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Growth Characteristics and Starch Productivity of Sugar Palms (*Arenga pinnata* Merr.) in Tana Toraja, South Sulawesi, and Tomohon, North Sulawesi, Indonesia

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Abstract: We investigated differences in the growth characteristics and starch productivity of tall sugar palms with high sap productivity according to plant age (estimated: 3–25 years) and growth stage (early trunk elongation to dying stage) in Sandabilik (SB) Village, Tana Toraja, South Sulawesi, and in Taratara (Ta) Village, Tomohon, North Sulawesi, Indonesia. The number of years until the emergence of the first female inflorescence after the seedling stage was approximately 10–12 years in SB Village and 8–10 years in Ta Village, and that until the end of sap collection was approximately 20 and 15 years, respectively. In both villages, trunk elongation and leafing occurred until the emergence stage of the first female inflorescence, and the highest trunk weight was estimated to be 1500–2000 kg during the period from the emergence stage of female inflorescences to the early emergence stage of male inflorescences; the pith starch percentage also reached the highest values, 30–40%, and the starch content was estimated to be 100–250 kg during this period. After that, the pith starch percentage and content tended to decrease in the dying stage. However, it was suggested that the starch content might increase with the passage of time after the end of sap collection in plants that have maintained large leaf areas and high leaf chlorophyll content even in the dying stage.

Keywords: growth characteristics, growth stage, interview survey, leaf area, starch productivity, sugar palm

Introduction

The sugar palm is widely distributed in tropical South and Southeast Asia and is considered to have originated in the Indo-Malay Archipelago (Mogea et al., 1991). Generally, it is cultivated near residential areas from the lowlands to an altitude of 1400 m. The center of its distribution is Indonesia, including East Kalimantan, North Sumatra, West Java, and North Sulawesi. It is a versatile palm and is considered an essential crop in many areas (Mogea et al., 1991). In particular, sugar sap (*nira*) is collected from the cut end of the inflorescence stalk, and it is used as a beverage directly or it is boiled to produce brown sugar (*jaggery*). Moreover, it was fermented (*toddy*) to be used to distill alcohol—palm liquor (*arak*). However, there are few reports on the production of sap. The sugar palm is also used as a starch-accumulating palm (Yamamoto, 1998; Ehara, 2015), and the starch of the sugar palm is used to produce noodles (*sohun*) in Cirebon, West Java (Yamamoto, 2010). However, the sugar palm is not widely known as a starch resource, and reports on its starch productivity are insufficient as compared with those on the sago palm.

From this background, in previous reports, the authors (Yamamoto et al., 2021a; 2021b) reported on the actual conditions of sugar palm cultivation and sap production as well as growth characteristics and starch productivity of the sugar palms on Muna Island, Southeast Sulawesi, Indonesia, where the sugar palm is popularly cultivated and used. However, as has been revealed in sago palms (Yamamoto, 1998; Yamamoto et al., 2010; 2020b), growth and starch productivity could differ depending on the type (folk variety) and cultivation environment. Here, we report the growth characteristics and the starch productivity of the sugar palms in Tana Toraja, South Sulawesi, and Tomohon, North Sulawesi, where sugar palm cultivation and utilization are popular.

Materials and Methods

1. Growth characteristics

The survey was conducted in Sandabilik (SB) Village, Tana Toraja, South Sulawesi, in September 2013, and in Taratara (Ta) Village, Tomohon, North Sulawesi, Indonesia, in September 2014 (Fig. 1). In both villages, an interview survey was conducted with sugar palm farmers (4 and 9 farmers, respectively) regarding their cultivation and utilization. Based on the interview results, the tall sugar palm was selected for research because it was the major type in both villages. A total of 8 plants (estimated plant age: 5–25 years), including 1–3 plants in each of the 4 growth stages in SB Village, and a total of 8 plants (estimated plant age: 3–16 years), including 1–2 plants in each of the 5 growth stages in Ta Village, were selected and sampled (Table 1). The plant age from the seedling stage of each sampled plant was estimated by the owner. The growth stages were from early trunk elongation to the dying stage (the end of sap collection or plants of the same age as plants whose sap collection had ended) in both villages (Table 1). Regarding the emergence stage of male inflorescences, only one (SB Village) or two (Ta Village) emerged, so we call the stage "the early emergence stage of male inflorescences." Before the emergence of male inflorescences, 8–14 and 4–9 female inflorescences emerged on the plants in SB Village and in Ta Village, respectively (Table 1).

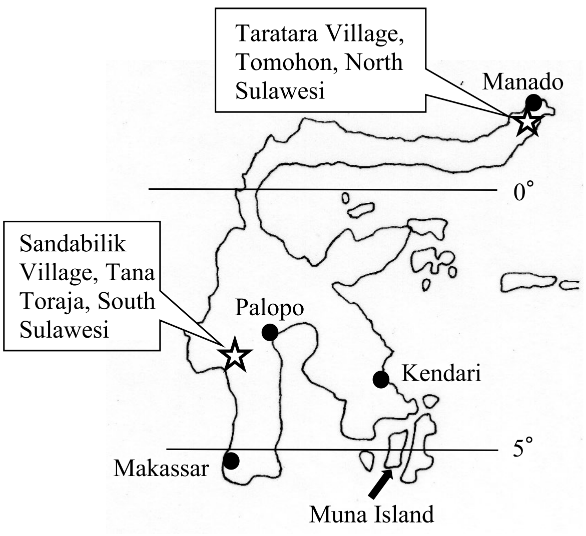

Fig 1. Map of Sulawesi Island and the survey sites

After felling the plants, the dead leaf sheaths on the trunks were removed, and the surviving leaves and leaf scars were counted. The plant length and trunk length were measured from the cut surface of the trunk base to the uppermost leaf tip and to the node of the uppermost leaf. As for leaf characteristics, the length (from the base of the leaf sheath to the leaf tip); the number of leaflets on the left and right sides of the rachis; the longest leaflet lengths on both sides of the rachis; their maximum widths and thicknesses (standard ABS Digimatic Caliper, Mitutoyo Co.); the SPAD values (SPAD-502, Minolta Co.); and the leaflet weights of the upper, middle, and lower leaves of each plant were measured. The longest leaflet thickness and SPAD value were measured at 5 points on the central part of the leaflet and shown as the average values. The whole or the central part of the longest leaflets was traced on tracing paper and taken back to Japan, and the leaf area was measured using a leaf area meter (AAM-10, Hayashi Denko Co.). The fresh weights of the longest leaflets traced were then

