Chemical Constituents of The Different Anatomical Parts of The Oil Palm (*Elaeis guineensis*) for Their Sustainable Utilization

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ABSTRACT

As the worldwide production of palm oil (*Elaeis guineensis*) is increasing, concomitant wastes of unutilized parts of the oil palm are also increasing. Thus, effective utilization of these wastes is expected. In this paper, therefore, the chemical composition of cellulose, hemicellulose, lignin and other minor cell wall components was studied for six different anatomical parts of the oil palm such as trunk, frond, mesocarp, endocarp (shell), kernel cake and empty fruit bunch (EFB). As a result, it was shown that cellulose is in a range between 20-40wt% with hemicellulose being 10-35wt%, whereas lignin in a range between 23-52wt%. More in detail, the shell contained the highest lignin about 52wt% but the kernel cake no lignin, while the rest in a range between 23-35wt%, being composed of guaiacyl and syringyl moieties without *p*-hydroxyphenyl propane residue. This is very similar to the hardwood-type lignin, rather than softwood-type lignin. On hemicellulose, mannan was rich in kernel cake, while glucuronoxylan rich in the other parts, with 1.8-8.5 xyloses per one uronic acid. Consequently, oil palm is not a good material for ethanol fermentation by yeast (*Saccharomyces cerevisiae*) because of high pentosan and low hexosan contents.

As a minor component, inorganic constituents were also studied from the ash by scanning electron microscopy equipped with energy dispersive X-ray analysis (SEM-EDXA). As a result, K, Si, Na, Ca, S, P and Mg were found as elements in all parts of the oil palm studied. Particularly, Si and K were abundant in the trunk, shell, mesocarp and kernel cake, while the frond and kernel cake contained, respectively, K, Ca and P in a large quantity. The elements of Cl, Fe and Al were, however, detected only in some parts. These elements found are important and prerequisite for the healthy growth of the oil palm. Therefore, it may be concluded that, upon the whole utilization of the oil palm, inorganic constituents found in this study must be returned to the plantation site.

These lines of information are useful for the efficient utilization of the whole parts of the oil palm which is necessary for the sustainable development of the biomass resources.

Keywords: Oil palm, Trunk, Frond, Mesocarp, Endocarp (Shell), Kernel cake, EFB, Chemical composition, Cellulose, Hemicellulose, Lignin, Extractives, Ash, Neutral sugar, Uronic acid, SEM-EDXA

1.0 INTRODUCTION

Global warming, which is mainly caused by the greenhouse effect resulting from carbon dioxide emissions from fossil fuels, needs to be addressed urgently as a worldwide energy and environmental problem. On the other hand, biomass, which is synthesized by photosynthesis using water and atmospheric carbon dioxide, is a resource that contributes to curbing global warming, and its wider use is anticipated. Of these biomass resources, biodiesel prepared from various natural oil resources is receiving a lot of attention as a fuel for automobiles and other such applications.

For the manufacture of biodiesel, many natural oil resources can be used, and palm oil and palm kernel oil obtained from the oil palm are seen as promising raw materials. Large-scale plantations are being established in southeast Asian countries such as Malaysia and Indonesia. The production of palm oil has doubled in 10 years since 1995; it reached 30 million tons in 2004, constituting 23% of the total world natural oil production(1). However, large quantities of by-products are generated in the production processes of palm oil, and effective use of such by-products is highly anticipated(2).

For example, because the oil palm is replanted every 25 to 30 years, in Malaysia alone, 5 million tons of trunks and 1.1 million tons of fronds are being disposed annually during replantation(3,4). Moreover, in the production processes of palm oil and palm kernel oil in factories, 7 million tons of mesocarp, 4.1 million tons of shell, 1.9 million tons of palm kernel cake, and 13.4 million tons of empty fruit bunches (EFB) are produced every year(5).

These by-products are used as animal feed or boiler fuel in palm oil production factories, but they have not been effectively used by taking advantage of their physical and chemical characteristics. Therefore, the promotion of their utilization is important from the point of view of biomass resource utilization as well as amelioration of environmental problems.

Identification of biomass plant classification and clarification of the relationship between the chemical, physical, and physiochemical characteristics are important for the effective use of biomass resources. In botanical classification, oil palm is classified as a monocotyledon angiosperm and is different from the broad-leaved dicotyledons, which are also classified as angiosperms. Moreover, it is very different from the coniferophyta, which are gymnosperms(6).

Thus, the objective of this study was to analyze the chemical composition, particularly the constituent sugars of hemicellulose, moieties of lignin constituents, and inorganic components. We also aimed at gaining a basic understanding of monocotyledonous oil palm for complete utilization of oil palms in future by comparing the data obtained for coniferous and broad-leaved trees.

2.0 EXPERIMENTAL MATERIALS AND METHODS

2.1 Materials (Samples)

Six parts were extracted from Malaysian oil palm (*Elaeis guineensis* Jacq.): trunk, frond, mesocarp, endocarp (hereafter called the "shell" in this paper), kernel (hereafter called "kernel cakes" because we used the residue left after extracting palm kernel oil from the kernel), and EFB (Fig. 1). After flouring each of these materials into 0.5 mm or less in diameter with a Wiley mill (1029-C, Yoshida Seisakusho Co., Ltd.), Soxhlet extraction was performed for 8 h using an ethanol:benzene solution (1:2 (v/v)) (both obtained from Nacalai Tesque, Inc., High Grade).

2.2 Analysis of Chemical Composition

Chemical composition analysis was performed on the materials extracted in 2.1, using the standard methods(7), for holocellulose, α-cellulose, Klason lignin, acid-soluble lignin, and ash. The analysis procedures are shown in Fig. 2.

