Malaysian Journal of Soil Science 2026 Vol. 30: 215-224
Received: 21/8/2026; Revised: 29/10/2026; Accepted: 5/11/2026; Online: 8/11/2026

Optimization of Sidimpuan Salak Frond Waste as Amelioration on Smallholder Sidimpuan Salak (*Salacca sumatrana* Becc.) Plantation Land

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ABSTRACT

Sidimpuan salak frond waste (SSFW), which has not been optimally utilized, has the potential to become an environmentally friendly local ameliorant material to increase the productivity of smallholder Sidimpuan salak (Salacca sumatrana Becc.) plantations. This study has examined the characteristics of SSFW and its effect on changes in surface charge and nutrient composition of Inceptisol on Sidimpuan salak (Salacca sumatrana Becc.) plantation ameliorated with SSFW. This study has used a completely randomized design with three replications and five treatment levels (SSFW doses: 0, 20, 40, 60, and 80 tons ha^{-1}). The characteristics of SSFW have moisture (14.15%), volatile matter (84.40%), ash (17.81%), fixed carbon (0.63%), pH (7.80), electrical conductivity (0.88 dS m^{-1}), CEC [26.60 cmol(+) kg^{-1}] and composition of macro (20.85% C, 0.53% N, 0.52% P and 0.53% K) and micro (12.97% Ca, 3.34% Mg, 4.72% S, 0.47% Mn, 11.61% Fe and others) nutrients and has active groups such as phenol and carboxyl. The application of 40 tons ha^{-1} of SSFW significantly increased the surface charge (pH H_2O, EC, and CEC) by 0.3, 0.06 ds m$^{-1,}$ and 1.60 cmol(+) kg^{-1}, respectively. Meanwhile, it is also significant to increase the availability of nutrients (organic C, total N, available P, and K-exch) by 0.45% C, 0.15% N, 19.64 ppm, and 0.56 cmol(+) kg^{-1} K, respectively. The chemical and nutrient characteristics of SSFW and the application of 40 tons ha^{-1} SSFW have significantly improved soil quality (Inceptisols) and support sustainable productivity on smallholder Sidimpuan salak (Salacca Sumatrana Becc.) plantation land.

***Key words**: Amelioration, Inceptisols, salak frond waste, Sidimpuan salak, smallholder plantation land*

INTRODUCTION

Salak Sidimpuan (*Salacca sumatrana* Becc.) is a typical horticultural commodity of the South Tapanuli region that has high economic and social value for smallholders. Salak cultivation is mostly carried out on land owned by smallholders with limited scale and simple technology (Nuddin *et al*., 2023). However, salak productivity in this region tends to stagnate and even decline due to declining land quality, low organic matter, poor soil structure, and limited nutrient and water retention (Suksmawati *et al*., 2021). This is exacerbated by the lack of organic fertilization, which calls for an approach that can sustainably improve soil quality by utilizing local resources.

One of the local potentials that has not been optimally utilized is the salak frond waste that is abundant in the people's salak plantations. So far, these salak frond waste have only been left to rot or burned, which can pollute the environment and potentially also become a breeding

ground for pests and diseases. The waste, if not processed further, is left to accumulate among the salak plants. The weathering process occurs naturally and lasts for ± 1 year. This waste contains organic compounds such as lignocellulose: 31,7% cellulose, 33,9% hemicellulose, 17,4% lignin, and 0,6% silica, and macro nutrients that can be utilized as soil ameliorants (Devi *et al*., 2019). Salak fronds naturally have the potential to be a cheap and sustainable amelioration material to improve soil quality and increase crop productivity. However, the use of salak frond waste as an ameliorant, especially in the specific context of Sidimpuan salak plantations, has not been optimized. Most of them focus more on conversion products such as compost or biochar. So, it is explicitly necessary to explore and characterize the chemical properties of salak fronds and the applicable dosage that is suitable for the marginal soil conditions of smallholder salak plantation land.

