520.7	351.3	391.3	380.7	369.5	259.2
		Glucose · · · (a)	48.6	60.9	45.8	61.9	150.1	52.0	59.8
		Fructose	11.7	11.5	11.9	8.4	8.1	8.9	11.6
		Sucrose	4.9	5.9	5.7	4.6	6.3	3.1	10.0
	Sugar contents (%)	Glucose	9.1	11.7	13.0	15.8	39.4	14.1	23.1
		Fructose	2.2	2.2	3.4	2.2	2.1	2.4	4.5
		Sucrose	0.9	1.1	1.6	1.2	1.7	0.8	3.9
Upper	Weight (kg)	OPT	220.2	210.2	128.1	133.4	170.7	154.4	113.0
		Glucose · · · (b)	36.2	45.0	28.5	41.9	87.9	37.5	37.7
		Fructose	6.0	6.0	5.0	3.2	3.5	2.7	4.7
		Sucrose	2.0	2.5	2.4	2.0	2.2	1.2	5.1
	Sugar contents (%)	Glucose · · · (c)	16.5	21.4	22.2	31.4	51.5	24.3	33.4
		Fructose	2.7	2.9	3.9	2.4	2.1	1.7	4.1
		Sucrose	0.9	1.2	1.9	1.5	1.3	0.8	4.5
Lower	Weight (kg)	OPT	312.9	310.5	223.1	257.9	210.0	215.1	146.2
		Glucose · · · (d)	12.4	15.8	17.3	20.0	62.2	14.5	22.1
		Fructose	5.7	5.5	6.8	5.3	4.6	6.2	6.9
		Sucrose	2.9	3.4	3.3	2.6	4.2	1.8	4.9
	Sugar contents (%)	Glucose · · · (e)	4.0	5.1	7.8	7.8	29.6	6.7	15.1
		Fructose	1.8	1.8	3.1	2.0	2.2	2.9	4.7
		Sucrose	0.9	1.1	1.5	1.0	2.0	0.9	3.4
Ratio		(b)/(a)	0.75	0.74	0.62	0.68	0.59	0.72	0.63
		(d)/(a)	0.25	0.26	0.38	0.32	0.41	0.28	0.37
		(c)/(e)	4.17	4.20	2.86	4.05	1.74	3.61	2.20

sucrose were extracted from OPT samples, regardless of the region or meal size.

The extractable sugar contents of each OPT region were estimated from their ROW values (Table 1). The composition of sugars extracted from the OPT meal is shown in Tables 2–7. Overall, upper and inner regions had higher estimated extractable glucose contents because of their higher ROW values and higher levels of extractable glucose in their OPT meal.

Table 8 shows the estimated extractable glucose, fructose, and sucrose contents in OPTs A–F. These estimates were calculated based on the values shown in Tables 2–7, the OPT disk diameter, height, and density. We estimated the extractable sugar contents for whole OPTs, upper regions of OPTs, and lower regions of OPTs (Fig. 3). Extractable fructose and sucrose contents were similar among all OPTs, regardless of age or fruiting condition. OPT E had the highest glucose content of all the samples.

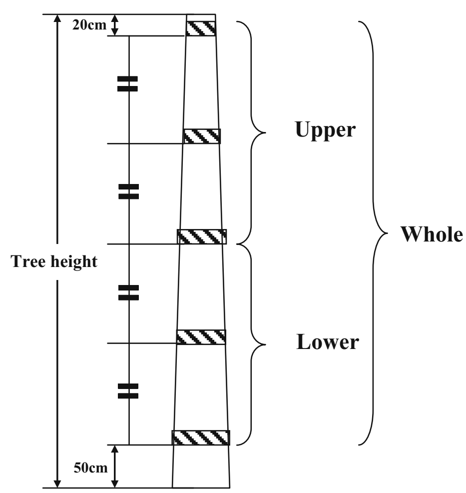

Fig. 3. The definition of whole, upper, and lower regions of OPTs

Estimated extractable glucose contents of OPTs of different ages

Figure 4 shows the estimated extractable glucose contents (%) of 31-year-old (A, B), 19-year-old (C, D), and 15-year-old (E, F) OPTs. The estimated extractable glucose content (%) of 25-year-old OPT II is also shown, although that palm was not separated into fruiting and nonfruiting samples.[11] The estimated extractable glucose contents of whole OPT A and B were 9.1% and 11.7%, respectively. These values were lower than those determined for 15-, 19-, and 25-year-old OPTs. For commercial bioethanol production from waste OPTs, highly concentrated solutions of carbohydrates should be used for fermentation and distillation. This result indicated that younger OPTs would yield the highest concentrations of carbohydrates, and therefore, OPTs should be harvested as soon as production of palm oil is completed. There were no significant differences among estimated extractable glucose contents (kg) of whole and upper OPTs of different ages, except for OPT E.

Estimated extractable glucose contents of fruiting and nonfruiting OPTs

We determined the estimated glucose weight ratios (extractable glucose content of upper OPT / extractable glucose

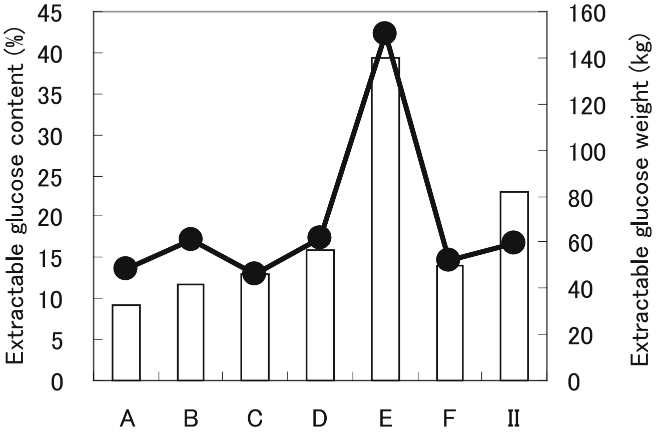

Fig. 4. Estimated extractable glucose content and weight in whole OPT *A–F* and *II*. *Bars* and *circles* show estimated extractable glucose content and extractable glucose weight, respectively