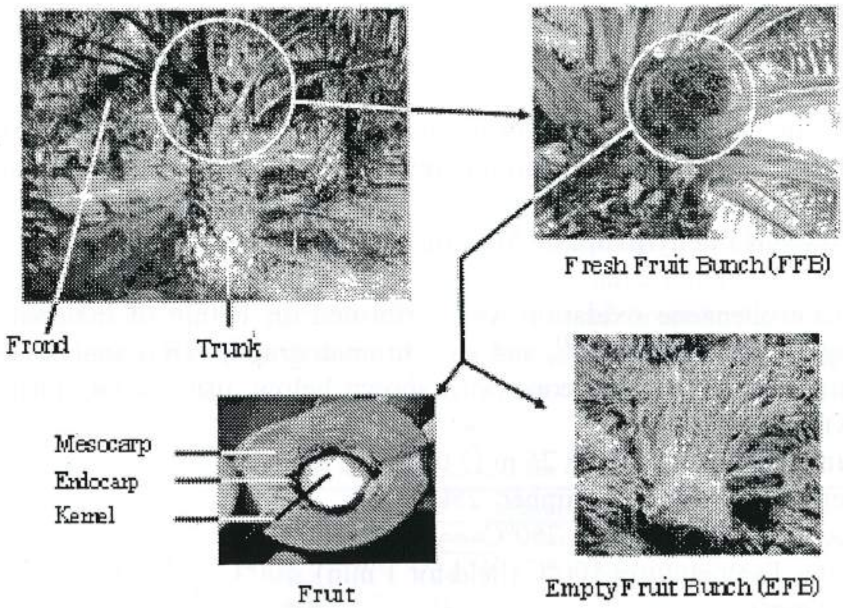

Fig. 1. Various parts of the oil palm.[2]

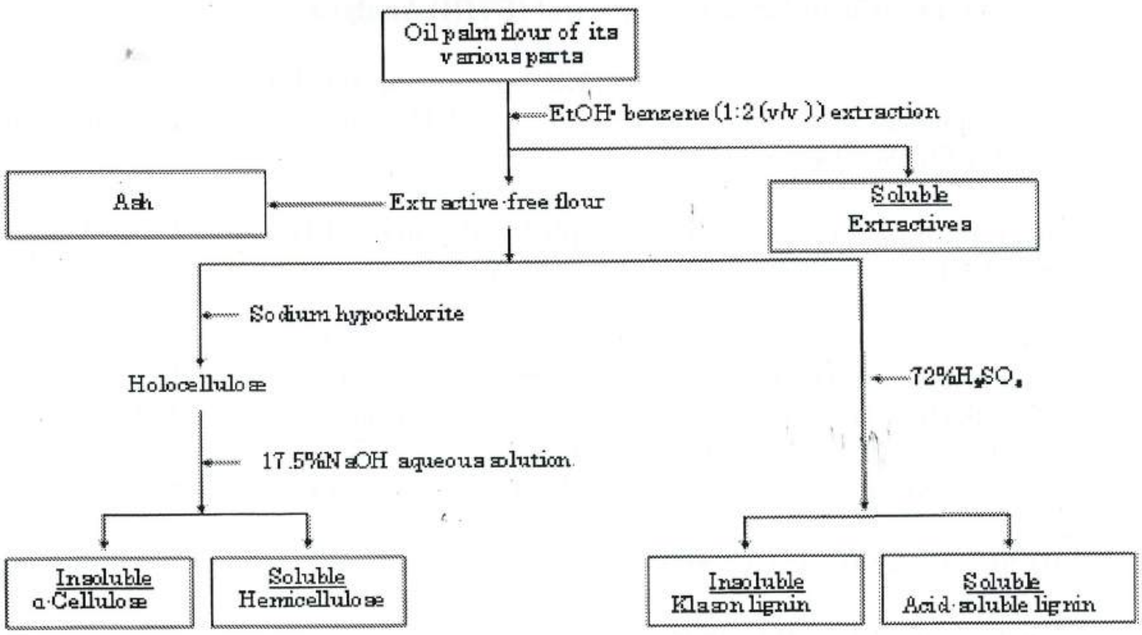

Fig. 2. A flowchart of the oil palm for the chemical composition analysis of its various parts.

2.3 Analysis of the Sugar Composition of Hemicellulose]

Approximately 300 mg of the holocellulose obtained in 2.2 was added to 30 ml of 2 M trifluoroacetic acid (TFA; Nacalai Tesque Inc., High Grade), and treated in an autoclave for 1 h at 120°C. Thereafter, TFA in the material was evaporation dried, and after dissolving the residue in 20 ml of water, the water-soluble part was filtered from the water-insoluble residue. Analysis of the neutral sugars in the water-soluble part was performed using ion chromatography (Dionex ICS-3000) at the conditions described below.

Column: CarboPac PA10
Column Temperature: 35°C
Carrier: H_2O
Flow Speed: 1.0 ml/min

Moreover, quantitative analysis for uronic acid was performed on 50 mg of the materials extracted in 2.1 following standard methods(8).

2.4 Analysis of Phenylpropane Moieties in Lignins

Alkaline nitrobenzene oxidation was performed on 10 mg of materials extracted in 2.1 following standard methods(9), and gas chromatography (GC) analysis was performed on the obtained sample at the conditions shown below, using a GC instrument (Shimadzu GC-18A).

Column: Shimadzu CBP5 25 m □ 0.25 mm diameter
Material Gasification Chamber: 250°C
Detector Apparatus: FID; 250°C
Column Temperature: 100°C (held for 1 min), 100°C □ 270°C (10°C/min), 270°C (held for 10 min)
Carrier Gas: He
Flow Speed: 1.5 ml/min

2.5 Fourier Transform Infra-Red Spectral (FTIR) Analysis

Two milligrams of the completely dried Klason lignin obtained in 2.2 was mixed with 200 mg of completely dried KBr and pelleted, and FTIR analysis was performed using a Shimadzu FTIR 8000 series spectrometer.

2.6 Scanning Electron Microscopy Coupled with Energy-Dispersive X-ray Analysis (SEM-EDXA)

The ash material obtained in 2.2 was sprinkled on the carbon tape stuck to the sample platform and SEM-EDXA analysis was performed without any metal deposition, using a scanning electron microscope (JSM-5800, JEOL Ltd.) equipped with an EDXA instrument (EDAX Corp., Phoenix), at an accelerating voltage of 20 kV. For characteristic X-ray mapping, Na-Kα (0.99 –1.08 keV) and Si-Kα (1.68–1.79 keV) X-rays were used.