The majority of Sidimpuan salak farmers manage their land on a small scale with limited inputs, resulting in limited routine fertilization. On the other hand, Inceptisol on smallholder salak plantations has various limitations that will affect crop productivity. One of the main problems is the low organic matter content and acidic soil pH, which limit the availability of nutrients for salak plants (Abdullah *et al*., 2025). In addition, low cation exchange capacity (CEC) causes nutrients to be easily leached and not stored effectively in the soil. Unstable soil structure causes compaction and aeration problems, which in turn disrupts salak root development. Unbalanced drainage will also worsen soil quality, so that without intervention in the form of amelioration based on local organic materials such as salak fronds waste, Inceptisol in salak plantations will experience a continuous decline in productivity. Thus, a local waste-based approach becomes very relevant to improve soil fertility and production cheaply and independently (Kumar *et al*., 2024). Salak frond waste available in the farmer's environment can be processed into applicable ameliorant materials, both in natural form and conversion products such as compost, biochar, and others. Salak fronds have promising physical and chemical potential with 10.5% water, 36.5% C, 0.91% N, 62.93% OM, and a 40.01 C/N ratio (Silaban *et al*., 2020). It can contribute to soil structure improvement, cation exchange capacity enhancement, and soil pH stabilization.

Optimization of agricultural biomass waste can be used as a soil ameliorant to improve tropical soil quality. However, the utilization of Sidimpuan salak fronds waste (SSFW) in wet tropical rainforest agroecosystems such as Sidimpuan, especially in salak plantations, is still limited. This will prove the utilization of local organic waste as an effective and efficient ameliorant alternative. This optimization will support the transformation of traditional agricultural practices towards ecologically based systems and local technologies. This study has examined the characteristics of SSFW and its effect on changes in surface charge and nutrient composition of Inceptisol on Sidimpuan salak (*Salacca sumatrana Becc.)* plantation land ameliorated with SSFW.

MATERIALS AND METHODS

This research was conducted from April to July 2025 at the Soil Chemistry and Fertility Laboratory, Faculty of Agriculture, and Central Laboratory, Universitas Andalas, Padang.

Experiment design

The experimental design that has been used in this study is a complete randomized design (CRD) with three replications and five treatments (Sidimpuan salak frond waste dose) of 0, 20, 40, 60, and 80 tons ha^{-1}.

Sidimpuan salak frond waste preparation

Sidimpuan salak frond waste (SSFW) was obtained from a smallholder salak plantation in Lembah Lubuk Raya, West Angkola, South Tapanuli, North Sumatra, Indonesia, at coordinates

Received: 21/8/2026; Revised: 29/10/2026; Accepted: 5/11/2026; Online: 8/11/2026

Lat 1.440161°; Long 99.221157°. The processing process begins with shredding the waste using a Chopper Hammer Mill machine, then the shredded results are sieved using a 2 mm sieve to obtain a uniform particle size (**Figure 1**).

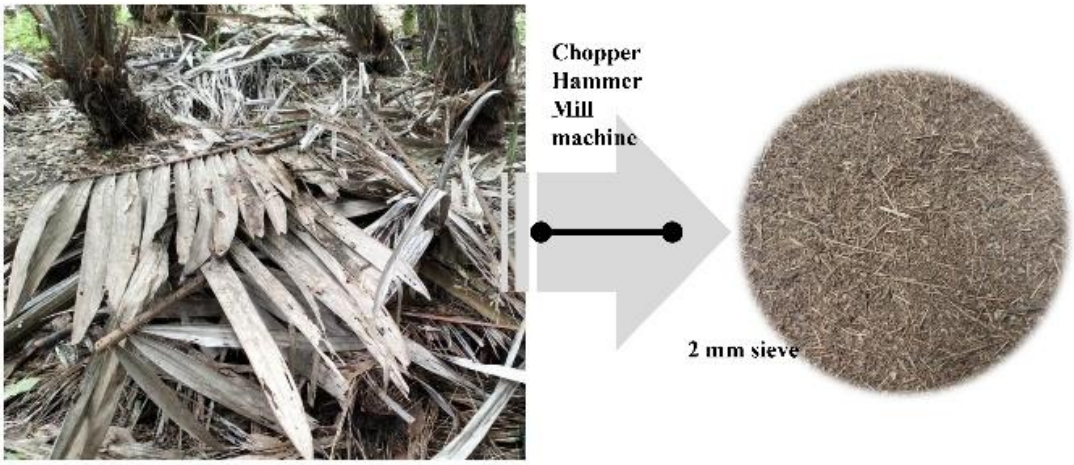


Figure 1. Sidimpuan salak frond waste

Soil sampling

Inceptisols soil was taken from a smallholder salak plantation in Sitinjak, West Angkola, South Tapanuli, North Sumatra, 22735 Indonesia at coordinates Lat 1.445144°; Long 99.164238°. Soil samples were taken at a depth of 0-20 cm from 5 collection points, which were then composited. Then, the soil was aerated for 2 × 24 hours. After drying, the soil samples were ground and sieved with a 2 mm sieve. After that, soil samples were taken for initial soil analysis or control. Soil samples were weighed as much as 500g of absolute dry weight equivalent into experimental pots according to the dose of each treatment. The soil was ameliorated with SSFW and stirred well, and watered with water to reach field capacity, then stirred well. Then the soil was incubated for 2 weeks. After incubation, soil samples were analyzed in the laboratory.

