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Full Length Article

Evaluating Sago Palm (*Metroxylon sagu*) Cultivation Practices: Aspects of Groundwater Level and Reduction of Starch during Harvest Transportation

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Abstract

Up to present, a favorable groundwater level for sago palm to thrive and to produce large trunk biomass post-trunk formation is not confirmed yet. Moreover, there is also no information of how the starch content reduces during harvest transportation and how peat and sea water media affecting the change of starch content on harvested logs. The objectives of this study were to investigate the effect of groundwater level on growth of sago palm post-trunk formation and change of starch content during harvest transportation *via* peat and sea water media. As sago palm is a crop that thrives in wetlands, certain groundwater levels need to be investigated to elucidate the most suitable growth environment for sago. The study used stratified randomized sampling method in selecting the palm sample. Three different blocks with different annual groundwater levels of 5.3, 6.8, and 28.5 cm were used. Trunk diameter, biomass, elongation rate, node length and frond emergence rate were measured. Harvested logs were sampled to track the reduction of starch content during floating in peat water and staying on seashore for 5 weeks. The results found that groundwater level of 6.8 cm gave the best trunk diameter and its biomass, followed by 5.3 cm, and they tended to show a significant decline when the level was deeper from soil surface (28.5 cm). Those two treatments (5.3 and 6.8 cm) also produced significant increases on trunk elongation rate (1.0 m/year) and its average node length (11.7 and 10.7 cm), respectively. The reduction of starch content in harvested logs on peat water (2.16%/week) was almost twice than those stayed on seashore (1.34%/week). From the above findings, we discovered that proximity of groundwater level for sago palm to thrive post-trunk formation on peatland was close to soil surface, which in turn suggested the importance of water management on its cultivation practice. It is also recommended that harvested logs transported *via* peat water should reach the mill within a week to avoid greater loss of starch, while sea transportation offers a viable alternative for longer transportation periods.

Key words: Groundwater level; Harvest transportation; Sago palm; Starch reduction; Trunk growth

Introduction

The increase of CO_2 would become major threat for agriculture in near future (Miraglia *et al*. 2009) and climate change was reported causing major impact on yield reduction of important food crops such as wheat, rice, and maize through a risk of drought (Ding and Xu 2023). Emphasizing other food crops, which are more tolerant to climate change, is highly required. Sago palm deserves a huge attention as an important suboptimal land-well adapted tropical food crop (Bintoro *et al*. 2018) to sustain food resilience for humans upon the phenomena of global climate change. It could thrive and produces starch even in poor soil nutrition- and anaerobic growing areas such as peatland and marsh area (Nitta *et al*. 2002; Ehara *et al*. 2021). Starch production was 150–300 kg in a trunk (Konuma 2018).

Studies on the effect of groundwater level on early establishment of sago palm seedlings and suckers in pot experiment and on mature palms have been scientifically documented. A one-year pot experiment using suckers as experimental materials found that water saturated (0 cm) and 20 cm groundwater level were suitable condition for them to produce significantly larger shoot base diameter and higher number of newly expanded leaves compared to 40

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cm (Irawan *et al*. 2009a). A larger shoot base diameter was also reported under waterlogged condition (Rembon *et al*. 2009). At saturated condition, leaflet-N content was significantly higher (20.9 mg g^{-1}) than that growing on 40 cm (15.7 mg g^{-1}) (Irawan *et al*. 2009a). A study found that the photosynthetic capacity of sago palm tended to be less optimal under prolonged waterlogged condition (Azhar *et al*. 2020a). It was greatly reduced under drought conditions where stomatal limitations become limiting factors (Azhar *et al*. 2020b). The position of groundwater level had been reported to influence the size of trunk diameter and height on mature sago palm growing on peat (Monda *et al*. 2022). However, in this study, the effect on trunk biomass, its growth, and frond emergence rates were not observed yet. Other study found that a temporary inundated area did not affect the trunk diameter and yield of starch in comparison to non-inundated one (Yater *et al*. 2019). However, detailed duration of inundation per unit time was unfortunately not reported. Such those information along with the fluctuation of groundwater level are very important to study the adaptability of sago palm growing in an unfavorable environment where lack of oxygen supply is encountered. Up to present, reports on the effect of groundwater level with detailed data on fluctuation and inundation time on trunk size and growth rate as well as frond emergence rate of mature sago palm were still limited.