3.0 RESULTS AND DISCUSSION

3.1 Analysis of Chemical Compositions

Table 1 shows the contents of cellulose, hemicellulose, lignin, extractives, and ash in the six parts (trunk, frond, mesocarp, shell, kernel cake, and EFB) of the oil palm obtained by chemical constituent analysis. The shell, designated endocarp in Fig. 1, is the hard shell-like substance surrounding the seed in the interior of the fruit. On the other hand, the kernel cake refers to the substance inside the seed, and the residue after palm kernel oil is extracted from the kernel.

These constituent analyses indicated that the cellulose content in the shell was low at 20.5 wt%, whereas it ranged from 30 to 40 wt% in the other parts. On the other hand, hemicellulose content was low in the mesocarp at 9.8 wt%, whereas it ranged from 22 to 35 wt% in the other parts. The total content of lignin, which represented the sum of Klason lignin and acid-soluble lignin, varied greatly depending on the part of the plant, being highest in the shell at 51.5 wt% (49.9 wt% + 1.6 wt%).

Klason lignin is insoluble in 72% concentrated sulfuric acid. Since there are hardly any substances that can be condensed and insolubilized by concentrated sulfuric acid treatment, such as polyphenols, in trees grown in a temperate zone like Japan, Klason lignin almost represents lignin itself. However, because tropical timbers have components that can be condensed and insolubilized by concentrated sulfuric acid treatment, other than the above-mentioned lignin, lignin content cannot be estimated from the Klason lignin content alone in many cases[10].

Table 1. Chemical composition of various parts of the oil palm (wt%).

Part	Cellulose*1	Hemicellulose*2	Lignin		Extractives*3	Ash
			Klason	Acid-soluble		
Trunk	30.6	33.2	24.7	3.8	3.6	4.1
Frond	39.5	29.8	21.2	2.1	1.7	5.7
Mesocarp	39.5	9.8	32.8	0.1	8.6	9.3
Shell	20.5	22.3	49.9	1.6	4.7	1.0
Kernel Cake	35.7	30.3	15.6*4	0.1*4	11.7	6.7
EFB	37.9	35.0	22.9	1.1	2.7	1.5

*1 Cellulose = α-Cellulose, *2 Hemicellulose = Holocellulose − α-Cellulose, *3 Ethanol: Benzene = 1:2 (v/v)

*4 Although these values could be obtained by the method with 72% H_2SO_4, they do not represent true lignin content as described later in Table 3.

The content of acid-soluble lignin ranges from 0.1 to 0.3 wt% in coniferous timbers and from 2 to 4 wt% in broad-leaved timbers in Japan[11]. On the other hand, in the oil palm, as shown in Table 1, the content was 3.8 wt% at maximum, which was as high as that in broad-leaved trees. This indicates that lignin in the oil palm, like that in broad-leaved trees, contains a large amount of non-condensed lignin comprising syringyl moieties.

Next, the content of the extractives in the mesocarp and kernel cake was higher than that in the other parts of the plant. Since mesocarps and kernel cakes are residual waste parts obtained after extraction of palm oil and palm kernel oil, they might be contaminated to some extent. In this study, however, the extracted oil was not considered in the chemical composition.

Ash content was remarkably higher in the palm oil when compared to the values for coniferous and broad-leaved trees in Japan where the content ranges from 0.3 to 0.6 wt%[12]. Because many tropical broad-leaved trees contain high ash content, it is considered that oil palm also has a similar content.

There have been some reports on the chemical composition for the same parts of oil palm. For example, Mae et al[13] reported that the proportion of cellulose, hemicellulose, and lignin in the shell was 31, 20, and 49 wt%, respectively, indicating that the lignin content was high, similar to that seen in this study. Wan Rosli et al[14] reported that the frond contained 86.5 wt% holocellulose, 62.3 wt% α-cellulose (24.2 wt% hemicellulose, derived as the difference between these two values), and 14.8 wt% lignin, suggesting a higher α-cellulose content than that seen in this study. Sun et al[15] reported that the trunk contained 41.4 wt% cellulose, 34.4 wt% hemicellulose, 16.5 wt% lignin, and 3.4 wt% ash, whereas the corresponding percentages in the EFB were 44.4, 30.9, 14.2, and 2.8 wt%. These results are mostly identical to the values seen in this study.

3.2 Analysis of Sugar Composition of Hemicelluloses

Table 2 shows the proportion of uronic acid in hemicelluloses comprising neutral and acidic sugars in the six parts of the oil palm. Please note that the hemicellulose content was calculated by summing the amounts of neutral sugars and uronic acid constituting hemicellulose, and that each sugar component is shown in wt%. From the results, it was shown that hemicellulose was mainly composed of xylose, and that the kernel cake contained mannose as its main constituent sugar as an exception. Moreover, although the trunk and frond contained higher proportions of arabinose than in the other parts, the absolute values were low at 2.7 and 1.5 wt%, respectively, as opposed to 1 wt% or less elsewhere.

Table 2. Hemicellulose and its neutral sugars and uronic acid of various parts of the oil palm.

Part	Hemicellulose*1 (wt%)	Sugars and uronic acid in hemicellulose (wt%) *2						Xyl/UA (molar ratio)
		Glc	Gal	Man	Ara	Xyl	UA	
Trunk	33.2	18.8	4.9	1.2	8.2	55.7	11.3	6.3
Frond	29.8	20.5	4.8	6.3	4.9	52.0	11.6	6.1
Mesocarp	9.8	23.2	4.0	5.8	1.7	48.9	16.5	3.8
Shell	22.3	21.8	2.4	n.d.	0.6	63.4	13.7	6.0
Kernel Cake	30.3	4.0	4.8	82.4	0.9	4.3	3.1	1.8
EFB	35.0	23.1	2.7	n.d.	1.5	63.0	9.6	8.5

*1 Based on the original wood, *2 Based on hemicellulose

Ara: Arabinose, Xyl: Xylose, Man: Mannose, Glc: Glucose, Gal: Galactose, UA: Uronic acid

n.d.: not detected

In addition, it was found that the xylose content was higher, if the uronic acid content was higher. Timell et al reported that there is 1 uronic acid for every 6 xyloses constituting the xylan of the coniferous fir (*Abies amabilis*)[16]. In the xylan of the broad-leaved white birch (*Betula papyrifera* Marsh.)[17], the composition ratio of xylose to uronic acid is reported to be 10 to 1. The oil palm is characterized in that the proportion of uronic acid side chains to xylose is as high as that in coniferous trees, wherein there is 1 uronic acid side chain for every 1.8 to 8.5 xyloses (an average of 6 xyloses).

