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Full Length Article

Determining Criteria of Harvestable Sago Palm (*Metroxylon sagu*) Cultivated on Deep Peat and Contents of its Macro- and Micronutrients in Shoot

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Abstract

Sago palm (*Metroxylon sagu* Rottb.) is normally harvested from bolting to flowering stages on a commercial scale. Since flowering stage can last for months and number of living fronds gradually reduces, proper harvest criteria need to be managed. The nutrient content of the shoot may provide knowledge to estimate the need of major and minor nutrients but information is still limited. Two experiments were performed to study harvest criteria particularly at flowerings stage and nutrient uptake on harvestable palm cultivated on deep peat. Contents of N, P, K, Ca, Mg, Fe, Mn, Zn, B, Cu, starch and moisture contents were analyzed. Fifteen selected palms at various development stages were distributed on around 350 ha cultivated area. A maximum starch content was observed at just after flowering followed by bolting stage (22.34–28.75%) and their differences were not significant. Palm at flowering stage carrying ≥5 living fronds still contained starch content above 20%. It significantly reduced to 11.96 and 8.61% when number of fronds were four and two, respectively. In 595.6 kg shoot dry matter, K (3,402.8 g) was majorly taken up followed by N (2,111.3 g), Ca (2,043.1 g), Mg (831.4 g), and P (274.0 g). Among micronutrients, Mn (60,663.6 mg) was majorly taken up followed by Fe (19,440.7 mg), Zn (11,100.0 mg), B (3,120.5 mg), and Cu (1,338.1 mg). In conclusion, palm at flowering stage carrying five number of fronds and above is still harvestable. Hence, to obtain high starch productivity, harvest should be managed on bolting and just after flowering stages.

Keywords: Developmental stages; Frond number; Harvestable palm; Shoot nutrient; Starch content

Introduction

Sago palm (*Metroxylon sagu* Rottb.) is a starch producing crop that possess high adaptability to thrive on acid soil (Ehara *et al.* 2021) such as peat, which is generally characterized by low availability of macro- and micronutrients (Kolka *et al.* 2016), and growing environment with temporary and long inundated periods (Yater *et al.* 2019; Monda *et al.* 2022). It is commonly harvested before fruiting stage (Jong 1995). Although Nakamura (2018) suggests that the trunk should be harvested during the time from just before flower initiation to flowering, the best stage to harvest is reported just before the onset of the inflorescence (Flach 1997). At this stage, starch content is maximum. However, issues of harvest management on commercial sago palm plantation are very complex involving many factors such as harvester basis, availability of harvesting access and harvester group, field-weed condition, and uneven distribution of harvestable palms at various development stages on cultivated blocks. Bolting stage is one of the recommended stages for harvest used by locals. However, the period required to attain bolting stage since transplanting among the planted materials varies remarkably. One of the reasons is due to low survival rate after transplanting. Based on plantation experiences, it is around 60%. As a consequence, planted materials have various ages after transplanting as retransplanting is performed frequently to maximize population density. In Riau Province, Indonesia, where the commercial sago plantation is established on deep peat, around 30% of the palms attained harvesting stage in about 11 years (Jong 2018). This issue leads to the use of a wide range of harvest criteria from bolting to flowering stages for harvest standard. Those stages are also practiced creating easy harvest management with distinct visual indicator on field. However, since the flowering stage may last for months (Jong 1995), variation of starch content in palms may occur. During flowering stage, palms carry various number of living fronds. It gradually reduces as the palm begins entering the dying stage.

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To keep the quantity of starch during flowering stage, more distinct visual indicator needs to be determined to predict the content of starch in palms as it may be strongly related with number of living fronds. Latest studies involving a lot of trunk morphologies and estimation of starch yield in several sago growing areas in Indonesian regions such as Maluku (Yamamoto *et al.* 2020a), West Papua (Yamamoto *et al.* 2020b), Papua (Yamamoto *et al.* 2020c), and West Pontianak (Yamamoto *et al.* 2020d) with specific folk-varieties have been well documented. However, development stages of the sampled palm were mostly limited to before flowering and they were growing on mineral soil. Reports on starch content produced by the palm cultivated on peat during flowering stage and its relation to number of living fronds are still very limited.