On a large-scale sago plantation cultivated on undrained peatland, such as which is now located in Tebing Tinggi Island, Riau Province, Indonesia, establishment of processing mill is managed to be located near the strait. Cultivated blocks are distributed with various distances from mill. Some of them, which are located distantly from the mill, are close to the strait, making it an option of access of harvest transportation. Besides, different topographies are also constraint for harvest transportation. As one sago log could weigh around 100 kg on average, huge efforts have to be made when raising the logs from lower to higher grounds through canal where it is the main access of log transportation. Those conditions cause a longer duration of harvest transportation to the mill, which normally takes about 4–6 days. In such a case, logs can stay on peat water in canal for days or even over a week, and the reduction of starch content in pith will also occur. However, reports of starch reduction during harvest transportation are very scarce. In semi-traditional mills located close to the strait, huge number of rafted-sago logs, purchased from distant areas, are normally gathered in seashore or river for days to reduce deterioration (Singhal *et al*. 2008) before they are processed to mill. Based on the above issues, this study was undertaken to find out the most favorable environment in the context of groundwater level for sago palm growing after trunk formation. Moreover, change of starch content during harvest transportation *via* peat water and sea was compared to study the rate of reduction. The result may deliver a suggestion for the standard of harvest management on starch quality.

Materials and Methods

Experimental site

The study was performed in 2017 in a cultivated sago palm area established on undrained deep peat where no fertilizer was applied. The experimental site belonged to PT National Sago Prima, a subsidiary of PT Sampoerna Agro Tbk. The site is located in Tebing Tinggi Island, Regency of Kepulauan Meranti, Riau Province, Sumatera Island, Indonesia. Three different cultivated blocks (A, B and C) having size of approximately 48 h each were selected. Those blocks had different groundwater levels fluctuated throughout the year. The size of each block was about 48 h. The latitudes of block A, B and C were 0°47'15"N 102°56'24"E, 00°47'50"N 102°55'44"E, 0°49'01"N 102°54'33"E, respectively. A detailed location following the geographical location displayed from Google Earth is shown in Fig. 1.

Cultivation management practice

The sago palm plantation, located at an altitude of 8–12 m above sea level, were established on peatland since 1996 with a total concession area of 21,418 ha. Among them, about 4,000 ha had been regularly harvested since 2008. The sago palm cluster was planted in an 8 m × 8 m square planting space. The cultivation management was organized by using block and each block had size of approximately 48 ha. No chemical fertilizer was applied after planting. The undrained water management relying on rainwater was employed to facilitate harvest transportation, nursery site, regular operational activities, and to maintain peat restoration. Canal with 4–6 m wide and 2.5 m deep was made surrounding the blocks. Regular upkeep included debris removal on the cluster and manual weeding by slasher on harvesting path and surrounding the cluster (1 m away from cluster). They were done once a year. In this site, sago palm was normally harvested at the age of 12–14 years after planting.

Installation of piezometer to measure groundwater level fluctuation

A 600 cm-hollow long PVC pipe with a diameter of 15 cm was used as a piezometer to record fluctuation of groundwater level. Holes with 1 cm in diameter were made on its 550 cm pipe length. The part of 550 cm pipe's length was then vertically installed underground, the remaining 50 cm length stayed above the ground. The groundwater pressure pushed the water inside the standpipe until the level of water inside the standpipe was equal to the surrounding groundwater level. One unit of piezometer was installed on three different blocks with different topography at the end of 2016. The fluctuation of soil water level was recorded manually every week from January to December 2017.

Rainfall in the location was recorded automatically using a mini whether station (Davis Vintage Pro II, USA) during the rain.

Experimental details and treatment

This study was composed of two different aspects of sago palm cultivation practice. The first aspect was to study the effect of groundwater level on diameter and biomass of harvestable trunk as well as trunk elongation and frond emergence rates during young trunk growth stage (YTGS). The second aspect was to study the change of starch content on harvested logs *via* peat and sea water media during harvest transportation.