Akmar et al[18] processed the trunk and EFB of the oil palm using water, hot water, and 2 mol/l TFA, and analyzed the solution obtained by further processing the residue with TFA in a GC analysis. They detected sugars such as arabinose, galactose, glucose, mannose, and xylose in each solution. Moreover, as a result of quantitative analysis, it became clear that glucose is the most prevalent sugar followed by xylose. Because glucose is thought to be mainly derived from cellulose, it is suggested that the trunk and EFB contain xylose as the main constituent sugar of hemicellulose. Wan Rosli et al[19] reported the following constituent sugars of the oil palm frond: 66.6 wt% glucose, 28.9 wt% xylose, 2.2 wt%

mannose, 1.5 wt% arabinose, and 0.9 wt% galactose, indicating that xylose was most abundant. These results agree with those of this study. Daud et al[20] used ^{13}C NMR spectroscopy to analyze the sugar content of the kernel cake and determined that the main component of hemicellulose is galactomannan. In the present study, the mannose content of the hemicellulose of the kernel cake was 84.8 wt% and the galactose content was 4.8 wt%, which closely agree with the results of Daud et al.

From the above results, it is assumed that the hemicellulose in the five parts other than the kernel cake is glucuronoxylan, which contains a relatively high content of uronic acid residue. As shown in Table 2, the constituent sugars of all parts of the oil palm were distinct, and their effective use, by utilizing their characteristics, is expected. For example, the parts abundant in xylose can be converted to xylitol, an artificial sweetener, whereas the mannose-rich kernel cake can be used as a substrate for ethanol fermentation.

3.3 Analysis of Phenylpropane Moieties in Lignins

The relative molar ratios of guaiacyl (G), syringyl (S), and p-hydroxyphenyl (P) moieties in lignin of the six parts of the oil palm obtained by alkali nitrobenzene oxidation are shown in Table 3.

Table 3. Molar ratio of syringyl and *p*-hydroxyphenyl residues to guaiacyl residue in the lignin of the various parts of the oil palm.

Part	Lignin (wt%)	G : S : P (mol/mol)
Trunk	28.5	1.0 : 3.5 : 0.0
Frond	23.3	1.0 : 1.4 : 0.0
Mesocarp	32.9	1.0 : 1.2 : 0.0
Shell	51.5	1.0 : 0.7 : 0.0
Kernel Cake	0	n.d.
EFB	23.0	1.0 : 2.8 : 0.0

G: Guaiacyl unit, S: Syringyl unit, P: *p*-Hydroxyphenyl unit
n.d.= not detected

Alkaline nitrobenzene oxidation produced vanillin, syringaldehyde, and p-hydroxyphenyl aldehyde from the G, S, and P moieties of lignin, respectively[21]. In this way, the moieties constituting lignin can be clarified. The obtained results are shown in Table 3. While vanillin and syringaldehyde were obtained, hardly any *p*-hydroxyphenyl aldehyde was detected in lignin of all the parts of oil palm. From this result, it became clear that G and S moiety lignins are present in all the parts, the latter in a large amount. However, vanillin, syringaldehyde, and *p*-hydroxyphenyl aldehyde were not detected in the kernel cake, implying that the kernel cake contains almost no lignin. Therefore, the content of Klason lignin in the kernel cake, which was 15.6 wt%, unlike the other five parts, appears to reflect sulfuric acid-insoluble substances other than lignin. Therefore, the lignin content of the kernel cake is shown as 0 wt% in Table 3.

Run-Cang et al[22] subjected lignin of the trunk and EFB to alkali nitrobenzene oxidation, and reported that the amount of the main oxidation products obtained was in the order of syringaldehyde and vanillin, and that the main constituent moieties of lignin were S and G moieties. These results agree with those of this study.

3.4 Fourier Transform FTIR Analysis

The FTIR spectra near 1270 cm^{-1}, for Klason lignin obtained for the six parts of the oil palm are shown in Fig. 3. At this wavenumber, absorption due to the methoxy group of lignin was confirmed in the FTIR spectra for the trunk, frond, mesocarp, shell, and EFB, whereas almost no absorption was found for the kernel cake. Therefore, it is suggested that lignin is present in five plant parts: trunk, frond, mesocarp, shell, and EFB, whereas almost no lignin is present in the kernel cake.

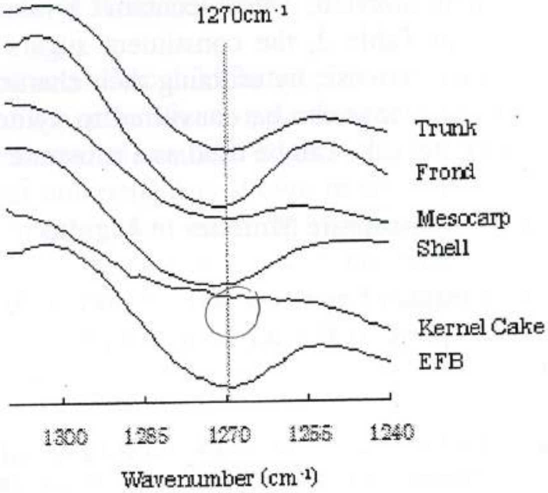

Fig. 3. FT-IR spectra of the lignin in the various parts of the oil palm.

3.5 Ash

Table 1 shows the ash content in each material. It is suggested that there is a variation in the ash content, ranging from 1.0 wt% in the shell to 9.3 wt% in the mesocarp, depending on the part of oil palm. Moreover, the color of the ash also varies as shown in Fig. 4, ranging from brownish red in the trunk, kernel cake, and EFB; white in the frond; dark brown in the shell; and reddish brown in the mesocarp, indicating that the types and composition of elements of the ash vary according to the plant part. In order to clarify the elements included in each material, EDXA was performed.