Nutrients taken up by sago palm at 8, 10 and 13 years after planting and at flowering stage had been studied by Yamaguchi and Okazaki (1998). However, micronutrients reported on earlier study are still limited on Cu and Zn. Other elements such as Fe, Mn, and B are still not reported. Those micronutrients are reported as the trace metal elements that play a broad role in the peatland system (Bhattacharyya *et al.* 2018; Zhang *et al.* 2020). In order to maintain high productivity in sustainable cultivation, it is important to know the total mass of those nutrients in shoot of sago palm at harvesting stage to obtain a clear description of what major and minor nutrients required by sago palm to thrive on peatland. However, studies on shoot nutrients of sago palm are still limited.

Based on the above information, this study was undertaken to determine harvest criteria associated with changes in starch and number of living fronds especially during flowering stage. Implication of this finding would support the standard practice for the harvest management of sago palm on deep peat in determining the suitable harvest criteria at flowering stage. The contents of macro- (N, P, K, Ca Mg) and micronutrients (Cu, B, Fe, Zn Mn) in shoot of harvestable palm at bolting stage was also described to identify the need of major and minor nutrients on deep peat.

Materials and Methods

Site of study

A field study was performed in 2022 on sago palm (*Metroxylon sagu* Rottb.) cultivated area belonging to PT National Sago Prima, a subsidiary of PT Sampoerna Agro Tbk. The plantation was established on deep peat soil located at Tebing Tinggi Island, Meranti Regency, Riau Province, Indonesia. The study comprised two different experiments. Experiment 1 was to study a change in starch content on harvestable palms carrying different number of living fronds at various development stages. Experiment 2 was to study the uptake of macro- and micronutrients on shoot of harvestable palm at bolting stage.

Experiment 1: Determining criteria of harvestable palm particularly at flowering stage

Experimental design and selection of harvestable palm: A stratified randomized sampling method was used in experiment 1. Thirteen harvestable palms were selected based on the standard of plantation's harvesting practice criteria. The development stages were distributed from bolting (three palms), just after flowering (two palms), and flowering (seven palms) stages. Two palms at dying stage were selected for comparison because they are not usually harvested due to low starch content. The ages of those palms were estimated to be about 12–14 years after transplanting. These development stages are illustrated as Fig. 2. The selected palms were distributed on about 350 ha of cultivated blocks and they carried various number of living fronds. Detail distribution of 15 palm samples used in experiment 1 at the sampling site based on geographical position by google earth is shown on Fig. 1. The sites, where the sample palms were cultivated, had never been applied by any kinds of fertilizer.

Measurement of trunk morphology and pith sample collection: The trunk's fresh biomass, length, diam at breast height (DABH), and the number of living fronds on the palms were measured. The DABH was taken at 150 cm above the soil. The trunk was harvested following the plantation's standard procedure. After felling, the palm trunk was separated from the crown. The lowest living frond marked the topmost point of the trunk. The trunk length was measured from the base to the terminal axis at the node of the lowest living frond. It was then cut into ~1 m-long logs. The total fresh biomass of the trunk was calculated by summing up the weight of all logs. A 5 cm thick disc was taken from each log as a sample from which a 100 g fresh pith sample was collected, representing the central, middle, and outer layers of the trunk's cross-section.

Experiment 2: Contents of macro- and micronutrients in shoot at bolting stage

Selection of harvestable palm: An healthy harvestable palm at bolting stage having 10 m long trunk and carrying 23 living fronds was selected and harvested. The latitude where the palm was sampled was 0°48'53"N 102°57'11"E. The palm grew in a cluster as a mother palm and it produced five large-size suckers at rosette stage. Three suckers had frond base diam of about 30–35 cm. The other two suckers had size of about 10–15 cm.