Experimental design

Due to huge variation of growth of existing palms in the cultivated blocks, a stratified randomized sampling method was used to minimize the variation of the data. Palms at about similar growth among the treatments were selected and sampled.

Protocol for data collection

Data collection and research procedures performed on three different aspects are explained below.

Effect of groundwater level on trunk diameter and its biomass at harvesting stage

To study the effect of groundwater level on trunk diameter and biomass, 25 harvested palms obtained from each block were sampled in December 2016. A total of 75 harvestable palms were used. The length of harvested palms on the site was mostly around 600–700 cm. Those below 600 cm were few. To represent the condition of actual sample, those with length 600 cm and above were selected and used in this study. The harvested palm was separated from the crown. The lowest living frond marked the uppermost trunk position separating the trunk and its crown. Before the trunk biomass was weighed, it was sectioned into each 1 m long log. The trunk average diameter was obtained from the data of each log diameter from the bottom to top positions.

Effect of groundwater level on trunk growth, frond emergence rate, and node length at YTGS

To study the growth of trunk in detail, palms with height below 2.5 m were selected in January 2017. The results of growth after one year were measured in December 2017. Ten palms on each block were selected. A total of 30 palms were used. Due to difficulty in finding the number of palms at about the same growth, based on its similar trunk diameter, the number of living fronds was used to indicate the criteria of selected palm. As we observed on block, palms carrying number of living fronds less than 7 were very few. Therefore, palms carrying 7 living fronds and above were used in this study. The trunk diameter was measured at breast height for those with the height above or equal to 150 cm. Those with height below 150 cm were measured at the trunk node of the lowest living frond. The height of the trunk was measured from the soil surface to the top part of the trunk node of the lowest living frond. The youngest living unfolded frond after the spear leaf was tagged and recognized to mark the difference between the old and newly emerged fronds for the measurement of annual frond emergence rate. The average node length was measured by calculating the length of trunk elongated in a year divided by the number of nodes that appeared in the surface of the trunk.

Change of starch content during harvest transportation

Harvested logs obtained from the above study were used to study the change of starch content during harvest transportation. Twelve fresh logs with around 1 m long of each log were selected in October 2017. The weight of log was about 100 kg on overage. Six logs were floated on peat water for 5 weeks following the procedure of harvest transportation performed on the plantation (Fig. 2a). The other 6 logs stayed on the seashore for 5 weeks and affected by the ebb and tide (Fig. 2b). Number of logs represented the number of replications. Each log was sampled each week for moisture and starch content analysis. Prior to observation, 100 g of fresh pith sample, representing the middle and outer parts of the log obtained from 5 cm long sectioned log at cut-end position, was collected from all logs to indicate sample at week 0. Before the other pith samples were collected from the treated logs on other observation periods, 5 cm long log measured from the cut-end position was sectioned and removed. Thereafter, pith was collected from the next cut-end position following the same method described at week 0. It was performed to avoid collecting the samples having direct contact with water and the sample could represent the overall pith condition in log.

Analysis of moisture and starch contents in pith

A 50 g of fresh pith sample was dried up in the oven at 105°C for 6 h for the determination of pith moisture content. The other 50 g fresh sample was used for starch analysis performed on a wet basis. It was analyzed using DNS (Dinitrosalicylic acid) acid reagent following the method described by Miller (1959). The glucose value was determined using a spectrophotometer (UV-1200, SHIMADZU-Japan) at 540 mm wavelength. Starch was determined by multiplying glucose concentration with 0.9.

Statistical analysis

The data obtained in this study were analyzed by one-way

Fig. 1: Site of study in Tebing Tinggi Island, Regency of Kepulauan Meranti, Riau Province

Fig. 2: Five day-old harvested sago palm logs during harvest transportation from field to mill *via* peat water (a) and those stayed on seashore for weeks awaiting to be processed on mill (b)

ANOVA using Statistix v. 9.1 analytical software. A post hoc test by Tukey (HSD) was performed when F-value was less than 0.05 to find out differences among treatments.

