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The Potential of Valorized Sisal Decorticated Waste in Rearing of Black Soldier Fly

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Abstract: The use of sisal decorticated waste (SDW) for various applications is limited due to its high acidic content. This is the first study of its kind regarding the use of SDW as a substrate for the growth of the black soldier fly (BSF). Pre-treatment was a necessary and challenging step performed on the waste to meet the minimum requirements for the rearing of BSF. The SDW was sun dried, sieved, and decomposited and neutralized to form the final products that were used for the rearing of BSF. The resultant waste had fourteen (14) elements; the essential elemental form results were Ca, P, K, Mn, Fe, Cu, and Zn at varying levels, which are all essential for animal growth. The SDW contained 10 ± 0.01 percent of crude protein, 11 ± 0.02 moisture and energy (1615 kcal/g of sisal decorticated waste). The sun dried BSF larvae were reared on SDW that contained 53 ± 0.005 percent of crude protein, 4 ± 0.01 percent of crude fat, a moisture content of (10 ± 0.1)%, carbohydrate percent of (43 ± 0.01)%, and ash percent of (37 ± 0.08). When rearing was finished, 3000 g of dried pre-treated waste yielded more wet BSF larvae, (336 ± 41.3) g, compared to 3000 g of fruit waste, which yielded (244 ± 4.16) g of wet BSF larvae. Therefore, based on this study, SDW is a promising potential feed for rearing BSF because it had a better reduction of the waste by 52%. Furthermore, the harvested BSF larvae contained sufficient nutritional value to feed poultry and fish.

Keywords: black soldier fly; environmental management; industrial wastes; sisal decorticated waste; waste treatment

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1. Introduction

Managing sisal decorticated waste (SDW) as an industrial waste in most Tanzanian sisal factories is still challenging [1–3]. Applying sisal decorticated waste in the rearing of the black soldier fly (BSF) and obtaining the viable agricultural products (animal feed and organic fertilizer) has not been performed so far. This is due to existing challenges, including the presence of sisal fibers and low pH in the SDW, which affects the feeding rate and growth of BSF [3]. Therefore, it needs to be pretreated for better results. This study anticipated the use of SDW as a substrate for BSF growth, as it is easily available and bears low cost.

The sisal fiber, which is produced during the decorticating process, accounts for only 3 to 6% of the total weight, with the remainder being waste [4,5]. This huge amount of generated sisal waste (about 94 to 97%) should be effectively managed as resource recovery in attempt to avoid the negative effects that it has on the environment, including soil and underground water pollution [6,7]. Various studies show that sisal decorticated waste is used in biogas production [8–10], mushroom cultivation [5,11] as animal feed [12,13], and it goes further in the fattening of goats and sheep [14,15]. However, in all reported studies, SDW needs to be pre-treated for better results [16,17].

BSF technology is a resource recovery that uses organic wastes as a substrate, and it produces BSF larvae, which is used as alternative source of protein for livestock [18,19]. Various studies have been conducted on rearing BSF using different substrates, including vegetable waste, chicken feed, and biogas digestate. The essential amino acids found on BSF larvae grown on chicken feed, vegetable waste, biogas digestate, and restaurant waste differ from one another due to the nutrients that they have. For instance, lysine, valine, and arginine levels constitute between 20 and 30 g kg^{-1} on the dry matter of BSF larvae, which are grown in chicken feed, vegetable waste, biogas digestate, and restaurant waste [20]. For the case of protein content, previous studies showed that BSF larvae reared on organic substrate ranged between 35% and 49% on dry matter [21]. Moreover, it is emphasized that mixed diets work better and yield higher nutrients than individual diets when used to rear BSF. BSF larvae raised in a diet containing a mixture of banana and spent grain in a 1:1 ratio had a protein content of 45.61%, and the protein content that was raised in banana fruit was only 36.50% [22,23]. Therefore, the organic waste produces BSF larvae that have potential nutrients for animal feed if pre-treated well [24–26]. This study used pre-treated SDW for the growth of BSF larvae and the understanding of its nutritional contents that fit the poultry and fish feeding industries.