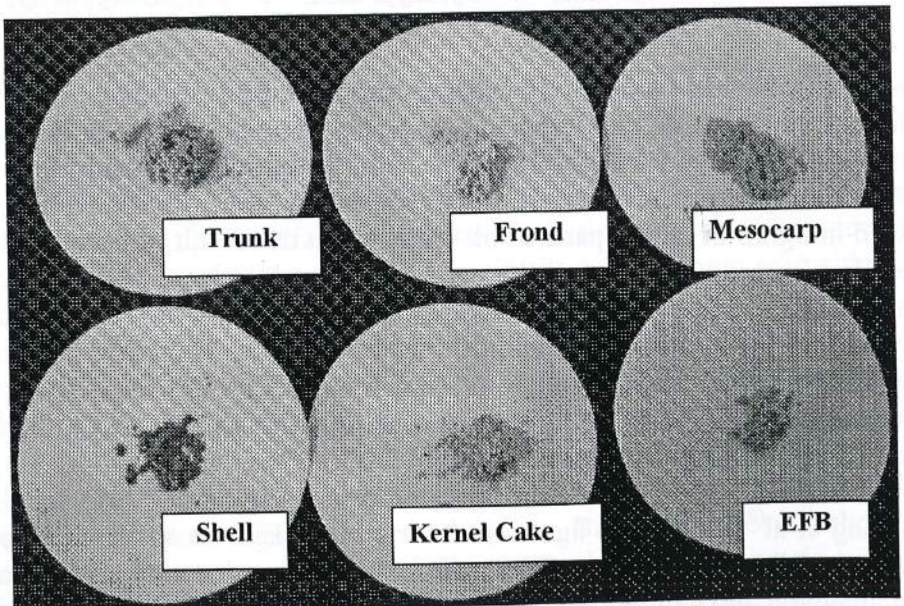

Fig. 4. The ash from 6 different parts of the oil palm.

3.6 SEM-EDXA of the Ashes

3.6.1 Trunk

The SEM-EDXA results for the ash obtained from the trunk are shown in Fig. 5. SEM photograph in (a) shows various shapes, e.g., fluffy (oval), needle-shaped (rectangle), and spherical (circle).

These materials were observed under the light microscope. When viewed through a polarizing microscope under cross nicols, the needle-shaped materials exhibited birefringence, suggesting that they are crystalline. On the other hand, the spherical and fluffy materials did not exhibit birefringence, indicating that they are not crystalline. From the study conducted by Saiki et al[23], it can also be concluded that the needle-shaped materials were crystalline.

Next, the EDXA spectra in the visual field of (a) are shown in Fig. 5 (b). Results suggest that Na, Mg, Al, Si, P, S, Cl, K, and Ca are present. Moreover, Na-Kα X-ray mapping of the visual field of (a) shown in (c) indicates that Na is present in materials other than the spherical ones. The results of EDXA analysis for the needle-shaped crystals are shown in

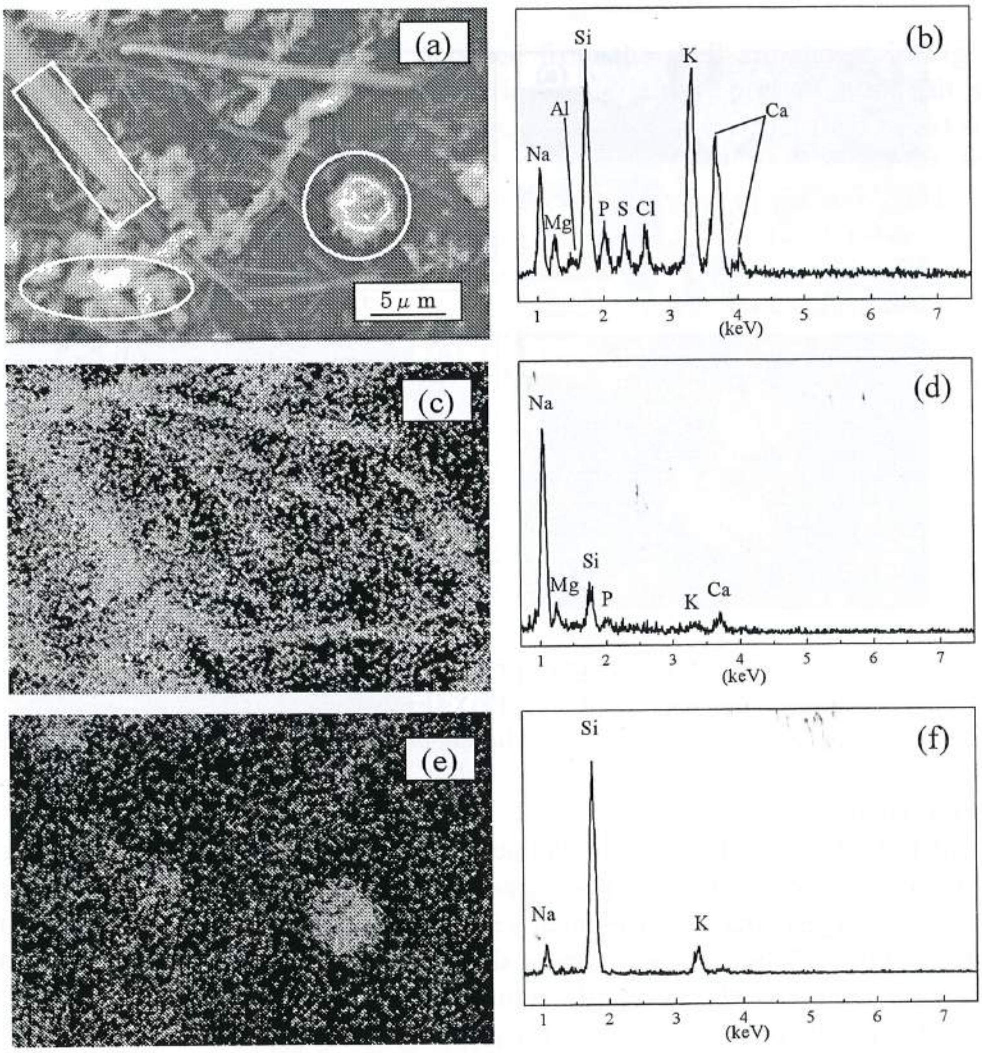

Fig. 5. SEM-EDXA on ash from the Trunk.