Results

Fluctuation of groundwater level and precipitation during 2017

During 2017, groundwater level in Block A mostly stayed above the soil surface with an annual average of 5.3 cm and inundated for 231 days (Fig. 3). A lower groundwater level next to Blok A was Block B. It was seasonally waterlogged with an annual average of -6.8 cm and inundated for 98 days. Different conditions were seen in Block C where it stayed below soil surface and the groundwater level could reach -53 cm during dry season. The movement of groundwater level on the observed blocks corresponded to the rate of precipitation. Total precipitation was 1,874 mm.

Effect of groundwater levels on trunk diameter and its biomass

The largest trunk diameter was achieved when annual groundwater level stayed at 6.8 cm (43.7 cm) followed by 5.3 (41.9 cm) and a significant decline was observed on -28.5 cm (40.5 cm) (Table 1). Annual groundwater level of -6.8 cm also produced the largest trunk biomass (114.1 kg) but it was not significantly different with 5.3 cm (111.1 kg). A significant decline of trunk biomass was observed when annual groundwater level stayed at -28.5 cm (99.5 kg).

Effect of groundwater levels on growth of trunk and fronds

At the start of observation, no significant differences were found on trunk height. The height ranged from 0.8–2.2 m (Table 2). However, significant differences were observed

Table 1: Effect of groundwater level on diameter and biomass of trunk

Palm No.	Trunk diameter[1] (cm)			Avg. trunk biomass[2] (kg 100 cm^{-1})		
	Annual average of groundwater level (cm)					
	5.3	6.8	28.5	5.3	6.8	28.5
1.	45.0	40.8	44.4	120.4	100.7	104.7
2.	42.4	47.2	38.2	100.7	133.9	88.3
3.	44.3	41.1	39.6	119.2	108.3	93.2
4.	42.4	43.6	39.3	101.5	112.4	97.9
5.	39.9	45.5	40.8	86.4	127.6	99.5
6.	40.1	45.3	40.0	87.0	128.3	97.0
7.	40.3	37.3	41.6	92.4	87.0	103.5
8.	43.6	47.5	39.4	128.3	133.4	98.7
9.	43.0	44.0	38.1	118.6	109.1	91.7
10.	40.7	43.6	42.1	115.5	104.3	114.5
11.	38.9	46.7	38.5	96.3	125.4	92.5
12.	44.5	43.6	41.4	132.2	112.2	104.2
13.	42.4	50.1	41.3	132.4	120.9	106.8
14.	41.4	45.0	37.6	119.8	129.6	90.6
15.	42.2	39.8	36.5	115.9	101.6	96.3
16.	41.6	42.8	39.3	123.2	116.9	87.0
17.	42.8	43.0	43.3	107.3	109.9	113.5
18.	37.0	45.4	37.5	82.9	127.3	83.2
19	42.2	42.7	43.4	115.9	109.3	100.3
20.	41.6	36.0	38.9	123.2	81.0	85.0
21.	39.5	44.4	45.3	94.2	122.5	131.3
22.	39.4	43.7	39.5	108.2	110.1	86.0
23.	46.5	48.8	39.1	131.4	134.9	90.6
24.	43.7	42.9	43.4	112.4	106.5	125.7
25.	42.6	42.7	44.4	112.8	99.6	104.7
Avg.	41.9b[3]	43.7a	40.5b	111.1a	114.1a	99.5b
CV[4] (%)	5.10	7.35	6.02	13.39	12.52	12.20
SE[5]	0.43	0.64	0.49	2.98	2.86	2.43

Note: [1]Average trunk diameter of each 1 m long trunk is measured from the bottom to top positions. [2]Average of trunk biomass is expressed as fresh biomass in each 100 cm long trunk. [3]Numbers followed by the same alphabetical orders among treatments are not significantly different by Tukey ($P > 0.05$). [4]CV: Coefficient of variance. [5]SE: Standard error

Table 2: Trunk growth at the onset of observation on three different annual averages of groundwater levels