Soil ameliorant analyses

The analysis of ameliorant followed the standards of the decision of the Minister of Agriculture (MOA) No. 70/ MOA/ SR.140/ 10/ 2011 on the minimum technical requirements of soil conditioners, namely proximate analysis, pH (H_2O, KCl 1M, and PZC), electrical conductivity (EC), liming potential, CEC, organic C, total N, and oxide composition with a PANalytical Epsilon 3XL Benchtop X-ray fluorescence (XRF) Spectrometer. Analysis of functional groups with IRT Racer 100 fourier transform infrared (FTIR) spectroscopy Shimadzu A21706 (Singh *et al*., 2017). Meanwhile, soil analysis focused on changes in surface charge [pH (H_2O, KCl 1M, and PZC), electrical conductivity (EC), mineral and organic matter composition, and CEC] and major nutrient composition such as organic C, total N, available P, and K-exch (Soil and Fertilizer Instrument Standard Testing Center, 2023).

Statistical analysis

The results of the ameliorant and soil analysis were subjected to statistical analysis using software (Microsoft Excel 2016 and SPSS 23). The statistical analysis used was the analysis of variance (ANOVA) and Duncan's multiple range test (DMRT). After detecting a significant effect with ANOVA, DMRT was used as a post hoc test to identify which specific group means differ from each other. Significance levels were determined as follows: if F count > F table at

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the 5% level, the results are significant and marked with [*], and if F count > F table at the 1% level, the results are very significant and marked with [**]. The [*] and [**] annotations reflect the significance levels of these differences.

RESULTS AND DISCUSSION

Sidimpuan salak frond waste (SSFW) has chemical characteristics with high potential as a soil ameliorant (**Table 1**). Proximate analysis showed an average moisture content of 14.15%. The very high volatile matter content of 84.50% indicates that SSFW is rich in easily degradable organic compounds, which are beneficial for supporting soil microbial activity. High volatile matter (>60%) indicates a high content of labile organic compounds, easily decomposed, and supports the growth of soil microbes (Boone *et al*., 2025). Ash content of 17.81% indicates the presence of inorganic minerals that have the potential to be a source of nutrients for plants. High ash content reflects the presence of inorganic minerals such as Ca, Mg, and K, which function as nutrients in the soil and also as an indicator of the potential to improve soil fertility (Hamidi *et al*., 2021). However, the fixed carbon content of only 0.63% indicates that most of the carbon in this waste is labile and easily degraded. Low fixed carbon indicates that organic matter is labile and easily broken down by microorganisms and has a short residence time in the soil, and contributes more quickly to nutrient mineralization (Bunti *et al*., 2021).

The SSFW has a pH of H_2O and KCl 1M of 7.80 and 7.30, respectively, indicating neutral to slightly alkaline properties, which can increase the pH of soils such as Inceptisols. Organic matter with a neutral to slightly alkaline pH (around pH 6.5-8.0) is very effective in neutralizing acidic soils such as Inceptisols and Ultisols, because it can increase nutrient availability and reduce Al^{3+} toxicity as well as increase soil microbial activity, and help the mineralization process. Meanwhile, the pH point zero charge (PZC) is 6.80, which indicates that SSFW has a surface charge that tends to be negatively charged, making it effective in absorbing nutrient cations. pH PZC is the pH at which the particle surface is uncharged. If the pH H_2O > PZC, the surface of the material tends to be negatively charged and can attract and adsorb positively charged ions such as NH_4^+, K^+, and Ca^{2+} (Fairuzi *et al*., 2025). Organic matter with a lower PZC tends to have high cation adsorption ability, which is very important for increasing nutrient availability to plants (Parija *et al*., 2023).