2. Results and Discussion

2.1. Generated Waste

The SDW generated during sisal fiber production was analyzed in relation to the age of the sisal plants inserted into the decorticator machine. The results were as follows.

As observed in Table 1, the weight of each bundle (W1) varied even though there was an equal number of sisal leaves. This variation was caused by the age of the sisal plants. The first harvest occurs when the sisal plants are aged three (3). The harvest is repeated every six (6) months if the farm is effectively maintained and after nine (9) to twelve (12) months if the farm is not well managed [27]. The weeds and other grasses along the rows are removed as part of the management. The older sisal leaves weigh more than younger ones. For the production of one (1) ton of sisal fiber, it generates 24 tons of SDW [10,28]. The use of the disposed SDW in various functions, including the rearing of BSF larvae, can reduce methane emissions [29].

Table 1. Generated sisal decorticated waste.

S/N	Plant Age (Years)	Weight of Bundle W1 (Kg)	Weight of Wet Waste W2 (Kg)	Weight of Dry Waste W3 (Kg)	%Weight of Wet Waste	Mean ± SD (%/*w*) of Wet	%Weight of Dry Waste	Mean ± SD (%/*w*) of Dry Waste
1	3	46.6	33.8	8.7	72.53		18.67	
2		93.2	68.1	16.31	73.07	68.78 ± 6.96	17.5	17.76 ± 0.81
3		47.9	29.7	8.2	60.75		17.12	
4	6	104.3	45.1	17.3	43.37		16.59	
5		137.6	42	20.1	30.52	36.32 ± 6.52	14.61	16.41 ± 1.71
6		143.7	50.4	25.9	35.07		18.02	

According to the results obtained and presented in Table 1, the older sisal leaves produce less amounts of waste than younger ones (first harvest) when decorticated. This is evident when the weight of each bundle is compared to the weight of sisal waste generated before decortication. The mean average (68.78 ± 6.96) of the wet SDW of 3 years showed significant difference with the wet SDW (36.32 ± 6.52) of 6 years at ($t < 0.05$). Moreover, the mean averages of dry SDW at 3 years and 6 years were (17.76 ± 0.81) and (16.41 ± 1.71), respectively. Such averages also show a significant difference at ($t < 0.05$). The obtained data correlated with the previous studies, implying that the amount of SDW being generated is large [27,29] enough to fulfill the demand of the substrate needed for BSF rearing.

2.2. Physiochemical Parameters of Fresh Sisal Decorticated Waste

The obtained findings for sisal waste physiochemical parameters are presented in Table 2.

Table 2. Physiochemical parameters of fresh sisal decorticated waste.

Physiochemical Parameters	Value ($\bar{x} \pm$ SD)
pH	4.5 ± 0.06
Conductivity (µS/m)	1523 ± 0.03

The pH of the fresh sisal decorticated waste was 4.52 ± 0.06, which implies that SDW is acidic. Previous studies reported that SDW has a pH 4 [30] and pH of 4.8 [31]. Therefore, this justifies that fresh sisal waste is acidic in nature. Furthermore, the study found the sisal waste had a conductivity of 1523 µS/m. This indicates that sisal waste has ions and specifically cations [31]. Moreover, those cations are also essential elements for poultry and fish feed.

2.3. Elemental Profile of Sisal Decorticated Waste

Table 3 shows the essential elements that are found in sisal decorticated waste.

Table 3. Elemental profile of sisal decorticated waste.