Table 1. Sugar palm plants harvested for measurement in Sandabilik Village, Tana Toraja, South Sulawesi, in 2013, and in Taratara Village, Tomohon, North Sulawesi, Indonesia, in 2014, and their growth stages

Plant No.	Estimated plant age (yrs)[1)]	Growth stage (Remarks)
(Sandabilik Village)		
1	5	Early trunk elongation
2	5	Early trunk elongation
3	9	Before emergence of female inflorescence (two years before)
4	10	Before emergence of female inflorescence (one year before)
5	16	Emegence of male inflorescence (first male emerged about two years earlier but sap was not collected; 12 female inflorescences emerged)
6	19	Dying (sap collection ended two months earlier; sap collected for 30 months; eight female inflorescences emerged)
7	19	Dying (sap collection ended seven months earlier; sap collected for three years; 14 female inflorescences emerged)
8	25	Dying (sap collection ended one year earlier; 13 female inflorescences emerged)
(Taratara Village)		
11	3	Early trunk elongation
12	4	Early trunk elongation
13	8	Late trunk elongation
14	10	Emergence of female inflorescence (four female inflorescences emerged)
15	11	Emergence of female inflorescence (nine female inflorescences emerged)
16	11	Emergence of male inflorescence (two male inflorescences emerged and sap collection had just started; eight female inflorescences emerged)
17	16	Dying (just before sap collection ended; seven female inflorescences emerged)
18	15	Dying (sap collection ended about one year earlier; seven female inflorescences emerged)

1) Years after seedling stage (estimated by the farmers).

measured with a portable electronic balance (HL-200, Hikaru Kyoei Co.). The average specific leaf area (SLA) per plant was calculated from the SLA per fresh weight of the longest leaflets of the upper, middle, and lower leaves. The leaflet weight per plant was calculated by multiplying the number of leaves and the average leaflet weight of the three leaves. The leaf area per plant was calculated from the leaflet fresh weight per plant and the average SLA per plant. The leaf area per leaf was calculated by dividing the leaf area per plant by the number of leaves per plant. In addition, the average leaflet area was calculated by dividing the leaf area per leaf by the number of leaflets per leaf.

The trunk was cut into two parts—the upper and lower parts—at the lowest surviving leaf node, and they were cut evenly at 1–5 positions depending on the length. Then, a 2–3 cm thick disk was cut from each cut surface of the trunk (3–9 disks in total). The bark and the outer pith fiber tissue (hereafter, bark) were separated from the inner pith (hereafter, pith), and their weights were measured separately (Yamamoto et al., 2021b) to calculate the pith weight ratio. Then, 50 to 90 g of the pith was radially measured (0.1 g unit) by the above-mentioned electronic balance and collected. Furthermore, the trunk was cut out from the cutting position of each disk to a length of about 50 cm (log), and the upper and lower diameters and weights were measured with a ruler and a 100 kg bar scale, respectively. Then, the volumes of the upper and lower trunks were calculated from their lengths and the average diameters of the logs, and the volume was multiplied by the average density of each log (log weight/log volume) to estimate the upper and lower trunk weights. The sum of the upper and lower trunk weights was taken as the trunk weight per plant. The pith samples were dried in a temporary drying oven (around 80 °C) for two days, brought back to Japan, and further dried in a ventilation drying oven at 65 °C for 2 days to measure the dry weight.

The dried pith part was crushed and ground to 100 mesh or less by a Wiley mill (WT-150, Sanki Seisakusho Co.) and a fine grinder (T1-100 sample mill, CMT Co.) and subjected to the following analysis.

2. Analysis of total sugar and starch

The total sugar and starch of the pith were analyzed in accordance with the method of Murayama et al. (1955). That is, 0.2 g of ground pith sample was extracted with 80% hot ethanol at 80 °C three times. Starch was then extracted from the residues using 4.6*N* $HClO_4$ for the hydrolysis of starch to glucose six times. The total amounts of sugar and starch were quantified as glucose using the anthrone method (Tamura, 1975). That is, 0.5 ml of the extracted total sugar or starch solution and 5 ml anthrone reagent were taken in a test tube (length: 10 cm; inner diameter: 15 mm) in ice water and reacted in boiling water for exactly 10 minutes and then put into ice water to stop the reaction. After taking the test tube out of the ice water and cooling it to room temperature, the absorbance of the solution at 620 nm was measured using a spectrophotometer (U-1900, HITACHI Co.). The total sugar percentage (on a dry-weight basis) was expressed as glucose, and the starch percentage was expressed by multiplying the glucose percentage by 0.9. The average pith dry matter and total sugar and starch percentages per plant were determined by the average values of all of the pith samples collected from the disks. The starch content per plant was calculated as starch content = the trunk fresh weight × the pith weight ratio/100 × the average pith dry matter percentage/100 × the average pith starch percentage/100.