Palm No.	Trunk height (m)			Trunk diameter[1] (cm)			Number of living frond		
	Annual average of groundwater level (cm)								
	5.3	6.8	28.5	5.3	6.8	28.5	5.3	6.8	28.5
1.	1.6	1.8	1.6	43.9	35.9	34.1	13	8	7
2.	2.2	1.4	1.8	39.5	40.9	35.7	10	10	8
3.	1.8	1.7	1.0	42.4	36.9	35.8	8	7	8
4.	1.6	1.5	2.0	40.8	40.6	39.4	9	9	10
5.	1.8	1.2	1.5	36.6	41.4	38.5	8	11	7
6.	0.9	1.5	1.9	42.7	44.1	38.2	9	10	7
7.	2.0	1.7	1.0	38.5	44.4	39.2	7	11	8
8.	2.2	0.8	2.0	39.8	43.8	39.4	7	8	8
9.	1.4	1.6	1.4	43.9	40.8	39.2	11	9	7
10.	1.7	2.1	1.6	39.5	37.9	38.2	9	9	7
Avg.	1.7a[2]	1.5a	1.6a	40.8a	40.7a	37.8b	9.1a	9.2a	7.7b
CV[3] (%)	22.75	24.21	22.79	5.94	7.36	4.99	20.36	14.31	12.32
SE[4]	0.12	0.12	0.11	0.77	0.95	0.60	0.59	0.42	0.30

Note: [1]Trunk diameter is measured at breast height for trunks with length ≥ 1.5 m and those with length below 1.5 m is measured at the lowest living frond position. [2]Numbers followed by the same alphabetical orders among treatments are not significantly different by Tukey ($P > 0.05$). [3]CV: Coefficient of variance. [4]SE: Standard Error

on trunk diameter and number of living fronds. Those two variables shown in palms growing under annual groundwater level of 5.3 (40.8 cm and 9.1) and 6.8 (40.7 cm and 9.2) cm were higher than those in palms under 28.5 cm (37.8 cm and 7.7).

Palms growing under annual groundwater levels of 5.3 and 6.8 cm produced higher trunk elongation rate (1.0 m/year) and longer node length (5.3 cm: 11.1 cm and 6.8 cm: 10.7 cm) compared to those under 28.5 cm (0.8 m $year^{-1}$ and 8.3 cm) (Table 3). However, their frond emergence rates were similar. Frond emergence rate ranged from 8.4–8.7 fronds/year.

Table 3: Effect of groundwater level on trunk elongation and frond emergence rates as well as average node length after a year of observation

Palm No.	TER[1] (m $year^{-1}$)			FER[2] (number of fronds $year^{-1}$)			Average node length (cm)		
	Annual average of groundwater level (cm)								
	5.3	6.8	28.5	5.3	6.8	28.5	5.3	6.8	28.5
1.	1.3	0.7	0.5	6	9	7	11.8	8.9	6.1
2.	1.0	1.2	0.8	9	9	7	10.4	10.8	8.5
3.	0.8	0.6	0.8	9	8	7	10.5	10.7	8.8
4.	1.2	1.1	1.0	11	9	13	10.8	11.4	7.6
5.	0.8	1.1	0.7	7	9	9	10.1	11.8	7.1
6.	1.1	1.3	0.7	7	11	9	14.6	11.0	7.9
7.	1.1	1.1	0.9	9	9	11	9.7	11.3	9.3
8.	1.1	1.0	1.1	11	9	9	11.4	10.5	9.6
9.	1.1	1.1	0.9	9	6	7	11.6	11.8	9.2
10.	0.8	0.9	0.6	6	8	6	10.0	9.3	8.6
Avg.	1.0a[3]	1.0a	0.8b	8.4a	8.7a	8.5a	11.1a	10.7a	8.3b
CV[4] (%)	19.23	21.75	22.45	21.88	14.39	25.57	12.82	9.09	13.25
SE[5]	0.06	0.07	0.06	0.58	0.40	0.69	0.45	0.31	0.35

Note: [1]TER: Trunk Elongation Rate. [2]FER: Frond Emergence Rate. [3]Numbers followed by the same alphabetical orders among treatments are not significantly different by Tukey ($P > 0.05$). [4]CV: Coefficient of Variance. [5]SE: Standard Error