Soil chemical properties around the sampled palm and analysis method: About 1 kg of topsoil sample (20 cm from soil surface) was collected at a distance of 1 m away from the cluster. Soil pH, C-organic, total-N, CEC, exchangeable K, Ca, and Mg, available P, Cu, Fe, B, Mn, and Zn were analyzed. The content of total-N in soil was analyzed by the Kjeldahl method. Organic carbon (OC) was analyzed by Walkley and Black's method (Walkley 1947), and the value

Fig. 1: Distribution of sampled palms on experiment 1 at site of study located in Tebing Tinggi Island, Meranti Regency, Riau Province, Indonesia

Fig. 2: Development stages of sago palm at bolting stage with 14 living fronds (a), just after flowering stage with 11 living fronds (b), flowering stage with 8 (c), 6 living fronds (d) and dying stage without living fronds (e). The bolting stage is indicated by the appearance of short fronds at the top of crown and whitish petiole (dusted-circle red color). Just after flowering is indicated by emergence of folded inflorescence stalk. In commercial scale, the stages described on pictures a, b, c, and d are generally used for harvest standard

was determined using UV-spectrophotom (UV-1200, Shimadzu, Japan) at 561 nm. CEC, exchangeable K, Ca and Mg were analyzed by ammonium acetate at 1 M and pH 7 (Shuman and Duncan 1990). Available P was analyzed using Bray II method. Cu, Fe, Mn and Zn were analyzed using 25% HCl method while B was analyzed using borate ester distillation method.

Measurement of trunk morphology, pith sample collection, and distribution of shoot fraction: In experiment 2, shoot was divided into two components: trunk and crown. The trunk consisted of pith and bark fractions. The biomass of bark was calculated by multiplying trunk fresh biomass with 22.32% based on the study on log debarking performed by the plantation on deep peat. The crown consisted of spear leaf, leaflet (excl. midrib), midrib, rachis, petiole and leaf sheath, and edible bud (young shoot) fractions.

Analysis of dry matter percentage, moisture, and nutrient content in shoot: Dry matter was obtained after the sample was dried up in an oven at 80°C for 48 h. Moisture content was measured after they were dried in the oven at 105°C for 6 h. Contents of N, P, K, Ca, Mg, Mn, Fe, Zn, B, Cu and starch were analyzed. N was analyzed by the Kjeldahl method. P and B were analyzed by UV-spectrophotom (UV-1280, Shimadzu, Japan) at 410 and 420 nm, respectively. K was analyzed by flame photom (Jenway PFP7-UK) while Ca, Mg, Cu, Zn, Mn and Fe were analyzed by Atomic Absorption Spectrophotom (PerkinElmer PinAAcle 500-US). The starch content was determined as glucose using DNS reagent (Miller 1959). The α-amylase activity was determined by recording absorbance at 540 nm (Amoah *et al.* 2024) using UV-spectrophotom (UV-1200, SHIMADZU-Japan). Starch was determined by multiplying glucose concentration with 0.9.

Statistical analysis

The data of shoot morphology, biomass, and starch of each development stage obtained from experiment 1 were analyzed by one-way ANOVA using Statistix 9 analytical software version 9.1. A post-hoc test by Tukey HSD was performed when value of $P < 0.05$. A single factor (development stage) was divided into five treatments (bolting, just after flowering, flowering with ≥5 and ≤4 living fronds, and dying stages. Those treatments comprised of two to six replications.

Results

Experiment 1

Shoot morphology, pith, and starch of harvestable palm at various development stages: The averages of trunk biomass, length, and DABH of 13 harvestable trunks cultivated on peatland were 763 kg, 745 cm, 40.11 cm, respectively (Table 2). The number of living fronds at bolting (10–21) were similar to just after flowering (16–17) stages. A significant rapid reduction in the number of fronds occurred ahead dying stage. The pith dry matter percentage and starch content at just after flowering were maximum followed by bolting, flowering, and dying stages. Palms at flowering stage showed various starch content from 8.61–28.12% and it significantly declined to 1.50–7.22% at dying stage (Table 2).

Trend of number of living fronds and starch content with the progress of development stage: Linear relationship between starch content and number of living fronds was observed (Fig. 3). To see the trend of starch content reduction at flowering stage described in Fig. 4, number of living fronds is divided into two-point averages. Those are above and equal to or below five fronds. Distinct differences of those variables with the progress of development stage were observed (Fig. 4). Starch content still increased from bolting to just after flowering before it continued decreasing thereafter (Fig. 4).