Results

1. Interview survey

Table 2 shows the results of interviews with sugar palm farmers in SB and Ta Villages. Both villages are located in mountainous areas at an altitude of about

Table 2. Results of interviews with sugar palm farmers about the characteristics of sugar palms in Sandabilik Village, Tana Toraja, South Sulawesi, and in Taratara Village, Tomohon, North Sulawesi, Indonesia

Interviewed item	Sandabilik Village (900 m asl)	Taratara Village (600 m asl)
Folk variety	Iduk Lando (tall) Iduk Denak (short)	Aker Rangkak (tall) Aker Pendek (short)
Years from seedling to trunk formation (years)	4–5	2–3
Year from seedling to the flowering of first female iflorescence (years)	10–13	7–8
Order of emergence of female inflorescences	Basipetal	Basipetal
No. of emerged female inflorescences	3–15	2–12 (Avg. 5–7)
Duration of female inflorescence emergence	1	0.5–1
Order of emergence of male inflorescences	Basipetal	Basipetal
No. of emerged male inflorescences	20	22–23
Duration of sap collection (years plant^{-1})	3–10	4–6 (Max. 7)
Duration of sap collection (months inflorescence^{-1})	4–6 (Max. 13)	3–6
No. of male inflorescences from which sap collected (No. plant^{-1})	10–20	5–8
Average sap amount (L plant^{-1} day^{-1})	8–9	7–40 (the higher the male inflorescence position, the higher the sap production)
Average No. of tapping plants (plants person^{-1} day^{-1})	8–10	8–10

*Interview responses are shown only for tall types.

600 m (Ta Village) and about 900 m (SB Village). Ten to 12 sugar palm plants were planted on flatlands or lands with various slopes around houses with almost no cultivation management, and sap was collected. Two types of sugar palms, tall and short types, were cultivated in both villages, but the major type was tall, which produces a large amount of sap. The short and tall types were 12 m and 20 m or taller up to the first female inflorescence, respectively. Interview responses in Table 2 are shown only for tall types. The sugar palm is propagated by naturally germinated seeds (seedlings), and trunks are formed in about 4–5 years in SB Village and 2–3 years in Ta Village. In both villages, leaf emergence is completed in about 10 years, and the first female inflorescence emerges at the axil of the uppermost leaf, followed by the downward emergence of 3–15 (SB Village) and 2–12 (Ta Village) female inflorescences, and then about 20 male inflorescences, on average, downwardly. Of the emerged male inflorescences, 10–20 in SB Village and 5–8 in Ta Village were used to collect sap over 3–10 and 4–6 years, respectively. Pretreatment (pounding the inflorescence stalk and the trunk just above the stalk) and sap collection were performed in the same manner as in the previous report (Yamamoto et al., 2021a) on Muna Island, Southeast Sulawesi. Bamboo cylinders (50 cm length with a diameter of 10–12 cm; 5–6 L) were used in SB Village and 25 L plastic tanks in Ta Village as containers for collecting sap. In the case of beverage or sugar production, sap was collected twice a day—in the morning and evening—and in the case of palm liquor production in Ta Village, it was irregularly collected once a day. The volume of sap collected per day was 8–9 L (SB Village) and 7–40 L (Ta Village). The sap was used as a beverage for self-consumption and sale (SB Village) or the production of brown sugar and palm liquor (Ta Village). Starch was not extracted in SB Village but was extracted in Ta Village during the dry season. Plants unsuitable for sap collection are used for starch extraction, and the optimum stage for starch extraction is around the emergence stage of the first female inflorescence. Starch is extracted in the same manner as that of the sago palm (Yamamoto et al., 1998) by crushing the pith with an ax-shaped tool. The starch yield per plant is about 80 kg as wet starch. The starch is used as a staple food, *papeda* (a paste that is put in soups), and as a material for making cookies.

2. Sampling survey

The estimated plant ages (EPAs) of the sampled plants were 5–25 years for SB Village and 3–16 years for Ta Village; the emergence stages of the first female inflorescence (FI) were estimated to be 10–12 and 8–10 years, respectively. In addition, the starting and ending times for sap collection, respectively, were estimated to be 15 and 20 years for SB Village and 10 and 15 years for Ta Village (Table 1).

In both villages, the plant length grew to around 20 m or more until the emergence stage of the first FI after the completion of leafing from around 15 m in the early trunk elongation (ETE) stage, and the change was small thereafter (Table 3). The number of leaves and leaf scars as well as the plant length increased until the emergence stage of the first FI and remained at 40–60 leaves thereafter. The maximum number of leaves was 24–28 after the emergence stage of the first FI to the early emergence stage of male inflorescences (MI) and then decreased in the dying stage. The trunk length showed a high positive correlation with the EPA in both villages, but it increased to the maximum value in the emergence stage of the first FI; thereafter, the change was small, at 15–20 m. The trunk diameter changed little with the EPA and was in the range of 30–40 cm. The trunk weight changed from 1700 to 3100 kg in SB Village and 1500 to 1900 kg in Ta Village after the emergence stage of FI; however, there were large differences among the plants, even at the same growth stage, and the change in trunk weight during this period was not observed clearly. The trunk weight showed a strong positive exponential correlation with the trunk length in both villages, and it also showed a

Table 3. Growth characteristics of sugar palms at different growth stages in Sandabilik Village, Tana Toraja, South Sulawesi, and in Taratara Village, Tomohon, North Sulawesi, Indonesia

Plant	Total	No. of leaf		a + b	Trunk			
No.[1]	length (m)	scars (a)	living (b)		length (m)	diameter (cm)	weight (kg)	volume (m^3)
(Sandabilik Village)								
1	15.7	14	12	26	2.5	28.6	186	0.159
2	13.5	8	12	20	3.5	31.9	292	0.276
3	22.5	23	14	37	11.5	31.4	997	0.915
4	25.9	39	14	53	14.9	28.9	1141	0.989
5	27.6	32	26	58	19.9	37.9	2787	2.245
6	23.6	40	9	49	15.9	34.8	1738	1.595
7	24.2	27	13	40	17.7	33.8	1847	1.565
8	27.0	34	13	47	20.8	39.9	3101	2.640
Average	22.3	29.2	14.2	43.4	13.3	31.9	1348	1.167
SD	4.7	11.8	4.5	13.0	6.3	5.4	1003	0.828
CV (%)	21.2	40.4	31.5	30.0	47.6	17.0	74.4	71.0
rs [2]	*0.740**	*0.681*	*0.055*	*0.618*	*0.874***	*0.841***	*0.902***	*0.923***
(Taratara Village)								
11	11.5	0	14	14	1.3	33.3	127	0.111
12	17.1	9	12	21	2.8	32.0	244	0.228
13	21.6	22	18	40	10.1	44.3	1723	1.592
14	21.7	20	28	48	13.7	35.1	1495	1.310
15	23.2	30	26	56	16.6	31.9	1469	1.297
16	21.0	16	24	40	15.3	37.5	1856	1.662
17	21.3	26	14	40	14.5	34.8	1615	1.391
18	23.8	38	14	52	16.9	29.8	1450	1.282
Average	20.1	20.1	18.8	38.9	11.4	34.8	1247	1.109
SD	4.0	12.0	6.3	14.6	6.2	4.5	670	0.597
CV (%)	20.0	59.4	33.7	37.5	54.2	12.9	53.7	53.8
rs [2]	*0.801**	*0.858***	*0.173*	*0.778**	*0.898***	*-0.115*	*0.777**	*0.751**

1) Refer to Table 1. 2) Correlation coefficients with the estimated plant age (years) (Table 1). * and **: significant at $p< 0.05$ and $p< 0.01$, respectively.