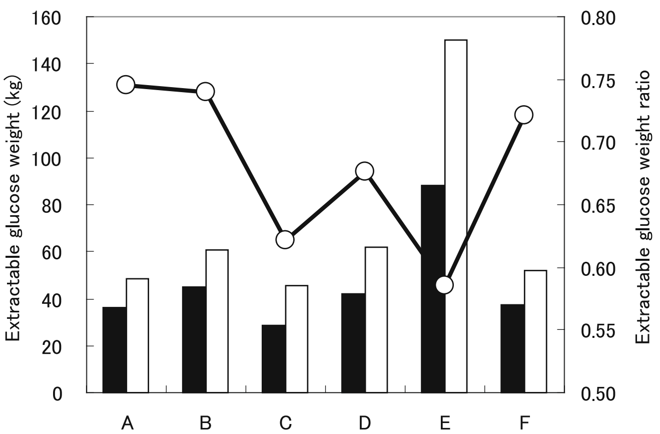

Fig. 5. Extractable glucose distribution of OPT *A–F*. *Solid bars*, *open bars*, and *circles* show the extractable glucose weight of upper OPT and whole OPT and the extractable glucose weight ratio [extractable glucose content of upper OPT / extractable glucose content of whole OPT], respectively

content of whole OPT) of fruiting and nonfruiting OPTs. The estimated glucose weight ratios of OPT A and B (31-year-old) were 0.75 and 0.74, respectively. Those of OPT C and D, (19-year-old), and E and F (15-year-old), were 0.62, 0.68, 0.59, and 0.72, respectively (Fig. 5). These results suggested that the upper parts of OPTs would yield more concentrated glucose solutions than the lower parts of OPTs. Comparison of the distribution of extractable glucose showed that upper, nonfruiting OPTs had higher carbohydrate contents than upper, fruiting OPTs. In this study, oil palms with bunches of black (unripe) or reddish-orange (ripe) fruits were classified as fruiting, and those with bunches of decayed fruits or male flowers were classified as nonfruiting. Before ripening, the mesocarp contains a high percentage of carbohydrates.[5] The carbohydrates in OPTs is consumed as oil is produced in the fruits; therefore, fruiting oil palms contained lower levels of carbohydrates in the upper trunk region compared with the same region of nonfruiting palms. This result suggested that if only upper regions of OPTs are used in bioethanol production, the OPTs should be harvested after fruiting, rather than during fruiting, to obtain the most concentrated sugar solutions. After fruiting has finished, the fruits decay and new male flowers appear. At this time, carbohydrates would be stored in OPTs. For this reason, we suggest that the best time to harvest OPTs for bioethanol production is the period when new male flowers appear.

In this study, the differences in sugar composition of hot water extracts from OPTs of different growth stages were revealed. However, the individual differences of hot water-extractable glucose contents from OPT A–F were very large, especially for OPT E. Further in-depth studies on the sugar composition of many OPTs could help resolve the source of these individual differences.

Estimation of extractable glucose and ethanol concentrations using two bioethanol production runs

The process of bioethanol production from OPTs comprises four major operations: (1) crushing; (2) hot water extraction, liquefaction, and saccharification; (3) fermentation; and (4) distillation. We estimated the amount of extractable glucose in two bioethanol production runs, *A* and *B*. In run *A*, whole OPT C (19-year-old fruiting palms, weight of OPT: 351.3 kg, weight of extractable glucose, fructose, and sucrose: 45.8, 11.9, and 5.7 kg, respectively) was used as the source material. In run *B*, upper OPT D (19-year-old nonfruiting palms, weight of OPT: 133.4 kg, weight of extractable glucose, fructose, and sucrose: 41.9, 3.2, and 2.0 kg, respectively) was used as the source material. Previously, we reported that the hot water-extractable glucose yield using 18 g OPT meal in 80 ml water was only 15% lower than that for 1 g OPT meal in 80 ml water.[11] Under low water-to-OPT-meal ratio extraction conditions, the amount of glucose extracted was estimated to be 38.9 kg using run *A* and 35.6 kg using run *B*. Therefore, the amount of extractable glucose obtained using run *B* was only approximately 10% lower than that obtained using run *A*, despite the much lower weight of OPT used in run *B*.

The ethanol concentrations (%) after fermentation using runs *A* and *B* were calculated based on the glucose (ethanol conversion: 95%[19]), fructose (ethanol conversion: 90%[19]), and sucrose (ethanol conversion: 70%[20]) concentrations in the OPT meal extracts. The estimated ethanol concentration using runs *A* and *B* was 1.7% and 3.2%, respectively, i.e., the concentration of ethanol using run *B* was estimated to be approximately twice that obtained using run *A*. In the distillation process, the concentration of ethanol has a major effect on energy demand, especially at concentrations below 4%.[21] Using run *B*, the estimated concentration of ethanol was closer to 4%. From another point of view, the estimated ethanol production from OPTs per 1 ha harvested area using run *B* was 3.5 kl/ha (calculated based on a planting rate of 142 OPTs per 1 ha).[11] This value is similar to those for corn and sugar cane (2.1 and 5.2 kl per 1 ha cultivated area, respectively).[22] Further research is required to increase the concentration of ethanol obtained from OPTs to levels similar to those obtained from corn and sugar cane (i.e., 7%–15%[23]).

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