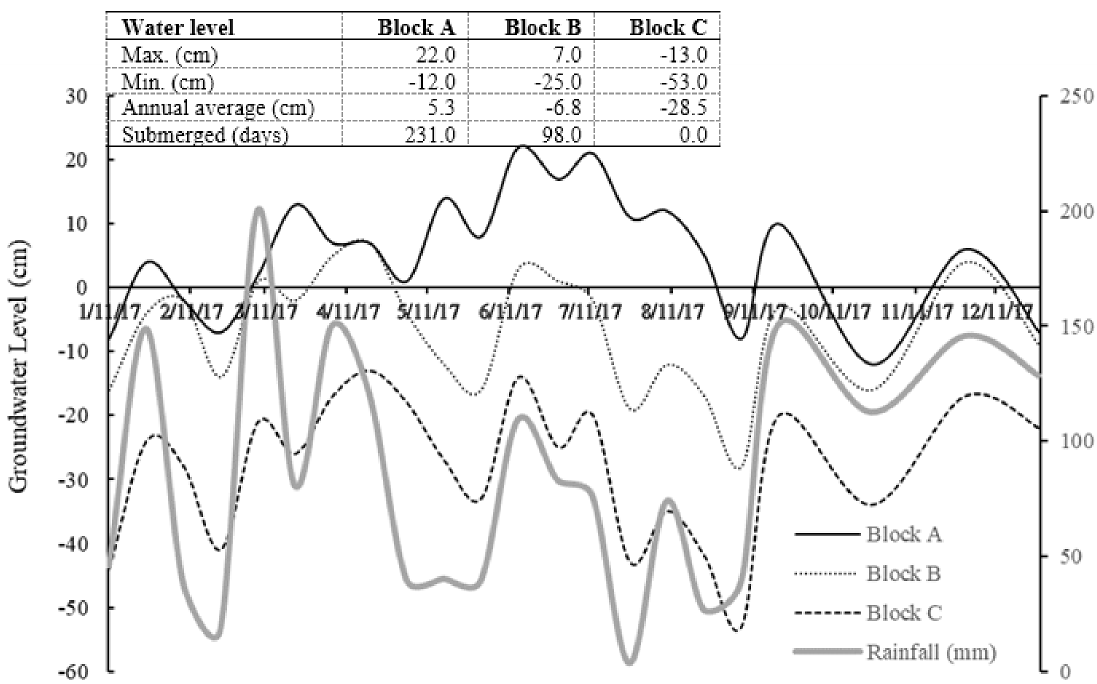

Fig. 3: Groundwater fluctuation on three different blocks and precipitation during 2017

Change of starch content during harvest transportation

Moisture and starch contents in fresh pith samples from harvested logs ranged from 60.05–74.14% and 19.14–30.23%, respectively (data not shown). On average, reduction of starch content in harvested logs transported *via* sea water (1.34%/week) was much lower compared to peat water (2.16%/week) (Table 4). The trend of starch reduction was linear (Fig. 4). Higher reduction of starch content from week 1 to 5 on peat water, which was about twice, was consistently observed in comparison to those transported *via* sea water.

Discussion

A prolonged and seasonal waterlogged condition with annual average of groundwater level position close to soil surface created the most favorable environment for sago palm to thrive. A positive effect on trunk diameter found in this study was in agreement with previous report of Monda *et al.* (2022). They found a positive correlation between groundwater level and trunk diameter measured at breast height growing on peatland. Different results were observed on mature palm growing on a natural sago habitat on mineral soil in South Sorong, Indonesia. A temporary inundated

Table 4: Moisture, starch and reduction of starch contents of harvested logs when floating on peat water and staying on seashore on different weeks of observation