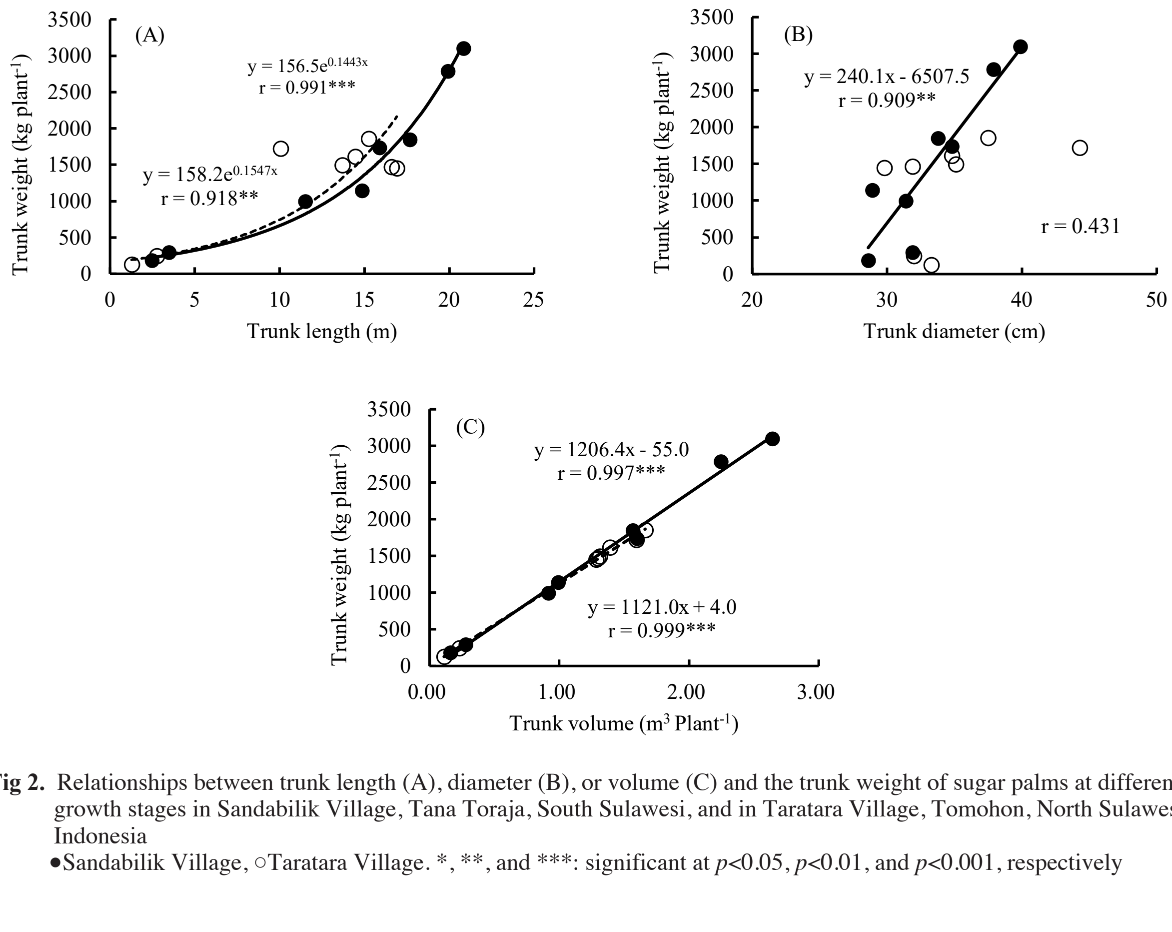

Fig 2. Relationships between trunk length (A), diameter (B), or volume (C) and the trunk weight of sugar palms at different growth stages in Sandabilik Village, Tana Toraja, South Sulawesi, and in Taratara Village, Tomohon, North Sulawesi, Indonesia

●Sandabilik Village, ○Taratara Village. *, **, and ***: significant at p<0.05, p<0.01, and p<0.001, respectively linearly strong positive correlation with the trunk diameter in SB Village (Fig. 2A and 2B). The trunk volume showed a very strong positive correlation with the trunk weight in both villages (Fig. 2C). Comparing the growth characteristics of both villages, plants with greater growth were seen in SB Village, such as Plant No. 5 and No. 8, but the differences between the two villages were small except for these plants (Table 3).

In both villages, the leaf length was 10–12 m during the vegetative growth period; however, it became shorter with the EPA after entering the reproductive growth stage, and it became 8–9 m in the dying stage (Table 4). The number of leaflets per leaf was about 300 during the vegetative growth period, which tended to decrease with the EPA in SB village, but the change was small in Ta Village. The longest leaflet length was about 200 cm in the emergence stage of FIs in both villages, and it tended to become shorter toward the dying stage. The maximum width, thickness, and SPAD value of the longest leaflet tended to increase with the EPA; however, the differences after the emergence stage of FIs were small, and the maximum values were 11–12 cm, 0.47 mm, and 91, respectively (Table 4).