(d), in which a strong peak of Na, as a characteristic element, was visible. This suggests that Na is localized to needle-shaped crystals. On the other hand, Si-Kα X-ray mapping of the visual field of (a) and the results of EDXA for the spherical materials are shown in (e) and (f), respectively. From these results, it appears that Si is localized to spherical materials. (a) Scanning electron micrograph, (b) EDXA spectrum for (a), (c) Distribution map of Na-K α X-rays for (a), (d) EDXA spectrum for needle crystals, (e) Distribution map of Si-K α X-rays for (a), (f) EDXA spectrum for sphere substances

3.6.2 Frond

The SEM-EDXA results for the ash obtained from the frond are shown in Fig. 6. SEM photograph in (a) shows that fluffy and spherical materials are present in the ash. The EDXA spectra of the visual field of (a) are shown in (b). Results suggest that the following elements are present: Na, Mg, Si, P, S, Cl, K, and Ca. Moreover, Si-Kα X-ray mapping of the visual field in (a) shown in (c) indicates that Si is mainly concentrated in spherical materials. The spectra of the spherical materials are shown in (d), in which a characteristic strong Si-Kα X-ray peak was observed. From these results, it appears that Si is localized to the spherical materials similar to the trunk.

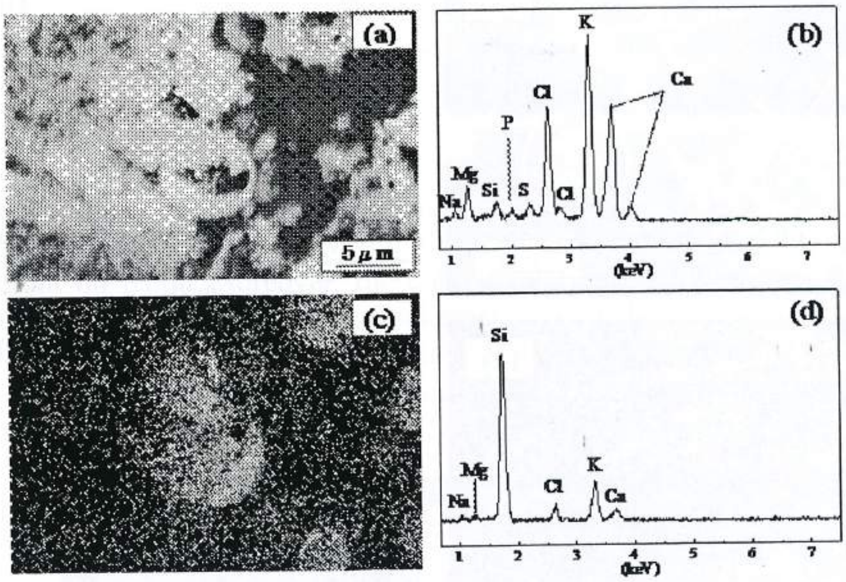

Fig. 6. SEM−EDXA on ash from the Frond.
(a) Scanning electron micrograph, (b) EDXA spectrum for (a),
(c) Distribution map of Si-K α X-rays for (a), (d) EDXA spectrum for sphere substances

3.6.3 Mesocarp

The SEM-EDXA results for the ash obtained from the mesocarp are shown in Fig. 7. SEM photograph in (a) shows the morphologies of the fluffy and spherical materials. EDXA shown in (b) suggests that many elements such as Na, Mg, Al, Si, P, S, K, Ca, and Fe are present. Moreover, Si-Kα X-ray mapping shown in (c) and the results of EDXA spectra of the spherical materials shown in (d) indicate that Si is localized to spherical materials similar to the results obtained for the other parts.

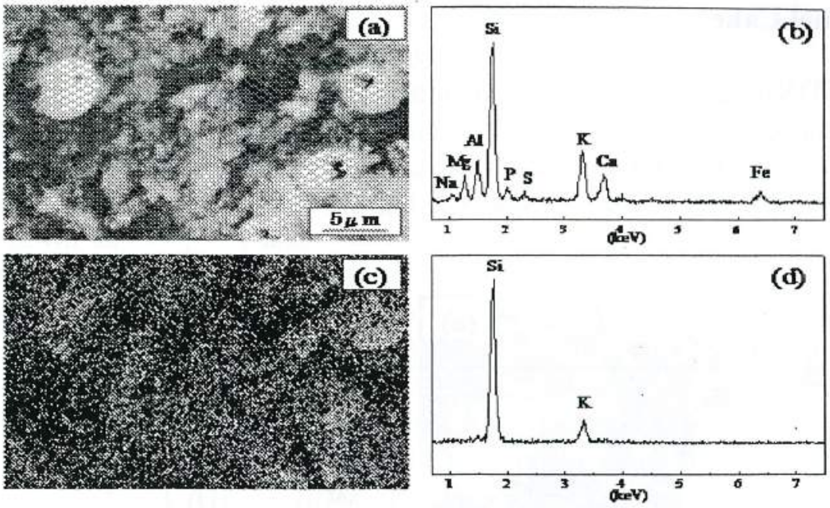

Fig. 7. SEM−EDXA on ash from the Mesocarp.
(a) Scanning electron micrograph, (b) EDXA spectrum for (a),
(c) Distribution map of Si-K α X-rays for (a), (d) EDXA spectrum for sphere substances

3.6.4 Shell

The SEM-EDXA results for the ash obtained from the shell are shown in Fig. 8. SEM photograph in (a) shows that fluffy and spherical materials are present in the ash, similar to the findings in the trunk and frond. The EDXA spectra in the visual field of (a) are shown in (b). Results suggest that many elements such as Na, Mg, Al, Si, P, S, K, Ca, and Fe are present. However, a small amount of Fe, which was not seen in the trunk and frond, was detected. Si-Kα X-ray mapping shown in (c) and EDXA spectra of spherical materials shown in (d) indicate that Si is localized to spherical materials.