Week	Moisture content (%)		Starch content-wb[1] (%)		Reduction of SC[2] week^{-1} (%)		Stat. diff.
	FPW[3]	SSS[4]	FPW	SSS	FPW	SSS	
0	68.13 ± 1.89	67.88 ± 1.77	24.15 ± 1.99	24.86 ± 1.74	0.00 ± 0.00	0.00 ± 0.00	-
1	70.68 ± 1.95	69.10 ± 1.78	21.85 ± 1.99	23.40 ± 1.66	2.30 ± 0.21	1.45 ± 0.20	*
2	71.94 ± 2.20	70.60 ± 1.85	19.28 ± 2.13	21.78 ± 1.87	2.58 ± 0.43	1.63 ± 0.30	*
3	74.62 ± 1.85	72.02 ± 1.79	17.08 ± 1.89	20.13 ± 1.84	2.20 ± 0.61	1.65 ± 0.15	*
4	76.70 ± 2.05	73.04 ± 1.75	15.23 ± 2.01	19.31 ± 1.66	1.85 ± 0.63	0.82 ± 0.25	*
5	78.34 ± 2.02	74.18 ± 1.66	13.34 ± 2.06	18.17 ± 1.63	1.89 ± 0.28	1.14 ± 0.09	*
Mean[5].					**2.16**	**1.34**	

Note: Mean ± standard error. [1]wb: wet basis. [2]SC: Starch content. [3]FPW: Fresh peat water. [4]SSS: Stay on seashore. [5]Average of each treatment is calculated from week 1-5. *: Different statistically by Tukey test ($P > 0.05$)

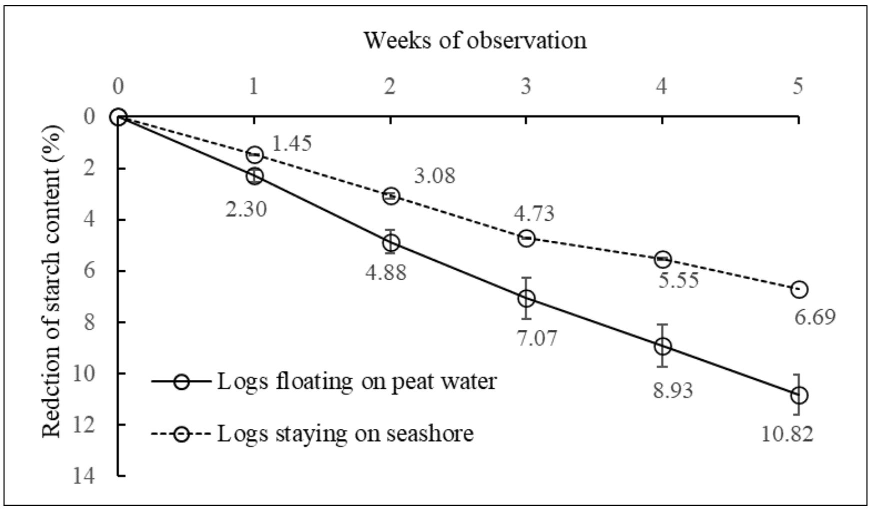

Fig. 4: Reduction of starch content on harvested logs when floating on peat
Water and staying on seashore for 5 weeks
Note: Bars show standard error

condition gave no significant difference in trunk diameter and yield of starch. However, it gave significant increase in pith fresh biomass in comparison to non-inundated (Yater *et al*. 2019) which was in accordance with the finding of this study on trunk biomass. Different soil types seem to cause different growth responses to groundwater level. To find out these differences, further studies are required.

Besides the frond emergence rate (Flach *et al*. 1986), trunk elongation rate is also an important indicator to determine the growth speed of sago palm. The trunk elongation rate in palms with annual groundwater level of 28.5 cm was about 20% slower than those in 5.3 and 6.8 cm and it also displayed the shortest average node length. The trunk elongation rates (1 m/year) under two last groundwater treatments were similar to those growing in mineral soil in semi-cultivated garden in Kendari, Southeast Sulawesi Province, Indonesia as reported by Yanagidate *et al*. (2009). The retarded growth of sago palm was shown when it produced higher number of fronds in forming the trunk with smaller increase of height. Growth behaviors of sago palm seedlings in response to an environmental stress such as high temperature had previously been reported by Irawan *et al*. (2009b). Under the highest temperature treatment (35–27°C), they produced a higher number of fronds, but their length was shorter compared to those growing under lower temperature (31–23°C).