The specific leaf area (SLA) of the longest leaflets tended to decrease with the EPA, and the leaflets thickened in both villages (Table 5). The leaflet weight per plant increased from the ETE stage to the emergence stage of FIs, changed little until the early emergence stage of MIs, and decreased in the dying stage. The leaf area per plant was 190–760 m^2 in SB Village and 180–820 m^2 in Ta Village. The average leaf area per leaf was 16–29 m^2 in SB Village and 13–41 m^2 in Ta Village. The average leaflet area was 525–1190 cm^2 in SB Village and 593–1396 cm^2 in Ta Village. The leaf area per leaf and leaflet area increased from the ETE stage to the emergence stage of FIs, remained high during the early emergence stage of MIs, and decreased in the dying stage. The leaf area per plant showed significant positive correlations with both the number of leaves and the average leaf area per leaf, but a stronger correlation was observed with the number of leaves in both villages (Fig. 3A and 3B). Moreover, the average leaf area per leaf was closely related to the average leaflet area, and the average leaflet area was closely related to the longest leaflet length as compared to the number of leaflets and the maximum width of the longest leaflet, respectively (Fig. 3C–F).

In both villages, the ratio of the pith weight to the trunk weight was around 90% in the ETE stage, but it decreased with the EPA and became 70–80% in the dying stage (Table 6).

Table 4. Leaf and leaflet characteristics of sugar palms at different growth stages in Sandabilik Village, Tana Toraja, South Sulawesi, and in Taratara Village, Tomohon, North Sulawesi, Indonesia

Plant No.[1)]	Average leaf length (m)	Average longest leaflet No. (leaf^{-1})	length (cm)	width (cm)	thickness (mm)	SPAD value
(Sandabilik Village)						
1	11.5	300	139	6.0	0.27	63.1
2	8.5	261	135	6.0	0.36	71.3
3	11.7	303	177	7.4	0.39	81.7
4	11.9	299	186	8.6	0.38	61.7
5	9.5	245	201	11.0	0.47	86.4
6	8.0	221	175	9.3	0.45	87.3
7	8.7	231	184	10.1	0.43	77.7
8	8.1	259	171	10.4	0.44	90.7
Average	9.7	264.6	161.0	7.9	0.38	76.3
SD	1.8	32.7	27.3	1.9	0.07	10.4
CV (%)	18.2	12.4	16.9	24.0	17.1	13.7
rs[2)]	*-0.649*	*-0.662*	*0.548*	*0.869***	*0.790**	*0.779**
(Taratara Village)						
11	9.0	221	121	5.6	n.m.[3)]	62.7
12	12.3	332	165	7.3	0.32	80.5
13	10.8	291	208	12.3	0.37	85.3
14	10.3	265	209	11.7	0.41	85.9
15	8.9	272	149	9.7	0.43	84.5
16	8.8	276	172	12.5	0.40	90.7
17	8.3	318	125	12.1	0.47	88.5
18	8.8	282	163	10.7	0.44	84.4
Average	9.7	282.1	163.9	10.2	0.41	82.8
SD	1.4	33.9	33.3	2.6	0.05	8.7
CV (%)	14.1	12.0	20.3	24.9	12.1	10.5
rs[2)]	*-0.621*	*0.281*	*-0.035*	*0.736**	*0.965****	*0.714**

1) Refer to Table 1. 2) Correlation coefficients with the estimated plant age (years) (Table 1). 3) Not measured. *, **, and *** : significant at $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.

Table 5. Characteristics of leaf and leaflet areas of sugar palms at different growth stages in Sandabilik Village, Tana Toraja, South Sulawesi, and in Taratara Village, Tomohon, North Sulawesi, Indonesia

Plant No.[1]	Longest leaflet SLA ($cm^2\ g^{-1}$)	Leaflet fresh weight ($kg\ plant^{-1}$)	Leaf area ($m^2\ leaf^{-1}$)	Leaf area ($m^2\ plant^{-1}$)	Leaflet area (cm^2)
(Sandabilik Village)					
1	22.5	84	15.8	189	525
2	23.1	91	17.5	210	671
3	19.1	210	28.6	400	943
4	19.3	212	29.3	410	979
5	15.9	477	29.2	758	1190
6	16.4	125	22.7	204	1027
7	15.5	154	25.2	328	1092
8	15.3	149	17.5	227	675
Average	18.4	187.6	20.6	340.8	887.7
SD	3.1	126.1	9.4	190.5	235.2
CV (%)	17.0	67.2	45.4	55.9	26.5
rs[2)]	*-0.928****	*0.172*	*0.060*	*0.059*	*0.359*
(Taratara Village)					
11	28.9	64	13.1	184	593
12	20.2	135	22.8	273	686
13	16.7	438	40.6	731	1396
14	15.4	535	29.4	824	1110
15	16.5	333	21.1	550	777
16	14.7	434	26.6	637	962
17	14.8	201	21.2	297	667
18	16.9	191	23.0	323	817
Average	18.0	291.2	24.7	477.3	876.1
SD	4.7	167.9	8.0	239.0	268.9
CV (%)	26.3	57.7	32.2	50.1	30.7
rs[2)]	*-0.755**	*0.252*	*0.116*	*0.148*	*0.060*

1) Refer to Table 1. 2) Correlation coefficients with the estimated plant age (years) (Table 1). * and **: significant at $p< 0.05$ and $p< 0.01$, respectively.