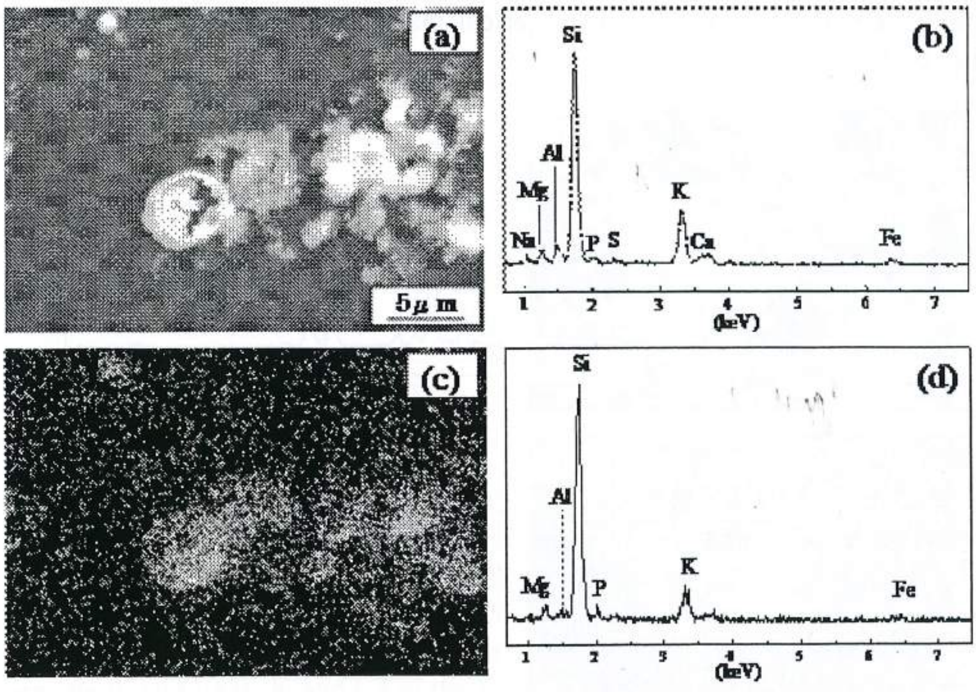

Fig. 8. SEM−EDXA on ash from the Shell.
(a) Scanning electron micrograph, (b) EDXA spectrum for (a),
(c) Distribution map of Si-K α X-rays for (a), (d) EDXA spectrum for sphere substances

3.6.5 Kernel Cake

The SEM-EDXA results for the ash obtained from the kernel cake are shown in Fig. 9. SEM photograph in (a) shows that only fluffy materials were present, whereas needle-shaped crystals and spherical materials were absent. EDXA shown in (b) suggests the presence of Na, Mg, Al, Si, P, S, K, Ca, and Fe.

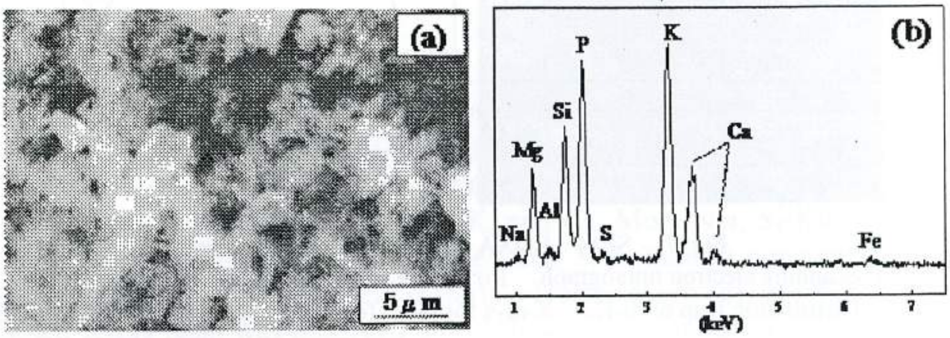

Fig. 9. SEM−EDXA on ash from the Kernel Cake.
(a) Scanning electron micrograph, (b) EDXA spectrum for fluffy substances

3.6.6 EFB

The SEM-EDXA results for the ash obtained from the EFB are shown in Fig. 10. Fluffy material and spherical materials were observed similar to the results obtained from the other parts except the kernel cake. EDXA shown in (b) shows the presence of many elements such as Na, Mg, Si, P, S, K, Ca, and Fe. Si-Kα X-ray mapping shown in (c) and EDXA spectra of spherical materials shown in (d), which revealed a strong Si-Kα X-ray peak, indicate that Si is localized to spherical materials similar to the results obtained for the other parts.

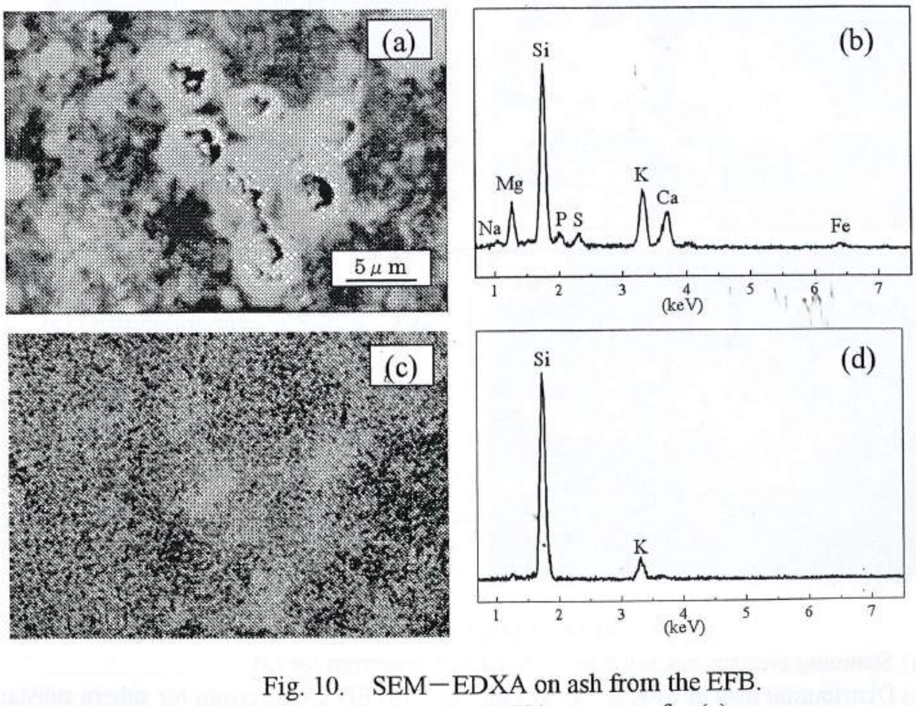

Fig. 10. SEM−EDXA on ash from the EFB.
(a) Scanning electron micrograph, (b) EDXA spectrum for (a),
(c) Distribution map of Si-K α X-rays for (a), (d) EDXA spectrum for sphere substances