Elements in SDW	Concentration (ppm) ($\bar{x} \pm$ SD)
Magnesium	19,662 ± 0.52
Aluminum	1290 ± 0.9
Phosphorus	7065 ± 0.54
Potassium	15,685 ± 0.203
Calcium	100,294 ± 0.117
Titanium	258 ± 0.18
Vanadium	38 ± 0. 2
Manganese	85 ± 0.14
Iron	3354 ± 0.19
Nickel	5 ± 0.02
Copper	26 ± 0.21
Zinc	70 ± 0.01
Rubidium	9 ± 0.05
Barium	659 ± 0.62

A total of fourteen (14) elements were present in the sisal decorticated waste that was analyzed. Calcium (Ca) was among the elements with a high value of 100,294 ± 0.117 ppm, whereas nickel (Ni) had the least value of 5 ± 0.02 ppm. This elemental profile proves that sisal waste has essential elements that can be fed by BSF larvae and later on produce products required by poultry and fish. According to previous studies, the essential elements that are required for feeding poultry and fish include calcium, iron, magnesium, potassium, sodium, and zinc [32]. Therefore, sisal waste is effective in the rearing of BSF larvae as it comprises essential elements that are required by poultry and fish [33].

2.4. Pre-Treatment of Sisal Decorticated Waste

The study findings show that the sundried, aerobic fermentation and addition of rice husk in the sisal decorticated waste enabled the pH to rise from 4.52 ± 0.06, which was measured in fresh sisal decorticated waste, to 7.57 ± 0.06 of the pre-treated sisal waste. Other parameters are shown in Table 4.

Table 4 shows that the pH increased compared to that of fresh sisal decorticated waste. This was due to the fact that it was mixed with rice husk, a fact that was consistently reported to range between a pH of 7.5 and 8 in other studies [34]. The obtained pH also suits the rearing of BSF, as it was reported to grow well at a pH between 6 and 10 [35–37]. Therefore, sisal decorticated waste should be sundried and mixed with water in order to be decomposed. The rice husk should also be added in the sisal decorticated waste before being used as a substrate for BSF larvae in order to yield significant product. This aspect has enabled the utilization of SDW in the rearing the BSF larva, thus enabling the once thought unfit biomass to be used for the production of larvae with high yields.

Table 4. Parameters of the pretreated SDW.

Nutrients	Measured Value
pH	7.5 ± 0.06
Moisture content (%)	11 ± 0.02
Organic matter (%)	71 ± 0.01
Protein (%)	10 ± 0.01
Energy (kcal)	1615 ± 0.58

2.5. BSF Larva Biomass Produces

The harvested BSF larvae obtained from FW and SDW are shown in Table 5.

Table 5. Weight of wet BSF larvae.

Samples	Weight of Wet BSF Larvae (Mean ± SD)
FW	244 ± 4.16
SDW	336 ± 41.3

FW-Fruit waste, SDW-sisal decorticated waste.

The 3000 g of substrate that contained the pre-treated sisal decorticated waste yielded fresh BSF larvae of about 336 g, which was more than the 3000 g of fruit waste that yielded 244 g, as shown in Table 5. Fruit waste (FW) was set as the control since it is organic waste, which is mostly used to feed BSF larvae production [38,39]. This study proves that pre-treated sisal decorticated waste can yield more BSF larvae compared to fruit waste. The mean weight of FW (244 ± 4.16) showed no significant difference with SDW (381 ± 41.33) at ($t < 0.05$). This implies that SDW can also be used as a substrate and produce the required output even if the FW is commonly used as a substrate in the rearing of BSF.

2.6. Reduced Waste

In all substrates (SDW and FW), BSF larvae managed to consume the waste and grow. Having been harvested, BSF larvae left uneaten substrate which was used to determine the reduced waste in comparison with SDW and FW trays treated the same, but BSF larvae were not introduced to it. The waste reduced after BSF larvae consumed the pre-treated sisal decorticated waste and fruit waste, as shown in Table 6.

Table 6. Percentage reduced waste.

Samples	Initial Substrate Weight (g)	Mean ± SD	%Waste Reduction
FW	3000	647 ± 0.26	78
SDW	3000	1434 ± 0.05	52

BSF larvae managed to reduce dried sisal decorticated waste by 52%, and dried fruit waste as the control was reduced by 78%. The obtained results in Table 7 show a positive correlation with previous studies, which indicates that waste reduction by BSF ranges from 58 to 70% [40], 53 to 80% [41,42], between 50 and 75%depending on the nature of the substrate [43]. Therefore, due to these findings, pre-treated sisal decorticated waste can be effectively managed using BSF, since the percentage reductions fall within the range being reported.