Experiment 2

Soil chemical properties around the sampled palm: Soil pH at the growing site was 3.75 (Table 3). OC and total-N were 56.98 and 1.39%, respectively. It resulted in 40.99 of C/N ratio. CEC, exchangeable cations of K, Ca and Mg were 71.02, 0.56, 11.00 and 8.87 cmol+/kg, respectively. Available of P was 167.15 ppm. B (23.69 ppm) was dominantly present followed by Zn (9.39), Fe (4.50), and Cu (0.72) (Table 3).

Shoot growth and distribution of shoot fraction: The total shoot fresh biomass was 1,511.3 kg with trunk weighing 1,250.6 kg (82.75%) and crown weighing 260.7 kg (17.25%) (Table 4). The trunk length was 11.2 m and it was composed of 10 sectioned logs. Trunk biomass consisted of 65.37% pith and 13.38% bark. The crown biomass consisted of 4.56% leaflet including midrib, 4.25% rachis, 7.70% petiole and rachis, and 0.75% edible shoot and spear leaf (Table 4).

Macro- and micronutrient contents of shoot fractions: The contents of all nutrients were dominantly present on edible bud (palm heart) than other fractions (Table 5). N was dominantly present on leaflet and spear leaf. P was majorly present in spear leaf followed by leaflet and rachis. After spear leaf, K and Ca were majorly present on petiole + leaf sheath. Mg was present in higher quantity in rachis and petiole + leaf sheath. The results showed that Mn was dominantly present on leaflets, spear leaf, and pith followed by Zn and Fe. Compared to Mn, Zn and Fe, the contents of B and Cu were lower on most of the fractions.

Log biomass, pith dry matter, starch yield, starch content in harvested trunk: The average of pith dry matter percentage was 41.85%. The highest starch content was found on 3rd to 4th log position from the bottom which gradually increased from bottom to top log positions. The selected palm produced 315.19 kg dry starch with an average starch content of 33.02% (Table 6).

Shoot moisture and nutrient contents: A 1,511.3 kg shoot fresh biomass consisted of 915.7 kg (60.59%) moisture and 595.6 kg (39.41%) shoot dry matter (Table 7). K was majorly taken up by sago palm followed by N and Ca. The contents of N and Ca in the shoot were very similar. Mg was the next nutrient present in higher quantity followed by P (Table 7). Among micronutrients, Mn was taken up at the highest portion followed by Fe and Zn, while B and Cu were two minor elements (Table 8).

Discussion

The number of living fronds and starch content reduced

Table 1: Detail description of development stages used in this study

Development stage	Explanation
Bolting stage (B)	This stage is indicated by the appearance of short fronds having length about 1.0–1.5 m produced at the top frond position and absence of inflorescence. The color of top leaf petiole is whitish. In this stage, no inflorescence is visually present. This stage can be seen in Fig. 2a.
Just after flowering (JAF)	Stage of just after flowering is indicated by the presence of partial inflorescence appeared at the terminal axis of the trunk. This stage can be seen in Fig. 2b.
Flowering (F)	Stage of flowering is indicated by the presence of full appearance of inflorescence. When the physical appearance of inflorescence looks dried, it marks the stage to be near the end of flowering stage. This stage can be seen in Fig. 2c and d.
Dying (D)	A dying stage is indicated by dried inflorescence and fronds. No living fronds are carried by the palm. This stage can be seen in Fig. 2e.

Note: Stages of B, JAF, and F are normally used as standard of harvest by commercial sago plantation

Table 2: Morphology, pith dry matter, starch content, and estimated starch yield of harvestable palm at various development stages cultivated on peatland

