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Nutritive Valorisation of Banana Tree (*Musa acuminata*) By-Products with Different Levels of Sodium Hydroxide

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Abstract: The aim of this study is to evaluate the effects of treatment with sodium hydroxide on the nutritional value of banana (*Musa acuminata*) trees to see if they can be used as a source of fibre for ruminants since there is large banana production and consequently some waste. The samples were collected and dried in an oven with a controlled air flow. They were then sprinkled with a sodium hydroxide solution (2, 4, 6 and 8% of dry matter) and placed in a suitable container. The chemical properties were analysed. The results show that sodium hydroxide treatment leads to a significant decrease in neutral fibre and acid lignin contents in both leaves and pseudostems. A significant ($p < 0.05$) increase was observed in ash, and digestibility values were lower in leaves, confirming the values for neutral detergent fibres. The total amount of gas produced was measured after 4, 8, 12, 24, 48, 72 and 96 h of incubation. The results showed that the gas production in the leaves was lower in all treatments compared to the pseudostem, which was consistent with the digestibility results. Analysis of the results showed that the best NaOH concentration to improve the nutritional value of *M. acuminata* was 6 and 8%.

Keywords: food sustainability; gas production; *Musa acuminata*; sodium hydroxide treatment; ruminants

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1. Introduction

To increase the economic interest in animal nutrition, it is important to find a simple and a practical method to improve the nutritional value. It is necessary to investigate the feasibility of including alternative food sources and to quantify animal responses in terms of economic productivity. One of the alternatives is the introduction of agribusiness by-products into animal diets. However, the composition of these foods and their appropriate economic and biological use in animal production have not yet been investigated. The circular economy plays a particularly important role in island regions such as the Azores, Madeira and the Canary Islands.

Livestock production in areas with direct grazing is often confronted with periods where pasture production is scarce due to normal pasture production curves or unfavourable weather conditions that strongly influence grass production [1]. It is therefore necessary to investigate whether it is possible to feed animals with non-conventional crops or by-products to supplement these periods of scarcity. Considering the various aspects of the nutritional value and its determination, increasing advances in the knowledge of the nutritional composition of food and analytical methods are critical in making the best practical decisions to meet the nutritional needs of animals.

Unconventional feed resources are generally defined as all feed resources that are not traditionally used for livestock breeding and are not used commercially to produce livestock feed. The scarcity of feed resources for livestock has led much of the research in animal nutrition to turn to investigating all possible ways of overcoming this nutritional

crisis. The most feasible recommendation is to incorporate the new non-conventional feeds into the diet and use appropriate complete feed technology to maximise the efficiency of feed resources [2]. There is a significant gap between the global supply and demand for concentrates and green-dried fodder used to feed livestock. To address this shortage, the supply of feed and forages for different production and functional areas of animals needs to be increased. The expertise on feeding systems developed in temperate climates may not be fully suited to the needs of tropical developing countries. A major constraint to the use of feeding systems adapted to temperate environments is that it is often irrelevant and unrealistic in tropical environments. Such systems effectively increase reliance on traditional feeds while ignoring the issue of feed storage and feed shortages, contributing to the increasing strain on global feed resources. To manage the demand–supply problem, it is critical to increase the availability of conventional feed resources for the various livestock production and management systems. One approach is to make use of non-traditional feed resources in livestock production systems, such as banana tree residues [3].

During the production cycle, the banana industry generates large quantities of solid residues from care and harvesting processes, in particular, pseudostems, leaves and banana peels. Improper disposal of these residues can lead to environmental and plant protection problems [4]. However, the residues generated from banana cultivation have great potential for use as biomass for various applications, such as fertiliser, animal feed, cellulosic material and energy production, as is the case with other crops such as sugar cane, coffee and rice. It is assumed that studies in which agro-industrial waste is recycled and used will contribute to the development of sustainable technologies and to regional and social development, thereby supporting the implementation of a circular economy.

The use of forages with low nutritional values, submitted to physical, chemical or biological treatments, can be an appropriate alternative to provide quality forage, meeting animals' nutritional requirements [5]. To increase the nutritional value of straw, several attempts have been made, and many chemicals were tested, but sodium hydroxide (NaOH) was the most effective. It has a greater hydrolysing potential (strong base) compared to other agents such as calcium hydroxide [$Ca(OH)_2$] and calcium oxide (CaO) [6,7].