Table 7. Nutritional value of BSF larvae.

Nutrients	Substrates	
	FW	**SDW**
Crude protein (%)	16 ± 0.006	53 ± 0.005
Carbohydrate (%)	39 ± 0.005	43 ± 0.01
Fat content (%)	32 ± 0.01	4 ± 0.01
Moisture content (%)	7 ± 0.05	10 ± 0.1
Ash (%)	9 ± 0.12	37 ± 0.08

2.7. Nutrition Value of BSF Larvae Fed with Pre-Treated Sisal Decorticated Waste

Table 7 shows that the nutritional value of BSF larvae was raised in different substrates.

Among other nutrients, the analyzed percent of crude protein of BSF larva raised in SDW (53 ± 0.005) showed a significant difference from the crude protein of BSF larva raised in FW (16 ± 0.006) at ($t < 0.05$). Other studies conducted in the past three years reported that the crude protein (CP) values obtained from BSF larvae reared on different substrate are as follows; fruit waste 12.9% [20], chicken manure 42.2% [44], and brewery waste 44.52% [45]. Among all the substrates that were reported to raise BSF larvae, the use of SDW in this study showed a high percent of crude protein (53 ± 0.005). The difference can be observed in Figure 1.

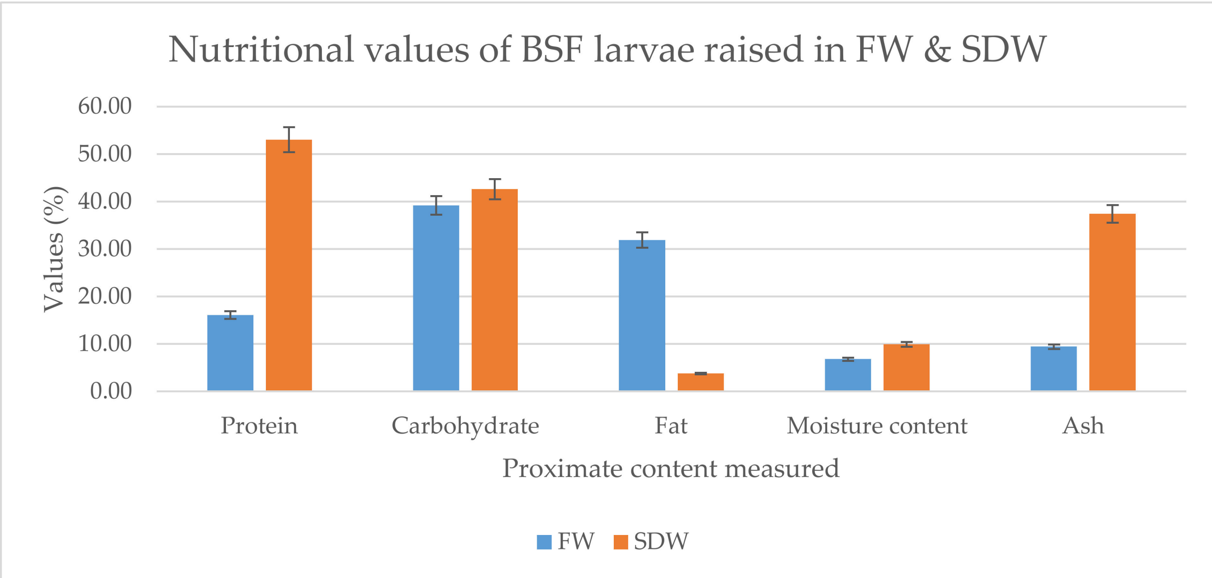

Figure 1. Nutritional value of BSF larvae raised in FW and SDW.