Table 1. Statistical description of characteristics from Sidimpuan salak frond waste

Analysis		Unit	Mean	SE	SD
Proximate	Moiture	%	**14.15**	1.14	1.97
	Volatile Matter		**84.50**	1.04	1.80
	Ash		**17.81**	1.08	1.87
	Fixed Carbon		**0.63**	0.12	0.21
pH	H_2O	unit	**7.80**	0.06	0.10
	KCl 1M		**7.30**	0.06	0.10
	PZC		**6.80**	0.06	0.10
EC		dS m^{-1}	**0.88**	0.01	0.01
CEC		cmol(+) kg^{-1}	**26.60**	0.12	0.20
Organic C		%	**20.84**	0.13	0.22
Total N			**0.53**	0.02	0.03

Note: PZC = Point of zero charge [(2*KCl) – H_2O]; EC = electrical conductivity; OM = organic matter; CEC = cation exchange capacity; CV = coefficient of variance; SE = standard error; and n = 15 samples.

The electrical conductivity (EC) of the SSFW is 0.88 dS $m^{-1,}$ which reflects the presence of dissolved salts in amounts that are still within safe limits for plants, but can increase nutrient availability in the soil. The EC in organic matter reflects the amount of dissolved salts. EC < 2 dS m^{-1} is considered not to cause salinity stress in most plants and indicates the availability of nutrients in ionic form (Shokri *et al*., 2024). The cation exchange capacity (CEC) of the SSFW,

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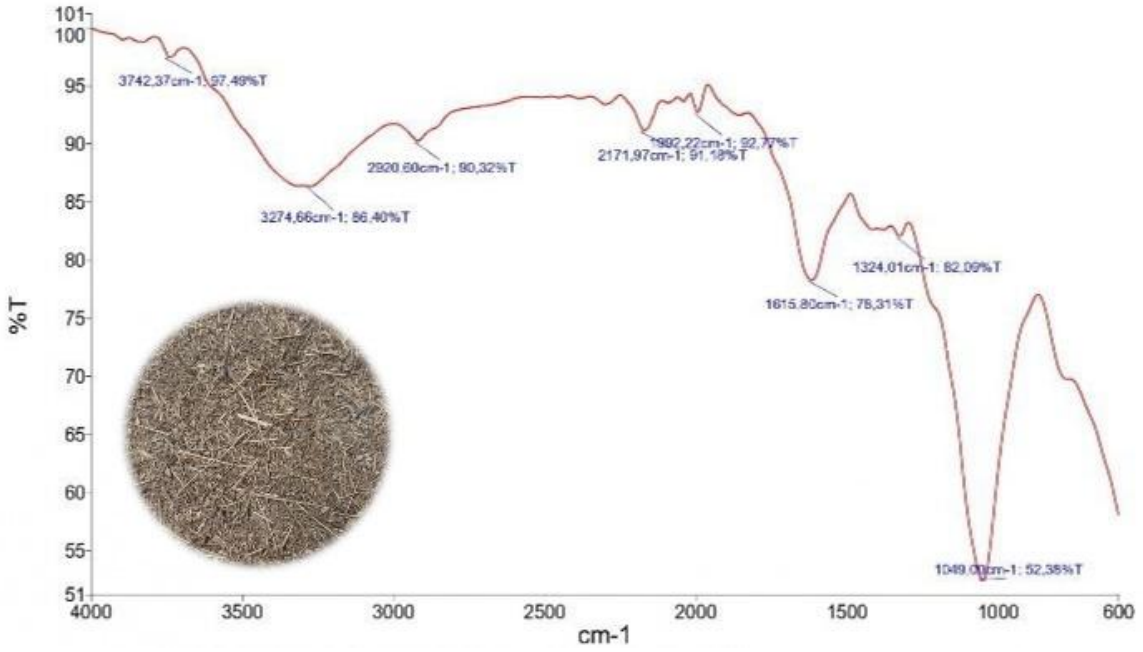
on the other hand, was 26.60 cmol(+) kg^{-1}, indicating that this effluent can effectively retain and supply cationic nutrients. Organic matter with high CEC has a good buffering ability against changes in nutrients in the soil, and improves fertilizer efficiency (Uddin *et al*., 2025).