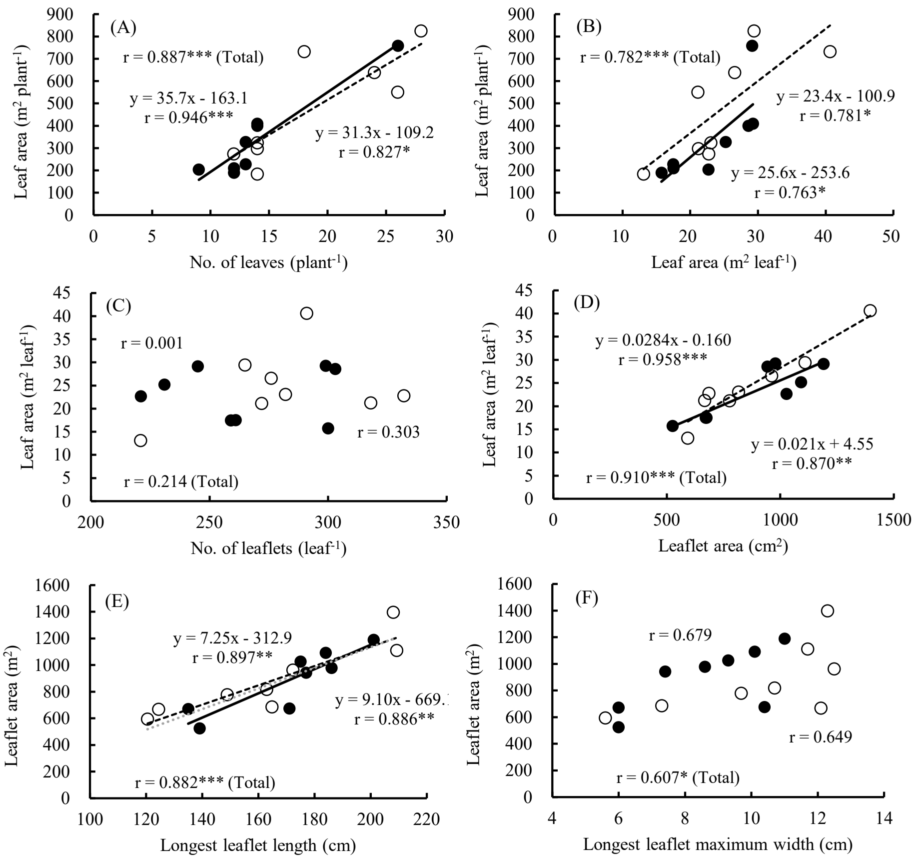

Fig 3. Relationships between the number of leaves per plant (A) or the leaf area per leaf (B) and the leaf area per plant, between the number of leaflets per leaf (C) or the leaflet area (D) and the leaf area per leaf, and between the longest leaflet length (E) or the maximum width (F) and the leaflet area of the sugar palms at different growth stages in Sandabilik Village, Tana Toraja, South Sulawesi, and in Taratara Village, Tomohon, North Sulawesi, Indonesia
●Sandabilik Village, ○Taratara Village. *, **, and ***: significant at $p<0.05$, $p<0.01$, and $p<0.001$, respectively

Table 6. Trunk and pith characteristics of sugar palms at different growth stages in Sandabilik Village, Tana Toraja, South Sulawesi, and in Taratara Village, Tomohon, North Sulawesi, Indonesia

Plant No.[1]	Pith[3]/trunk ratio (%)	Pith				
		DM[4] (%)	DW[5](kg)	T. sugar (%)	starch (%)	starch (kg)
(Sandabilik Village)						
1	87.1	16.1	26	28.1	1.9	0.5
2	91.0	21.0	52	29.6	1.8	0.9
3	84.0	20.1	164	31.3	2.4	4.0
4	81.6	30.0	286	28.1	13.1	37.6
5	77.2	46.8	1017	11.1	26.4	268.2
6	81.5	28.1	396	14.8	15.9	63.1
7	76.6	46.7	667	6.6	40.1	267.1
8	78.5	38.6	978	17.6	29.4	287.8
Average	*81.5*	*30.8*	*448*	*20.7*	*15.7*	*116*
SD	*4.7*	*10.6*	*396*	*8.5*	*12.9*	*133*
CV (%)	*5.8*	*34.4*	*88.3*	*41.3*	*81.9*	*114.4*
rs[2]	-0.814*	0.738*	0.839**	-0.775*	0.836**	0.821*
(Taratara Village)						
11	93.1	13.2	16	46.9	2.7	0.4
12	88.6	13.2	28	34.2	1.6	0.5
13	85.3	25.8	379	16.3	33.3	126.3
14	83.1	28.4	353	12.9	24.4	86.1
15	82.1	37.1	447	8.3	37.6	168.2
16	84.6	30.8	484	13.9	25.7	124.3
17	78.3	23.2	293	22.9	14.0	41.1
18	71.5	27.2	282	22.6	20.1	56.7
Average	*83.3*	*24.9*	*285*	*22.3*	*19.9*	*75.4*
SD	*6.5*	*8.3*	*176*	*12.8*	*13.2*	*61.5*
CV (%)	*7.8*	*33.3*	*61.8*	*57.3*	*66.0*	*81.5*
rs[2]	-0.913**	0.630	0.632	-0.600	0.449	0.357

1) Refer to Table 1. 2) Correlation coefficients with the estimated plant age (years) (Table 1). 3) Pith/trunk weight ratio. 4) Dry matter. 5) Dry weight. * and **: significant at $p<0.05$ and $p<0.01$, respectively.

The pith dry matter percentage increased from the ETE stage to the emergence stage of FIs at 30–40%; thereafter it remained in the range of 30–50% in SB Village and 20–30% in Ta Village. The pith dry weight increased with the trunk weight and was about 300–600 kg after the emergence stage of FIs in SB Village, although some plants had extremely heavy pith weights—around 1000 kg—in the early emergence stage of MIs and the dying stage. On the other hand, in Ta village, the highest value (350–500 kg) was observed during the period from the emergence stage of FIs to the early emergence stage of MIs, and it tended to decrease in the dying stage. The pith starch percentage was low—less than 3%—in the ETE stage, but it reached a maximum value of 30–40% in the emergence stage of FIs and showed a decreasing trend in Ta Village in the dying stage (Table 6). However, in SB Village, some plants showed a high starch percentage of 30–40% even in the dying stage. When analysis includes all pith samples used for the analysis of total sugar and starch (n=59 in SB Village; n=52 in Ta Village), the pith starch percentage showed a strong positive correlation with the pith dry matter percentage (SB Village: r=0.865, p<0.001; Ta Village: r=0.745, p<0.001) and showed a highly significant negative correlation with the pith total sugar percentage (SB Village: r=-0.831, p<0.001; Ta Village: r=-0.778, p<0.001). Moreover, the pith starch percentage showed a highly significant negative correlation with the pith total sugar percentage (SB Village: r=-0.708, p<0.001; Ta Village: r=-0.574, p<0.001). The pith total sugar percentage was found to be highest in the ETE stage and, in the dying stage, lower and higher in plants with higher and lower pith starch percentages, respectively.