Palm no.	Dev. stage	Trunk fresh biomass (kg)	Trunk length (cm)	Trunk DABH (cm)	Number of living frond	Pith dry matter (%)	Pith fresh biomass (kg)[6]	Starch content (%)-wb[7]	Est. starch yield (kg palm-[1])[8]
1.	B[1]	680	620	39.58	10.0	33.10	528	25.97	137.2
2.		723	742	36.65	20.0	32.09	562	22.34	125.5
3.		523	498	42.41	21.0	38.74	406	28.75	116.8
Sub avg.		**642±60.78**	**620±70.44**	**39.55±1.66**	**17.0±3.51a**	**34.64±2.07ab**	**499±47.21**	**25.69±1.86ab**	**126.5±5.90bc**
4.	JAF[2]	908	895	42.88	17.0	42.28	705	33.81	238.5
5.		768	747	41.39	16.0	39.21	597	32.56	194.2
Sub avg.		**838±70.00**	**821±74.00**	**42.14±0.75**	**16.5±0.5a**	**40.745±1.54a**	**651±54.38**	**33.19±0.63a**	**216.4±22.11a**
6.	F[3]	910	932	42.37	14.0	36.02	707	28.12	198.8
7.		795	756	40.24	13.0	33.07	618	26.28	162.3
8.		789	750	40.57	9.0	32.29	613	21.62	132.5
9.		720	670	35.43	6.0	34.55	559	25.46	142.4
10.		821	830	41.07	6.0	33.56	638	23.56	150.3
11.		759	720	41.29	5.0	31.61	590	20.94	123.5
Sub avg.		**799±26.31**	**776±37.73**	**40.16±0.99**	**8.8±1.58ab**	**33.52±0.65b**	**621±20.44**	**24.33±1.14b**	**151.6±10.93ab**
12.	F[4]	797	780	40.86	4.0	21.96	619	11.96	74.0
13.		723	742	36.65	2.0	17.20	562	8.61	48.4
Sub avg.		**760±37.00**	**761±19.00**	**38.76±2.11**	**3.0±1.00b**	**19.58±2.38c**	**590±28.74**	**10.29±1.68c**	**61.2±12.84cd**
14.	D[5]	814	824	43.40	0.0	16.05	632	7.22	45.7
15.		756	780	40.34	0.0	11.51	587	1.50	8.8
Sub avg.		**785±29.00**	**802±22.0**	**41.87±1.53**	**0.0±0.00b**	**13.78±2.27bc**	**610±22.53**	**4.36±2.86c**	**27.2±18.42d**
Stat. diff.		**ns**	**ns**	**ns**			**ns**		
Avg.[9]		**763**	**745**	**40.11**	**11**	**32.74**	**593**	**23.84**	**141.9**

Note: [1]Bolting stage. [2]Just after flowering stage. [3]Flowering stage with 5-14 living fronds. [4]Flowering stage with 2-4 living fronds. [5]Dying stage. [6]Pith fresh biomass is calculated by multiplying trunk fresh biomass with proportion of pith (77.68%) after debarking. Proportion of bark in trunk is 22.32% based on study performed by the plantation in deep peat soil. [7]Starch content, measured by wet basis, is obtained from the average of bottom, middle, and top trunk positions. [8]Estimated starch yield is calculated by multiplying pith fresh biomass with starch content. [9]Average value is obtained from the data of harvestable palms normally used on the plantation (no.1-13). ±: Standard error. Means followed by the same alphabetical orders among sub averages are not significantly different by Tukey HSD ($p<0.05$). ns: Not significant

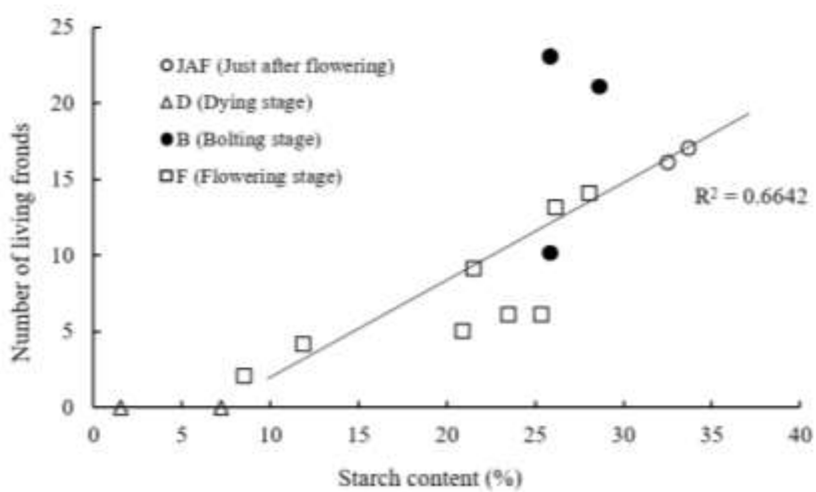

Fig. 3: Relationship between starch content on harvestable palm and number of living fronds