The organic C in SSFW of 20.84% is high and is an important source of energy for soil microbes, while supporting the formation of good soil structure. Organic matter with C above 15% is high and is the main source of energy for soil microbes, which is important for biological activity, decomposition, and soil aggregate formation, and also plays a role in increasing cation exchange capacity and water retention (Piccolo & Drosos, 2025). However, the total N in SSFW is only 0.53%, which is low for rapid decomposition. Organic matter with N <1% is considered to have low nitrogen content and is less optimal for rapid decomposition (Chiriac *et al*., 2025). High C and low N content, as in SSFW, in a high C/N ratio (>35), which slows down the activity of decomposing microbes and lengthens the decomposition time. Thus, SSFW has great potential as organic matter for soil quality improvement.

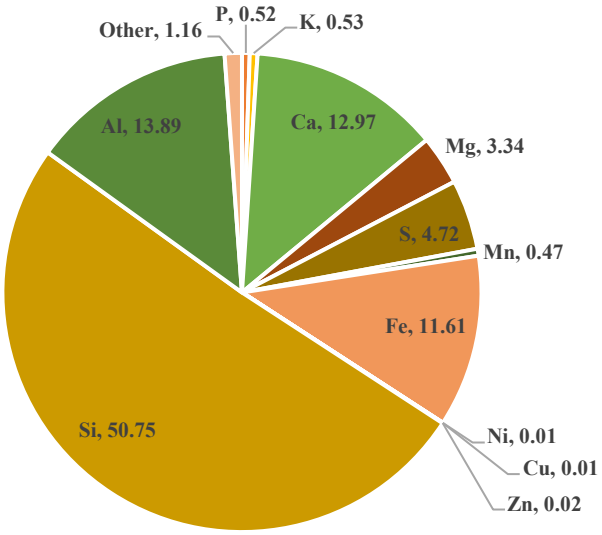
Based on the FTIR analysis of SSFW, various functional groups were identified that reflect the content of complex organic compounds typical of lignocellulosic materials (Figure 2A). The absorption bands at wave numbers around 3742.57 cm^{-1} and 3274.65 cm^{-1} indicate the presence of hydroxyl groups (-OH) derived from alcohol compounds, phenols, and bound water, which are common in cellulose, hemicellulose, and lignin. The presence of these groups is important because they contribute to the ability to form hydrogen bonds and increase the sorption capacity of water and cations (Galicia-Andr *et al*., 2021). The peak at 2920.08 cm^{-1} indicates the C-H stretching vibrations of methyl and methylene groups, which are part of the hydrocarbon chain structure of cellulose and lignin. Furthermore, the weak absorption at 2171.57 cm^{-1} indicates the possible presence of C≡C or C≡N groups, which, although minor, could be associated with conjugated aromatic compounds or complex nitrogen compounds in plant tissues. The strong band at 1615.86 cm^{-1} indicates the presence of aromatic C=C bonds, which strengthens the indication of the presence of lignin in the structure of the material. The peak at 1324.01 cm^{-1} is related to the stretching of C-O groups and O-H bending of phenolic or carboxylic groups, which also have an important role in the ionic activity and complexation ability of organic matter to metal or nutrient cations in soil. Another significant peak appeared at 1058.48 cm^{-1}, which is characteristic of C-O-C and C-O bonds in polysaccharide structures such as cellulose and hemicellulose. The FTIR spectra on SSFW are rich in active functional groups such as hydroxyl, carboxyl, phenolic, and ether, which support its role as a reactive organic matter in soil. The presence of these groups reinforces the potential of this material as an ameliorant due to its ability to adsorb water, nutrient ions, and increase soil microbial activity through the availability of easily degradable carbon compounds.

Based on XRF analysis of SSFW, it is known that the main component contained is silicon (Si) with a percentage of 50.75%, indicating that this waste is very rich in SiO_2 (**Figure 2B**). This high silica has the potential to be utilized for soil ameliorants. High silica content is associated with potential as a soil ameliorant, especially for improving the quality of marginal soils (Dariah *et al.*, 2025). Other major elements detected in significant amounts are Al_2O_3 at 13.89%, CaO at 12.97%, and Fe_2O_3 at 11.61%. These three elements are generally associated with structural components of plant tissues and may contribute to ash formation if the waste is used as biomass fuel. Elements such as SO_3 at 4.72% and MgO at 3.34% were also found. Meanwhile, nutrients such as K_2O, P_2O_5, and MnO were found in small amounts (<1%), but still have potential benefits in agronomic utilization. Trace elements such as ZnO, NiO, and CuO are present in very small amounts (less than 0.03%) and could be relevant for microelement recovery studies. Overall, the oxide composition of SSFW suggests potential utilization in amelioration technologies of marginal soils such as Inceptisols.