3.7 Comparison of the Component Elements

Based on the results above, Table 4 summarizes the constituent elements of the needle-shaped crystals as well as the non-crystalline fluffy and spherical materials, which constitute the ash of each part of the oil palm. The characteristic X-rays detected in each EDXA are shown as +++, ++, and + in the order of their intensity. Two morphologies, needle-shaped crystals and spherical materials, were found in the trunk; only non-crystalline fluffy materials were found in the kernel cake, while both fluffy and spherical materials were included in the rest. Moreover, both Si and Na were localized to spherical materials and needle-shaped crystals, while K and/or Si were localized to fluffy materials. The other elements Na, Ca, S, P, and Mg were always present in small amounts. In addition, Cl, Fe, and Al were found in some parts of the plant.

Table 4. Inorganic constitutes in ash from various parts of oil palm.

Parts	Shapes	Elements									
		K	Si	Na	Ca	Cl	S	P	Mg	Fe	Al
Trunk	Needle	+	++	+++	+			+	+		
	Fluffy	++	+++	+	+	+	+	+	+		+
	Sphere	+	+++	++							
Frond	Fluffy	+++	+	+	++	+	+	+	+		
	Sphere	++	+++	+	+	+ +					
Mesocarp	Fluffy	++	+++	+	+		+	+	+	+	+
	Sphere	++	+++								
Shell	Fluffy	++	+++	+	+		+	+	+	+	+
	Sphere	++	+++						+	+	
Kernel Cake	Fluffy	+++	+	+	+		+	++	+	+	+
EFB	Fluffy	++	+++	+	+		+	+	+	+	
	Sphere	++	+++								

+++: Extremely abundant ,
++ : Abundant ,
\+ : Existing

As for the constituent elements, K, Si, Na, Ca, S, P, and Mg were present in all the parts, and 8 to 9 elements were always detected. However, Cl, Fe, and Al were only found in the trunk; shell, mesocarp, kernel cake, and EFB; and trunk, mesocarp, shell, and kernel cake, respectively. It is thus clear that the kinds of elements present vary with the part of the plant. The two most prevalent elements in each part were as follows: Si and K in the trunk, mesocarp, shell, and EFB; K and Ca in the frond; and K and P in the kernel cake.

Taken together, it is clear that the kinds and amounts of elements present in the oil palm vary greatly from part to part. Therefore, we compared the ash content among various kinds of biomass resources.

In contrast to the oil palm which is a perennial plant classified as a monocotyledon angiosperm, timbers such as white birch (broad-leaved tree), which is a perennial plant belonging to the family of dicotyledonous angiosperms[(24)], or black spruce (coniferous tree)[(25)], which is a gymnosperm, contain 0.5 wt% or less ash. This value is significantly lower than that of the oil palm. It is reported that they contain Ca, K, and Mg as the main elements.

On the other hand, rice straw[(26)] and wheat straw[(27)], which are annual monocotyledons, are reported to have high ash content: 7.6 and 9.8 wt%, respectively. Large amounts of Si and K have been reported as the constituent elements. Moreover, rice husk[(28)] is also reported to contain Si and K as the main constituent elements. In addition, maize stem[(29)] is reported to contain 5.8 wt% ash, wherein Si is most abundant followed by Mg, Ca, and K. These results clearly suggest that any part of the oil palm has high ash content. The results of this study also showed that Si and K are the main elements in the trunk, mesocarp, shell, and EFB (excluding the frond and kernel cake). Although this could be a common feature of monocotyledons, the influence of soil in their habitats may be a factor that cannot be overlooked.

4.0 CONCLUSIONS

The objective of this study was to facilitate an effective use of the unused parts of the oil palm. We conducted chemical composition analysis of six anatomical parts: the trunk, frond, mesocarp, endocarp, shell, kernel cake, and EFB. The analysis of constituent sugars of hemicellulose and constituent moieties of lignin led us to clarify the following three points:

1. Lignin is not present in the kernel cake and is most prevalent in the shell. It is composed of G and S moieties, and P moieties are rarely present. The structure of lignin is similar to that in broad-leaved trees rather than that in conifers.
2. Hemicellulose in the kernel cake is composed of mannan, whose main constituent sugar is mannose, whereas hemicellulose in the other five parts is composed of glucuronoxylan, whose main constituent sugar is xylose. There were 3.5 to 8.5 xyloses per uronic acid residue.
3. The trunk has an inconsistent cell density and contains a low amount of cellulose[(30)] Therefore, it is not suitable for use as a structural material.

These results provide important basic knowledge about the six parts, useful for effectively utilizing the discarded parts that are not currently used and for enabling complete utilization of oil palm. It is desirable that this knowledge be also used to enable the use of sustainable biomass resources.

On the other hand, the elements constituting the oil palm ash found in this study are biogenic elements in living organisms. Therefore, the fronds and trunks, which are currently left unused in plantations, in fact, help in recycling the elements contained in the parts to the soil.

However, in order to extract oils from fruits, fresh fruit bunches are transported from the plantation areas to the factories. As a result, all the inorganic elements contained are removed at the plantations. After oil extraction, the separated mesocarp, shell, kernel cake, and EFB are used as boiler fuel in factories, material for activated carbon, or feeds for domestic animals, according to need. Moreover, although there are instances where these are recycled to plantations[31], they are discarded without being effectively used in many cases.

In these situations, complete utilization, wherein various parts of the oil palm are effectively used, is highly anticipated. In order to enable sustainable oil palm plantations, it is important to facilitate effective usage that takes into consideration the recycling of the inorganic components, which have been removed once, back to the soil of the forest areas. We hope that the results of this study would benefit such an endeavor.

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