On a commercial scale, soybeans and fish meal are the main source of protein in animal feeds. Crude protein reported in soybeans is comprised of 42.35% [46], 43.8% [47], and 41% [48]. This is less than that of BSF larvae, which is reared in sisal decorticated waste. This implies that BSF larvae are significantly used as animal feed because they provide the required nutrients for the growth of livestock and its bioconversion of waste in cleaning the environment.

2.8. Mineral Elements of BSF Larvae Reared in Sisal Decorticated Waste

Mineral elements that are essential in chicken feeds include copper, iodine, iron, manganese, selenium, and zinc [49]. Several studies have reported that zinc (Zn) is important in broiler chicken nutrition due to its role in several enzymes and metabolic functions [50,51]. The BSF larvae reared on SDW showed a high amount of calcium, 130,800 ppm, compared to BSF larvae reared on FW, which was 17,500 ppm. Calcium plays a great role in egg production, eggshell formation, and bone mineralization [52]. Table 8 shows that BSF larvae raised in SDW contain essential elements that are required for the sufficient growth of poultry and fish.

Table 8. Elemental composition of larvae fed with SDW and FW.

Elements	Na	Mg	Al	Si	P	S	K
SDW (ppm)	2378	23,280	1537	5957	15,050	3052	23,283
FW (ppm)	1610	1800	264	915	5447	1801	1373
Elements	**Ca**	**Mn**	**Fe**	**Ni**	**Cu**	**Zn**	**Se**
SDW (ppm)	130,800	120	2053	2.7	49	135	0.77
FW (ppm)	17,500	82	566	0.5	13	94	0.4

3. Materials and Methods

3.1. Description of the Study Area

SDW was obtained from the Mwelya sisal estate, which is located in the Korogwe District in the Tanga Region at latitude 4°91′0″ S and longitude 38°29′8″ E, as Figure 2 clearly indicates. The selection of the study area was based on the availability of sisal decorticated waste that was left untreated and disposed into the environment.

Figure 2. Preparation of sisal decorticated waste for BSF consumption.

3.2. Waste Generated

To quantify the generated sisal waste, the weight of each bundle comprising 30 sisal leaves was measured using the measuring scale before being fed into the decorticator machine. Having being measured, the fresh sisal leaves were harvested and tied in bundles, whereby each bundle of sisal plant leaves was placed in a decorticator machine in order to produce sisal fiber, while the waste was thrown to the damping place [53].

Wet sisal waste was collected, weighed, and sent to the drying yard. The dried sisal waste was sieved to separate flume tow from sisal waste residue. The weight of flume tow and other sisal plant residues that could be given to BSF was also measured and recorded.

3.3. Physiochemical Parameters of Fresh and Dried Sisal Decorticated Waste

The pH and conductivity of sisal waste were determined using the Hach 40HQD Multiparameter meter. These physiochemical characteristics were measured on-site (in an industrial area) immediately after the decortication procedure. Using a 250 mL beaker, the wet solid sisal waste was squeezed in an attempt to extract sisal waste juice. The multiparameter probe was placed into the beaker containing sisal waste juice in order to read the results. The same procedures were conducted after cleaning the probe and analyzing the pH and conductivity.

Later on, 10 g of dried sisal waste was dissolved into 100 mL of distilled water, and the process for measuring physiochemical parameters was repeated in the NM-AIST laboratory. The aim of dissolving the dried sisal waste was to observe the changes obtained after the sun drying of SDW.

3.4. Elemental Profile of Sisal Decorticated Waste

The sample of sisal decorticated waste was sun dried for five (5) days and ground to coarse powder using mortar and pestle. About 5 g of the powdered sample was processed to make the pellets using an automatic pelletizer. The pellets being made were analyzed using X-ray fluorescence spectrometry [54,55].

3.5. Pre-Treatment of Sisal Decorticated Waste

The sample of the sisal waste was collected immediately after decortications, sun dried, and sieved to produce the final product as indicated in Figure 3. The series of steps involved includes the following.