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(A)



(B)

Figure 2. Characterization of functional groups by FTIR (A) and oxide composition by XRF (B) of Sidimpuan salak frond waste.

The SSFW application on Inceptisols showed a significant effect on soil surface charge characteristics (**Table 2**). Increasing the effluent dosage from 0 to 80 tons ha^{-1} consistently increased the pH of Inceptisols on Sidimpuan salak plantation land. The application of SSFW at doses of 60 and 80 tons ha^{-1} was similar in increasing soil pH by 0.7 and 0.6 units, respectively, compared to the control. Meanwhile, the application of SSFW at doses of 40 and 20 tons ha^{-1} looks different in increasing the pH of Inceptisol on salak plantation land. This increase in pH reflects a decrease in soil acidity, which is thought to come from the alkalizing

nature of organic matter in SSFW (**Table 1**). Organic matter contains functional groups such as carboxyls and phenols that are alkalis (**Figure 2A**), which can neutralize soil acidity and increase pH gradually. This is in line with the increase in pH of Inceptisols due to SSFW application. Application of large amounts of organic matter can increase soil pH by adding basic cations such as Ca^{2+}, Mg^{2+}, and K^{+} and reducing Al^{3+} and H^{+} saturation, in tropical acid soils such as Inceptisols (Yang *et al*., 2024; La *et al*., 2025). This is supported by pH H_2O > PZC, which indicates that the soil is dominated by negative charges.

The SSFW application on Inceptisols caused a significant increase in electrical conductivity (EC), from 0.08 dS m^{-1} to 0.21 dS m^{-1} (**Table 2**). This increase reflects the accumulation of dissolved ions from the decomposition of organic matter in the effluent. Application of SSFW at doses of 80 and 60 tons ha^{-1} showed relatively equivalent increases in EC, at 0.13 and 0.10 dS $m^{-1,}$ respectively, compared to the control. Meanwhile, application of SSFW at doses of 40 and 20 tons ha^{-1} also showed almost similar EC increases of 0.06 and 0.05 dS m^{-1} compared to the control, although the values were lower compared to the doses of 80 and 60 tons ha^{-1}. The application of organic fertilizer consistently increased the dissolved ion content (which triggers the increase in EC (Asadu *et al*., 2024).

Table 2. Surface charge characteristics of Inceptisol from smallholder Sidimpuan salak (*Salacca sumatrana* Becc.) plantation land ameliorated with Sidimpuan salak frond waste.

Sidimpuan salak frond waste (ton ha^{-1})	pH (1:1)			EC	Composition		CEC
	H_2O	KCl 1M	PZC		Mineral	OM	
	unit			dS m^{-1}	%		cmol(+) kg^{-1}
0	4.6 c	4.4 b	4.2 c	0.08 c	72.32	27.68	29.20 c
20	4.8 b	4.5 b	4.2 c	0.13 b	70.20	29.80	29.60 b
40	4.9 b	4.7 a	**4.5 a**	0.14 b	69.58	30.42	**30.80 ab**
60	**5.2 a**	**4.8 a**	**4.4 ab**	**0.18 a**	69.00	31.00	**33.20 ab**
80	**5.3 a**	**4.8 a**	4.3 b	**0.21 a**	66.20	33.80	**33.60 a**
CV (%)	*2.02*	*2.16*	*2.31*	*13.51*	*7.20*	*16.37*	*6.39*
Duncan's Test	**	**	*	**	*ns*	*ns*	**
SE	*0.08*	*0.08*	*0.08*	*0.02*	*4.08*	*4.08*	*1.63*

Notes: Numbers in the same column followed by the same lowercase letter are not significantly (ns) different according to Duncan's test at the 5% (*) and 1% (**) level; PZC = Point of zero charge [(2*KCl) – H_2O]; EC = electrical conductivity; OM = organic matter; CEC = cation exchange capacity; CV = coefficient of variance; SE = standard error and n = 15 samples.