Table 3: Soil chemical properties at harvesting site

pH H_2O	C-organic (%)	N-total (%)	C/N	CEC ($cmol^+/kg$)	Exch. cation ($cmol^+/kg$)				Available (ppm)			
					K	Ca	Mg	P	Fe	Cu	Zn	B
3.75	56.98	1.39	40.99	71.02	0.56	11.00	8.87	167.15	4.50	0.72	9.39	23.69

Table 4: Shoot distribution ratio on harvestable palm at bolting stage

No.	Shoot component	Fresh biomass (kg)	Portion (%)
1.	Bark	262.6	17.38
2.	Pith	988.0	65.37
	Total of trunk	**1,250.6**	**82.75**
3.	Leaflet (inc. midrib)	68.8	4.56
4.	Edible bud and spear leaf	11.3	0.75
5.	Rachis	64.2	4.25
6.	Petiole and leaf sheath	116.3	7.70
	Total of non-trunk	**260.7**	**17.25**
	Total	1,511.3	100.00

Table 5: Distribution of macro- and micronutrient contents on sago palm shoot at bolting stage

No.	Shoot component	N	P	K	Ca	Mg	B	Cu	Zn	Mn	Fe
		(%)					(ppm)				
1.	Bark	0.337	0.016	0.569	0.207	0.144	4.98	3.03	16.09	25.47	39.65
2.	Pith	0.295	0.050	0.471	0.350	0.129	4.08	2.21	20.20	121.53	28.87
3.	Spear leaf	1.085	0.172	1.634	0.338	0.181	11.87	4.13	27.18	136.16	27.72
4.	Leaflet (exc. midrib)	1.333	0.080	0.735	0.416	0.175	8.83	1.58	18.20	142.85	41.24
5.	Midrib	0.511	0.052	0.450	0.230	0.143	5.79	1.32	8.28	71.09	28.18
6.	Edible bud (palm heart)	1.724	0.107	2.146	0.830	0.468	17.18	6.42	105.21	332.61	45.01
7.	Rachis	0.377	0.086	1.350	0.574	0.212	13.26	0.77	10.32	90.73	37.74
8.	Petiole+leaf sheath	0.378	0.045	1.596	0.634	0.205	16.68	1.21	10.25	77.47	55.86

Table 6: Log biomass and distribution of pith dry matter, starch content, and yield from different log position on sago palm at bolting stage

Trunk position (Log No.)	Log biomass (kg)	Pith dry matter (%)	Starch content (%)-wb	Starch yield (kg)
9 and 10 (Top)	237.4	42.86	33.02	61.93
7 and 8	222.0	40.50	30.91	54.21
6 and 5	241.0	42.35	32.40	61.69
3 and 4	241.0	44.03	34.25	65.21
1 and 2 incl. stump (Bot.)	309.2	39.53	29.54	72.16
Total	1250.6	41.85	33.02	315.19

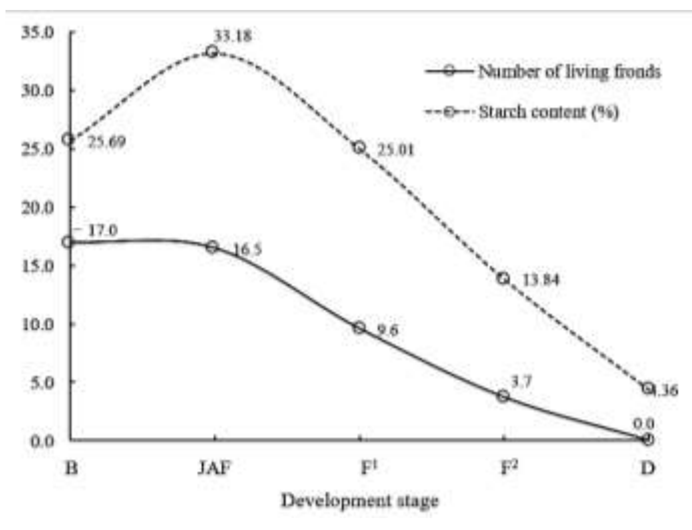

Fig. 4: Development stage of harvestable palm in relation to number of living fronds and starch content.
Note: [1]Palms at flowering stage carrying five living fronds and above. [2]Palms at flowering stage carrying 2 and 4 living fronds. Development stages of B, JAF, F1, F2, and D refer to Table 1.