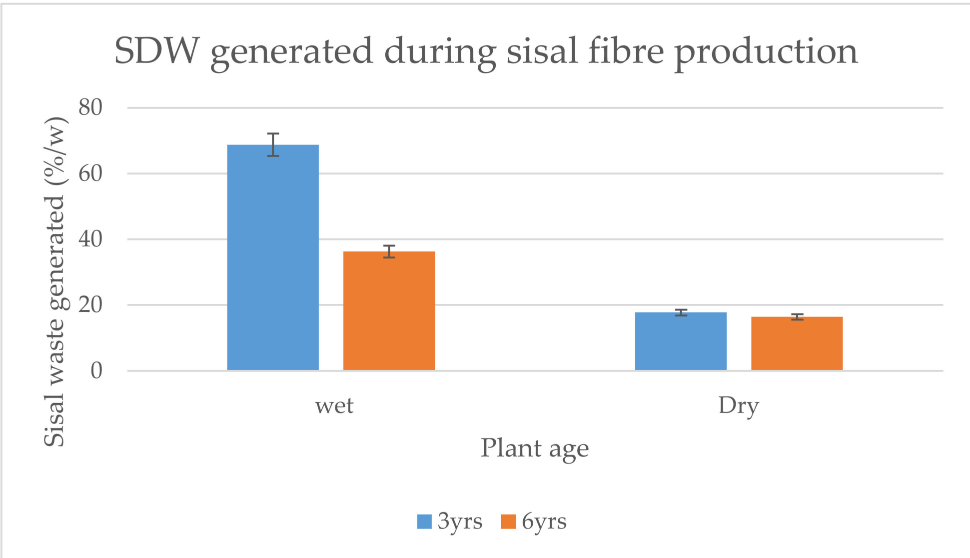

Figure 3. Amount of SDW generated during sisal fiber production.

3.5.1. Sun Drying

The decorticated wet sisal waste was collected and recorded. Furthermore, the wet sisal decorticated waste was sun dried for five (5) days until there was no change in weight. This procedure was performed in order to determine the weight of the dried sisal waste, which was further pre-treated in order to meet the required conditions for the rearing of BSF. The decorticated sisal waste was acidic with a pH of 4 [30], in which oxalic acid was reported to be the main acid [31] and succinic acid was reported as minor.

3.5.2. Sieving

The dried sisal waste was separated from flume tow as shown in Figure 2. The SDW is on the lefthand side, while the flume tow is on the righthand side of Figure 2. The flume tow constitutes the pieces of sisal fiber that are hard and cannot be consumed by BSF larvae. Therefore, they need to be separated by hands and later on sieved by a sieve plate of 2 mm diameter in order to obtain the fine sisal waste that can easily be consumed by BSF larvae.

3.5.3. Decomposition and Neutralization

The sun dried and sieved sisal waste was mixed with water in a 1:2 ratio of respective substrate–water (3 kg substrate for 6 L of water). This mixture of SDW and water was left to stay in an open rectangular tray (10 cm height; 35 cm width; 187 cm length), and the racking was performed three times a day in attempt to make a uniform mixture. The open trays containing pretreated SDW were placed in the vertical rack designed as a vertical farm for rearing BSF larvae for two weeks (14 days). Since the sisal waste had low pH [56] that does not perform well in the rearing of BSF [35], about 100 g of burned rice husk was added in the substrate–water mixture. The burned rice husk served a dual-purpose as the neutralization agent to raise the pH [57] and as the bulking agent to control the moisture content of sisal waste and the ensure growth of BSF [19]. After this process of decomposition and the raising of pH, the black soldier fly larvae of five days old were placed on the substrate, which was ready to consume.

3.6. BSF Larva Biomass

A total of 70 g of five-day-old larvae was introduced in the trays containing the sisal decorticated waste (SDW) that was pre-treated, and fruit waste (FW) was used as a control for the experiment. Both SDW and FW had three (3) replicates. The replicates of the sample were conducted to ensure the variability of the method caused by errors in the sample preparation processes. After sixteen (16) days, the black soldier fly larvae were harvested. Sieving was performed to separate BSF larvae biomass from the frass (substrate residue). The weight of wet and dried harvested BSF larvae was weighed and recorded.