Sago palm had three different rooting systems (Nitta *et al*. 2002) which tended to develop horizontally at younger ages and vertically at older ages (Miyazaki *et al*. 2016). One of them was small roots. It was formed from the large one which could emerge vertically right above the soil surface (Fig. 5) and it was suitable for transporting the air from the root to the shoot (Nitta *et al*. 2002). Therefore, this rooting system could help the palm thrive under anaerobic conditions.

Several reports indicate a high possibility that nitrogen-fixing bacteria is most likely involved in growth enhancement of sago palm under anaerobic condition. A beneficial microbial interaction in nitrogen-fixing activity through collaborative utilizations of starch, hemicellulose and their degradation products were reported by Shrestha *et al*. (2007). High activity of acetylene reductase assay (ARA) was found in roots. Several bacterial strains with their closest species to *Enterobacter cloaceae, Klebsiella penumoniae, K. oxytoca, Bacillus megaterium, Burkholderia* sp. and *Pantoea agglomerans* were successfully identified (Toyota 2018) and

Fig. 5: Small roots of sago palm emerged vertically above water on peat soil in a partially waterlogged condition

mostly found in roots rather than petiole and rachis (Shrestha *et al*. 2006). Nitrogen fixers were also present in moist sago starch and the rhizosphere (Shipton *et al.* 2010). An oxygen tension was known as environmental factor affecting nitrogen activity (Stal 2017). Anaerobic condition was required for the expression of nitrogenase activity which was commonly performed by N_2 fixer-facultative anaerobe such as genus of *Klebsiella* and *Clostridium* (Hill *et al.* 1984) in paddy ecosystem (Muerial *et al*. 2017).

A delay in harvest transportation *via* peat water media for a week should be avoided as it would reduce the starch content in harvested logs to about 2%. Normally, microbial invasion is present in logs at the cut-end position. The invasion is higher as they stay longer on field which in turn led to deterioration of starch quality (Singhal *et al*. 2008). The reduction of starch content in logs stayed in seashore in this study was about 60% lower than those floating on peat water. Seawater must have contacted the log surface during the tide. Studies had reported that salinity reduced microbial activities (Yan *et al*. 2015) such as respiration, nitrogen mineralization, and enzyme activities (Winchern *et al*. 2020) and an increase in salinity can inhibit the activity of many soil enzymes (Singh 2016). Fungi tend to be more sensitive to salt stress than bacteria (Kamble *et al*. 2014; Rath *et al*. 2016).

Those above results may imply that in order to obtain larger trunk size (diameter and biomass), proper water management by regulating it close to soil surface is indispensable in sago palm cultivation practices on peatland. Trunk size had been reported to have positive impact to the yield of starch although it was also strongly influenced by the starch content in pith (Yamamoto *et al.* 2003). A beneficial effect of implementing those practices seems to be strongly associated with the activity of nitrogen fixers in sago palm. However, the relationship between nitrogen-fixing activity and position of groundwater level are not yet reported and further studies are strongly required. In order to keep the starch quantity, schedule of harvest transportation should be properly managed. Loss of starch may affect the mill operational cost which in turn reduced the feasibility of upstream sago industry. Sea water can be a reliable alternative for harvest transportation management on sago palm business. Reducing the loss of starch may also be managed by establishing mini mills in the growing sites. The mill should be able to process harvested logs into dry pith. Transporting them is considered to be more beneficial from the viewpoints of biomass and time efficiencies, and also starch quality rather than fresh logs. Further studies on attempting the simulation of dry pith-harvest transportation and its effect on the starch quality, time, and operational cost efficiencies are required.

Conclusion

Proximity of groundwater to the soil surface appears favorable for sago palm growth on undrained peatland post-trunk formation. Duration of harvested logs transported *via* peat water should be managed within a week to minimize starch loss. Apart of that, sea transportation offers a viable alternative for longer transportation periods which can reduce starch loss to approximately 1%/week.

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Author Contributions

AFI was responsible for conceptualizing, conducting the study, collecting data, and writing the manuscript. FK was responsible for advising and suggesting the title and contents of the manuscript. MS was responsible for assisting the field study and providing photographs. EDP was responsible for editing the manuscript. GAR was responsible for directing the title. DA was responsible for directing the topic of study.

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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