Table 7: Contents of moisture and macronutrients on sago palm shoot at bolting stage

No.	Shoot component	MC	N	P	K	Ca	Mg
		(kg)	(g)				
1.	Bark	155.0	362.8	17.2	612.5	222.8	155.0
2.	Pith	574.5	1,219.8	206.8	1,947.6	1,477.3	533.4
3.	Spear leaf	1.6	4.6	0.7	6.9	1.4	0.8
4.	Leaflet (Exc. midrib)	27.4	307.3	18.4	169.4	95.9	40.3
5.	Midrib	8.6	49.8	5,1	43.8	22.4	13.9
6.	Edible bud	8.4	14.5	0.9	18.0	7.0	3.9
7.	Rachis	47.9	61.7	14.1	221.0	94.9	34.7
8.	Petiole and leaf sheath	92.3	90.8	10.8	383.5	152.4	49.3
	Total	**915.7**	**2,111.3**	**274.0**	**3,402.8**	**2,043.1**	**831.4**

Table 8: Contents of micronutrients on sago palm shoot at bolting stage

No.	Shoot component	B	Cu	Zn	Mn	Fe
		(mg)				
1.	Bark	536.1	326.2	1,732.0	2,741.7	4,268.1
2.	Pith	1,687.1	913.8	8,352.7	50,252.8	11,937.8
3.	Spear leaf	5.0	1.7	11.5	57.6	11.7
4.	Leaflet (Excl. midrib)	203.5	36.4	419.5	3,292.9	950.6
5.	Midrib	56.4	12.9	80.6	629.4	274.5
6.	Edible bud	14.4	5.4	88.3	279.2	37.8
7.	Rachis	217.1	12.6	169.0	1,485.4	617.9
8.	Petiole and leaf sheath	400.8	29.1	246.3	1,861.7	1,342.3
	Total	**3,120.5**	**1,338.1**	**11,100.0**	**60,663.6**	**19,440.7**

significantly as the development stage changed from bolting to flowering and ahead dying stages. Change in starch content with development stages in sago palm was also reported by Pei-Lang *et al.* (2006) and Achudan *et al.* (2020). Obvious reduction of starch content was observed from just after flowering ahead flowering stages (Fig. 4). A maximum starch content was observed just after flowering stage (Fig. 4), which is slightly different with finding of Flach (1997). Based on those results, sago should be harvested at bolting to flowering stage as suggested by Nakamura (2018). The starch content was gradually transferred from the bottom to the upper parts of trunk as the palm began to produce inflorescence at the terminal axis (Table 6). The starch stored on trunk played sink-source mechanism. It acted as a sink during the growth then it acted as source during generative stage. While focusing on development of generative organs, the palm gradually stopped producing newly emerged fronds (Table 2). As the palm entered the dying stage, the starch was soon diminished (Table 2).

Starch content gradually reduced along with gradual reduction in number of living fronds at flowering stage. Palm carrying five living fronds still contained starch content ~20%. It was significantly higher than those carrying four (11.96%) and two (8.61%) living fronds (Table 2). Palm with a very low starch yield is generally not harvested because it may reduce mill-starch extraction rate and increase operational cost of harvest due to low input. By using harvest criteria from bolting to flowering stages, where the number of living fronds was ≥5, the starch yield ranged from 116.8–235.5 kg per palm (Table 2). This yield was almost similar to the results of study of Ayulia *et al.* (2021) who worked on the same island where this study was conducted. It ranged from 82–318 kg per palm.