3.7. Reduced Waste

After harvesting the BSF larvae from the substrates, the remaining weight of the frass was also measured and compared with the initial substrate given to 5-day-old larvae [35]. Other trays containing FW and SDW were set as a control experiment, as five-day-old larvae were not introduced in it. The obtained difference explained that the waste was reduced by being consumed by BSF larvae. The following equation was used to calculate the percentage of reduced waste (Wr):

$$\%\mathrm{Wr} = (\mathrm{Wsub} - \mathrm{R})/\mathrm{Wsub}) \times 100$$

which is the ratio of consumed feed, which was calculated as the difference between dry weight of original substrate given (Wsub) and dry weight of residue (R) [58,59].

3.8. Nutrition Value of BSF Larvae Fed with Sisal Waste

The BSF biomass harvested in two different substrates, SDW and FW, whereby FW is a control experiment, was analyzed in an attempt to assess its nutritional values. The calorific value of the sisal waste sample was determined using the Adiabatic Bomb Calorimeter. The BSF biomass from each sample was dried, ground, and sieved in order to obtain the fine sample. About 0.2 g of each sample was completely combusted under 3000 kPa pressure, and calculations were performed to obtain the energy [60]. Moreover, the protein content was analyzed using the FLASH 2000 Organic elemental analyzer, which analyzes carbon, hydrogen, nitrogen sulfur, and oxygen (CHNS/O machine). About 1 g of BSF biomass from each sample that was dried and ground was placed in a sample tray and inserted in the analyzer machine. It was left for 12 min, and the value of nitrogen (N) was read [61,62]. Thereafter, the calculations were performed using the following formula:

$$\text{Crude protein} = \text{Mass of N\%} \times 6.25$$
$$\text{Whereby, N} = \text{Percentage by mass of Nitrogen}$$
$$6.25 = \text{Protein factor}$$

Fat was extracted from the samples and analyzed using the Soxhlet apparatus. About 5 g of a sample was put on a thimble and packed into a Soxhlet apparatus. The solvent used was normal heptane. During extraction, the homogeneous mixture of sample and normal heptane were exposed to heat at a temperature of 180 °C. Later, the fraction distillation was conducted, and calculations were made to obtain the amount of fat in the measured samples.

Carbohydrates were analyzed using the phenol sulfuric acid method. About 6 g of a sample was digested with phenol sulfuric acid and later analyzed using UV-Vis spectroscopy to obtain the absorbance and concentration. This formula was used to obtain the percent of carbohydrates in the analyzed samples.

$$\%\text{Carbohydrate} = \frac{x}{0.1} \times 100\%$$
$$\text{Whereby, X} = \text{mass obtained in the concentration}$$

About 5 g of a sample was passed through the oven at a temperature of 120 °C for 30 min. Later, it was burned in a muffle furnace at 520 °C for 2 h. After the experiment was over, the following formula was used to determine the percentage of ash:

$$\%\text{Ash} = \text{Ash weight} \times 100\%$$
$$\text{Original weight of sample}$$

3.9. Statistical Analysis

All data were statistically analyzed using student's t-test ($t < 0.05$) in order to compare the average of the parameters tested, which are sisal decorticated waste generated, BSF larva biomass, amount of waste reduced, and nutritional value of BSF larvae.

4. Conclusions

The results of this study reveal that sisal decorticated waste bears characteristics that can be used in the rearing of BSF. The analysis indicates that SDW has essential nutrients such as crude protein, fats, energy, and microelements that are required in the substrate that is used to feed BSF. The pre-treatment of sisal decorticated waste can be conducted to improve the quality of the substrate. The use of sisal decorticated waste as BSF substrate ensures waste reduction in sisal factories.

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