The pith starch content (yield) was largest during the period from the emergence stage of FIs to the early emergence stage of MIs, which was 270 kg in SB Village and 120–170 kg in Ta Village. Although the starch content tended to decrease in the dying stage, some plants showed high values of 270–290 kg in SB Village (Table 6).

Discussion

1. Growth characteristics

Two types of sugar palms—tall and short types—were found in SB Village in South Sulawesi and Ta Village in North Sulawesi; however, the tall type, with higher sap productivity, was mainly cultivated and used (Table 2). The survey areas had elevations of approximately 600 m (Ta Village) and 900 m (SB Village), and the sugar palms grew on flatlands or mountainous areas with various slopes; there were large differences in growth, even at the same EPA and growing stage (Tables 1 and 3). In Ta Village, the period from seedling to trunk formation and the flowering of the first FI were 2–3 years and 7–10 years, respectively—shorter than those in SB Village. The reason for this was not clear, but it was considered that temperature differences due to differences in elevation and soil characteristics between the two villages might cause differences in growth duration. According to the interview results, Tomohon had volcanic ash soil (Andosol: Mogea et al., 1991) with good aeration, high water retentivity, and high fertility. Mogea et al. (1991) and Smits (1996) reported that temperature and soil fertility affect sugar palm growth. In both villages, sugar palms were cultivated for the purpose of collecting sap, and no clear differences between the villages were observed in the range of the number of MIs emerged and the durations of sap collection per inflorescence and per plant; however, the number of MIs from which sap was collected was lower in Ta Village than in SB Village (Table 2). The volume of sap collected each day was significantly higher in Ta Village than in SB Village; it is necessary to clarify whether this difference is due to genetic differences in sugar palms and/or environmental factors. According to the results of interviews with farmers, the groundwater level is high and the volume of collected sap is large in Ta Village. As compared with the interview results obtained in a study on Muna Island, Southeast Sulawesi (Yamamoto et al., 2021a), the characteristics related to growth period and sap collection in this study were in the same range, and the volume of sap collected each day on Muna Island was intermediate between those of SB Village and Ta Village. Only one kind of sugar palm (Kowala) grew on Muna Island, and the plant length was close to that of the tall palms of SB and Ta Villages (Yamamoto et al., 2021b). It is necessary to clarify the genetic differences of sugar palms and the effects of genetic differences and environmental conditions of sugar palms on their growth and sap productivity depending on the growing areas.

As mentioned above, both villages are located in mountainous areas, and the growth conditions of sugar palms were variable, from flatlands to lands with various slopes; these environments affected the growth of sampled plants. It was estimated that this tendency was more significant in SB Village than in Ta Village (Table 3). In this way, the results of the sampling survey reflected differences in growth environments; however, from the results of the survey, it was found that leaf emergence and trunk elongation occurred until the emergence stage of the first FI, and there were 40–60 leaves and leaf scars (Mogea et al., 1991; Smits, 1996; Yamamoto et al., 2021b). The final trunk length was around 20 m or more, which was equivalent to or slightly longer than that of the sugar palms on Muna Island (Yamamoto et al., 2021b). Similar to the sago palm, the sugar palm's trunk diameter changed little with the EPA (Yamamoto, 1998) and ranged from 30 to 40 cm. However, in both villages, there were considerable differences in the trunk length and diameter after the emergence of FIs. The trunk weight and volume reached their maximum around the emergence stage of FIs; subsequently, their values varied considerably, 1500–3000 kg and 1.3–2.2 m^3, respectively. However, their values were estimated to be mostly in the range of 1500–2000 kg and 1.3–1.7 m^3, with the exception of plants with excellent growth (Plants No. 5 and 8) (Table 3). The maximum values of trunk growth characteristics of sugar palms in both villages were superior to those on Muna Island (Yamamoto et al., 2021b).

The changes in leaf characteristics with the EPA showed the same tendencies as reported in sago palms (Yamamoto et al., 2020a), as both are hapaxanthic palms (Tables 4 and 5). However, a long vegetative growth period of 15–20 years is followed by a short reproductive growth period (2–3 years) (Jong, 1995; Yamamoto et al., 2020b), in the case of the late-flowering sago palm variety whose growth period is almost the same as that of the sugar palms in this study. On the other hand, in sugar palms, vegetative growth ends in about 10 years, which is the midpoint of the entire growth period, and is followed by a long reproductive period (10–15 years). As compared with studies of sago palms (Yamamoto et al., 2014; 2020a), there were insufficient studies of sugar palms related to how leaf characteristics change with the EPA (Yamamoto et al., 2021b). Further detailed studies from seedling to dying stages are needed.

Comparing the maximum leaf characteristics of sugar palms obtained in this study with those of folk variety Para (Yamamoto et al., 2020a) of Jayapura in Papua, which has the highest starch productivity among sago palms, all characteristics of sugar palms were superior to those of Para, with the exception of leaf length, longest leaflet width, and leaflet area (Table 7). In particular, although the longest leaflet width was inferior, the number of leaflets per leaf was much higher, and the longest leaflet length was also longer as compared to those of Para; as a result, the leaf areas per leaf and plant of sugar palms were larger than those of Para. In sago palms, the starch productivity of folk varieties with almost the same growth period was closely related to differences in the dry matter production due to differences in the leaf area (Yamamoto et al., 2010; 2014; 2016). As compared to the sago palm, the sugar palm has an advantageous system in terms of dry matter production, and it is necessary to study the photosynthetic ability of leaves and the dry matter distribution ratios of each organ/part. The leaf areas per plant and per leaf and the leaflet area were more closely related to the number of leaves, the average leaflet area, and the longest leaflet length than to the leaf area per leaf, the number of leaflets, and the longest leaflet width, respectively. These relationships were the same as those of sago palms in terms of leaf areas per plant and leaf, but the relationship was different in leaflet area (Yamamoto et al., 2014, Yamamoto, 2018).