The trunk-crown biomass (82.75–17.25%) reported in this study was slightly different from that reported by Yamamoto (2018) in *Molat* folk-variety (73–27%) growing in mineral soil in Kendari, South Sulawesi at seven years after trunk formation. Besides development stage, morphological differences may also be influenced by folk-variety and soil type. Range of trunk biomasses of harvestable palms in this study (523–1184 kg) was comparatively lower than that of folk-varieties growing in Lake Sentani, Jayapura, Papua (611–2445 kg) (Yamamoto *et al.* 2020c). However, the number of living fronds at bolting and just after flowering stages (10–21) on deep peat were comparable with those growing in mineral soil. Harvestable sago palm folk-varieties before attaining flowering stage in Sentani, Jayapura carried 17.2–22.8 fronds (Yamamoto *et al.* 2020c). *Molat* folk-variety seven years after trunk formation in Southeast Sulawesi carried 21 fronds (Yamamoto *et al.* 2014). *Bemban* and *Buntal* at about 12 years after planting in West Kalimantan carried 21 fronds (Yamamoto *et al.* 2020b). Those at bolting stage in West Papua carried 11–25 fronds (Yamamoto *et al.* 2020d).

The contents of macronutrientswere in the order: K>Ca>N>Mg>P (Table 7). The result was slightly different from those reported in sago palm suckers on early establishment grown on peat (Irawan *et al.* 2009) and on 13-year-old sago palm growing on peat in Dalat, Sarawak, Malaysia (Yamaguchi and Okazaki 1998) with nutrient accumulation order K>N>Ca>P>Mg. However, similar uptakes of N and Ca found in those studies were similar to our study. It may be concluded that either N or Ca is the second largest element taken up by the palm after K (Table 5). As a starch accumulating crop, it is quite common that the element of K is required in a very high content as it relates to carbohydrate metabolism in plants (Gao *et al.* 2021; Ju *et al.* 2021; Šustr *et al.* 2024) besides its main role in regulating the opening and closing of stomata (Blatt 2016).

The order of micronutrient contents reported in this study was Mn>Fe>Zn>B>Cu (Table 8). This order was similar in sago palm cultivated on deep peat in Sungai Talau, Sarawak, Malaysia (Jong and Flach 1995). Compared to Mn, Fe and Zn, the elements of B and Cu were minor with almost 10 folded lower. On the contrary, the available content of B in soil was remarkably higher than Fe and Zn (Table 3). The remarkably higher contents of Mn (142.85 ppm), Zn (18.20 ppm) and Fe (41.24 ppm) than Cu (1.58 ppm) in sago palm leaflet found in this study (Table 5) agreed with that reported by Ando *et al.* (2007). Older study reported higher contents of Mn (151 ppm), Fe (96 ppm), Zn (30.9 ppm), B (12.3 ppm), and Cu (1 ppm) in sago palm leaflet on deep peat with soil pH ranging from 3.1–3.9 (Jong and Flach 1995) than this study. Those differences may be caused by micronutrient transformation and mobility in peat, which are mainly affected by environmental factors such organic acid, pH, RH, temperature, and moisture content (Jauhainen *et al.* 2014; Szajdak *et al.* 2020). Deficiencies of B (Singh 1982) and Zn (Kanapathy 1978) in oil palm on deep peat are common. Copper deficiency in sago palm on deep peat is shown by necrosis in tips of its leaflets (Jong and Flach 1995). Based on our findings and the above information, sago palm required Mn, Fe, and Zn in remarkably higher quantities than B and Cu.

Conclusion

To prevent a reduction of starch quantity during harvest, the implementation of harvest standard should be properly managed. Harvest criteria should be directed from bolting to just after flowering stages where the starch content is mostly above 25%. However, in case of flowering stage, palm carrying five living fronds and above is harvestable. It still contained starch over 20%. Harvesting palm carrying ≤4 living fronds should be avoided since the starch content is quite low, less than 13%, and the difference is significant. The need and effect of K-fertilizer and the critical levels of Mn, Fe, and Zn on growth and starch production should deserve further studies. Those elements were dominantly present on sago palm among macro- and micronutrients, respectively.

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Author Contributions

AFI was responsible for conceptualizing, conducting the study, collecting data, and writing the manuscript. BH was responsible for advising and suggesting the title and contents of the manuscript. DS was responsible for editing the manuscript, providing photographs, and designing map of study site based on geographical location.

Conflicts of Interest

All authors declare no conflict of interest.

Data Availability

Data presented in this study will be available on a fair request to the first author.

Ethics Approval

Not applicable to this paper.

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