Soil organic matter (OM) composition increased from 27.68% to 33.80%, while mineral content decreased relatively little, reflecting the partial substitution of mineral fraction by organic matter (**Table 2**). The decrease in mineral composition and increase in organic matter in Inceptisols on Sidimpuan salak plantation land was not significant due to SSFW application. This increase in organic matter directly contributed to the increase in cation exchange capacity (CEC), which rose from 29.20 to 33.60 cmol(+) kg^{-1}. The SSFW application, especially at a dose of 80 tons 40 tons ha^{-1}, can increase the CEC of inceptisol by 4.40 cmol kg^{-1}, compared to the control. However, this increase was similar to the application of SSFW at doses of 60 and 40 tons ha^{-1} with an increase in CEC of 4.00 and 1.60 cmol(+) kg^{-1}, respectively, compared to the control. This was supported through increased surface charge (PZC pH) and nutrient holding capacity. The addition of organic matter significantly increased CEC due to functional groups in humus and other organic matter, while the contribution of the mineral fraction remained stable (Carbonized *et al*., 2024). The increase in organic carbon stock increased the zero point of charge (pH PZC), which supports the increase in the charge-holding capacity of plant-important nutrients.

The SSFW application on Inceptisols showed a gradual increase in organic C along with a significant increase in dosage (**Figure 3A**). Application of SSFW with a dose of 80 tons ha was able to increase organic C by 1.07% C, compared to the control (**Figure 3A**). However,

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it is different in the application of doses of 60 - 20 tons ha^{-1} with the same increase at 0.49%; 0.45% and 0.05%, respectively, compared to the control. The SSFW application contributes positively to the accumulation of soil organic matter, especially at higher doses, which in turn can have implications for CEC and nutrient retention. Increasing the dose of exogenous organic matter increased the mineralization of SOC and organic C proportionally, especially at higher doses, thus improving nutrient retention and CEC (Domouso *et al*., 2024).

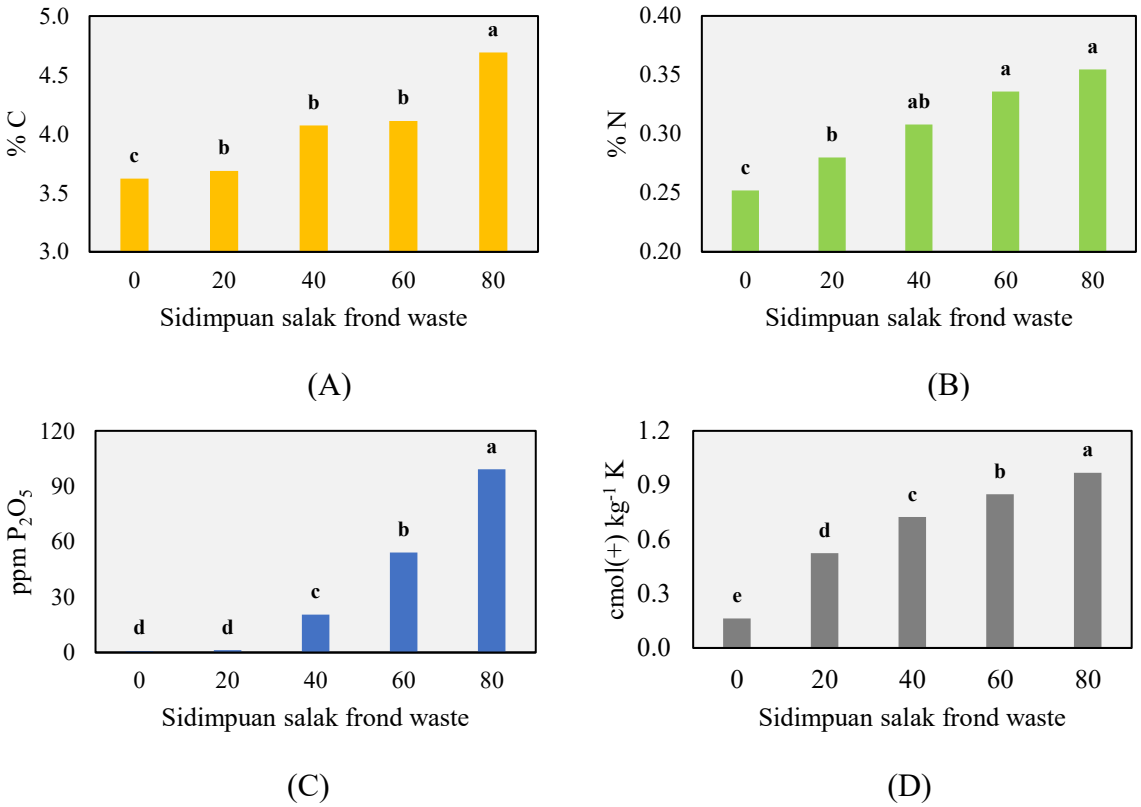


Figure 3. Nutrient composition of organic C (A); total N (B); available P (C) and K-exch (D) in Inceptisol from smallholder Sidimpuan salak (*Salacca sumatrana* Becc.) plantation land ameliorated with Sidimpuan salak frond waste.