2. Starch productivity

The pith dry matter percentage was low in the ETE stage, which is similar to that of the sago palm (Yamamoto et al., 2003), increasing to 30–40% during the emergence stage of FIs in the early reproductive stage, and maintaining the values in the

Table 7. Comparison of the maximum values of leaf and leaflet characteristics of sugar palms (Sandabilik Village and Taratara Village) and sago palms (folk variety Para, Jayapura, Papua)

Characteristics	Sugar palm[1)]		Sago palm
	Sandabilik	Taratara	Para (Jayapura)[2)]
No. of leaves ($plant^{-1}$)	26	28	25
Leaf length (m)	11.9	12.3	13.5
No. of leaflets ($leaf^{-1}$)	303	332	178
Longest leaflet (cm)	201	209	191
Longest leaflet width (cm)	11.0	12.3	16.3
Longest leaflet thickness (mm)	0.47	0.47	0.38
Longest leaflet SPAD value	90.7	90.7	80.1
Leaflet area (cm^2 $leaflet^{-1}$)	1190	1396	1630
Leaf area (m^2 $leaf^{-1}$)	29.3	40.6	28.8
Leaf area (m^2 $plant^{-1}$)	758	824	641

1) Refer to Table 4 and 5. 2) Yamamoto et al. (2020b).

early emergence stage of MIs (Table 6). After that, the dry matter percentage showed a tendency to decrease in the dying stage, but it showed a high value of 40–50%, depending on the plant. As with the sago palm (Yamamoto et al., 2003), the pith dry matter percentage of the sugar palm was significantly and positively correlated with the pith starch percentage and significantly and negatively correlated with the pith total sugar percentage. The highest value of pith starch percentage was 30–40% during the period from the emergence stage of FIs to the early emergence stage of MIs, but the variation among plants during this period was as large as that of the pith dry matter percentage. The changes in pith dry matter and starch percentages with growth were similar to those of sugar palms on Muna Island (Yamamoto et al., 2021b). However, the pith dry matter and starch percentages in this study tended to be lower than those of sugar palms on Muna Island (Yamamoto et al., 2021b) and were lower than those of sago palms (Yamamoto et al., 2003; 2020b). The pith dry weight with growth showed the same changes as those of the trunk weight; as a result, the starch content (yield) obtained by multiplying the pith dry weight and the pith starch percentage was 100–250 kg during the period from the emergence of FIs to the early emergence stage of MIs. The starch content was almost the same as that of Muna Island's sugar palms (Yamamoto et al., 2021b) and was similar to that of early flowering sago palm folk varieties (Yamamoto et al., 2010; 2020b). In addition, as in the case of Muna Island palms, the pith starch percentage was as high as 30–40% even in plants after the end of sap collection, and some plants showed starch contents of 250–300 kg in combination with high pith dry weights (Table 6).

As described above, the optimum harvest stage for sugar palms, from the viewpoint of starch production, was the emergence stage of FIs. This result agreed with those obtained by Mogea et al. (1991), Smiths (1996), and Yamamoto et al. (2021b). However, in this study, the high starch contents also observed in plants in the early emergence stage of MIs were presumed to be due to the sap remaining uncollected (Plant No. 5) or sap collection only recently having been initiated (Plant No. 16). Therefore, the effects of the number of emerged MIs and the frequency of sap collection on the pith starch percentage and content as well as the pith dry matter percentage must be clarified. In addition, among plants whose sap collection had ended, high starch content was also observed. This means that the number of FIs and the degree of fruit development, the number of MIs, the amount and the period of sap collection, and the leaf area and photosynthetic capacity of leaves from the end of sap collection were involved in determining the starch content as well as the degree of plant growth (pith dry weight). In this study, these characteristics were not absolutely or sufficiently investigated, and their relationship with starch productivity in the dying stage could not be examined. However, among the three plants in the dying stage in SB Village, plants whose sap collection had ended two months earlier (Plant No. 6) had almost the same leaf area (Table 5) and SPAD values (Table 4) as a plant one year after the end of sap collection (Plant No. 8); however, the starch percentage was 15.9% in the former and 29.4% in the latter, almost double the difference. In addition, although the sap collection from Plant No. 7 and No. 8 had ended 7 months and 1 year earlier, respectively, there was a difference in the leaf area of 100 m^2 and 328 m^2 for the former and 227 m^2 for the latter, and the starch percentages were 40.1% and 29.4%, respectively. These results suggest the possibility that, by maintaining a large leaf area and high leaf SPAD values, starch accumulation can be maintained for a certain period after sap collection has ended. Considering these points, it is necessary to study the starch productivity of sugar palms in the future.

As described above, two types (tall and short) of sugar palm were growing in SB Village in South Sulawesi and in Ta Village in North Sulawesi, but the tall type, which has more sap, was mainly used for sap collection. Therefore, the sampling survey was conducted on tall sugar palms in both villages. The growth periods were presumed to vary depending on differences in altitude and soil environment between the two villages. The number of years until the emergence of the first FI after the completion of leafing was 10–12 years in SB Village and 8–10 years in Ta Village, and the sap collection was ended at around 20 and around 15 years, respectively. In both villages, trunk elongation occurred until the emergence stage of the first FIs, and the highest trunk weight was estimated to be approximately 1500–2000 kg during the period from the emergence stage of FIs to the early emergence stage of MIs. In both villages, the trunk weight was closely related to the trunk length. In the stage of the highest trunk weight, the pith starch percentage was also the highest, at 30–40%, and the starch content was estimated to be 100–250 kg. After that, the starch percentage was presumed to decrease, and the starch content tended to decrease in the dying stage. However, even in the dying stage, it was suggested that the starch content might increase due to starch accumulation in the pith after a certain period of time if the leaf area and leaf chlorophyll content remained large and high, respectively, after the end of sap collection. Sugar palms in both villages had better trunk growth but lower pith starch percentages than those on Muna Island, resulting in almost equal starch contents (yields).

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