The application of SSFW has a significant effect on increasing total N in Inceptisols (**Figure 3B**). The SSFW application at 80 ton ha^{-1} by 0.10% N, compared to the control. Meanwhile, the application of SSFW at doses of 60, 40, and 20 tons ha^{-1} showed an increase in total N of inceptisol by 0.09%, 0.06% and 0.03%, respectively, compared to the control. The SSFW is an effective source of organic N and provides essential macronutrients for plants (**Table 2**), especially total N. The application of organic matter can increase N mineralization and microbial activity that supports the release of organic N (Chiriac *et al*., 2025).

The SSFW application has a very significant effect on increasing the available P in Inceptisols (**Figure 3C**). Application of SSFW with a dose of 80 tons ha^{-1} is best in increasing available P by 98.31 ppm, compared to the control. Meanwhile, in contrast to the doses of 60 and 40 tons ha^{-1} can increase the available P by 53.31 and 19.64 ppm, respectively, compared to the control. However, the application of 20 tons ha^{-1} is the same as the control (0 tons ha^{-1}) in increasing available P inceptisols. This increase indicates that SSFW is a very effective source of organic P, especially at high doses. The sharply increased phosphorus availability is most likely due to the high P content in SSFW and the rapid mineralization process of organic matter, which significantly reduced phosphate fixation by the mineral fraction of Inceptisols. The availability of phosphorus is instrumental in the formation of roots, flowers, and plant

metabolic processes, and can increase the efficiency of utilization of other nutrients in the root system (Khan *et al*., 2023).

The SSFW application has a significant effect on increasing K-exch in Inceptisols (**Figure 3D**). Application without SSFW (control), K-exch was 0.16 cmol(+) kg^{-1} (low). K-exch increased sharply to 0.52, 0.72, and 0.85 cmol(+) kg-¹ at doses of 20 and 40 tons ha-¹, and continued to increase until it reached 0.97 cmol(+) kg-¹ at a dose of 80 tons ha-¹. Application of this effluent increased K-exch by more than 500% compared to the control. This increase indicates that SSFW is an effective source of organic and mineral potassium, especially at medium to high doses. Potassium is an essential macronutrient for plants, playing a role in enzyme activation, osmotic regulation, and photosynthetic product transport (Papadakis *et al*., 2023).

CONCLUSION

The characteristics of SSFW have moisture (14.15%), volatile matter (84.40%), ash (17.81%), fixed carbon (0.63%), pH (7.80), electrical conductivity (0.88 dS m^{-1}), CEC [26.60 cmol(+) kg^{-1}] and composition of macro (20.85% C, 0.53% N, 0.52% P and 0.53% K) and micro (12.97% Ca, 3.34% Mg, 4.72% S, 0.47% Mn, 11.61% Fe and others) nutrients and has active groups such as phenol and carboxyl. The application of 40 tons ha^{-1} of SSFW significantly increased the surface charge (pH H_2O, EC, and CEC) by 0.3, 0.06 ds $m^{-1,}$ and 1.60 cmol(+) kg^{-1}, respectively. Meanwhile, it is also significant to increase the availability of nutrients (organic C, total N, available P, and K-exch) by 0.45% C, 0.15% N, 19.64 ppm, and 0.56 cmol(+) kg^{-1} K, respectively. The chemical and nutrient characteristics of SSFW and the application of 40 tons ha^{-1} SSFW have significantly improved soil quality (Inceptisols) and support sustainable productivity on smallholder Sidimpuan salak (*Salacca Sumatrana* Becc.) plantation land.

ACKNOWLEDGEMENTS

The authors would like to thank Andalas University for providing access to the Central Laboratory as well as the Soil Chemistry and Fertility Laboratories during the conducting of this research.

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