The first report of using NaOH to improve the digestibility of fibrous feed dates from 1881, and several products have been tested over the last forty years [8]. According to Reis [9], among the most used substances for this purpose are sodium (N), potassium (K) and ammonium hydroxide (NH_4OH). They highlighted the great efficiency of NaOH; however, it had the disadvantage of contaminating the environment through excessive Na excretion in animal urine and faeces. Therefore, it is assumed that treatment with NaOH should be associated with the adjustment of the amount of NaCl in the diet [10].

In forage legumes, Reed [11] verified that the use of NaOH, besides improving the wall cell digestibility, also enhanced the solubility of nutritional factors, neutralizing the inhibiting effects of phenolic compounds such as tannins. With this, the treatment with NaOH is justified in forage legumes.

The use of these agents in the treatment of fibrous foods reduces the levels of NDF, ADF and ADL, increasing the in vitro digestibility of dry matter [10]. This occurs by partially solubilising hemicellulose and expanding cellulose, which favours the attack of microorganisms from the rumen to the cell wall [12–14].

The ability of ruminants to use fibre efficiently opens the possibility of exploring agricultural residues from tropical crops such as banana trees, which can also provide energy and protein. Considering the agricultural production in the Azores, bananas are the best representative of the permanent culture, with a production of four thousand six hundred fifty-seven tons in 2018. The banana tree is a perennial tropical plant of the Musaceae family, one of the world's most important crops. *M. acuminata* has a great economic and food value for many developing countries, and its production yields different by-products [15]. Generally, a banana tree is cut down after picking the fruit because a banana tree only bears fruit once. Afterwards, the tree decomposes. But it should not, because the rest can be used to feed ruminants, as it contains all kinds of nutrients. The

crude protein content of the leaves is the highest, followed by the peel and pseudostem. Both pseudostems and leaves contain moderate amounts of fibre but higher than banana peels. High levels of tannins in leaves and peels reduce their protein and dry matter digestibility and their value for ruminants. The low crude protein and high moisture content of pseudostems reduce the dry matter intake potential for ruminants. Due to the low digestibility of leaves and the low content of dry matter and crude protein in peels, protein concentrates should be supplemented to obtain high animal yields from ruminant-fed banana waste [16].

Therefore, the aim of this study is to investigate the effect of chemical treatment with the addition of sodium hydroxide (NaOH) on the chemical composition and nutritional value of *M. acuminata* residues in animal feed to determine whether it could be an effective way to assist in times of food scarcity.

2. Materials and Methods

This study was conducted in the Animal Nutrition Laboratory of Prof Doutor Gourlay Young do Amaral in the Department of Agricultural Sciences of the University of the Azores in Angra do Heroísmo, Terceira Island, the Azores, Portugal (38°39′30.93″ N; 27°14′0.303″ W). The climate of the region is classified as humid mesothermal with oceanic characteristics, with annual rainfall of around 1115 mm, an average annual temperature of 17.5 °C and an annual relative humidity of between 88 and 92% [17].

2.1. Forage Collection and Preparation

The plant, harvested by hand on Terceira Island, was chopped and divided by leaves and pseudostems, which were divided into three portions and then dried. Afterwards, to study the effect of NaOH on the nutritional value of *M. acuminata*, the samples were pulverised with a NaOH solution (control group, 2, 4, 6 and 8%). For each treatment, 1 kg of sample was placed in a plastic box with a lid and observed for seven days. After treatment, the samples were dried in a forced-air oven at 65 °C for 72 h. The dried samples were then ground through a 1 mm sieve using a Retsch mill (GmbH 5657, Haan, Germany). Therefore, the experiment followed a completed randomised design for each anatomic piece of the plant (i.e., leaves and pseudostems) with three replicates in each treatment (i.e., the doses of NaOH).

2.2. Chemical Analysis

These ground samples were analysed for dry matter (DM, method 930.15), crude protein (CP, method 954.01) and the total ash method (942.05), according to the standard methods of AOAC [18]. The acid detergent fibre (ADF), acid detergent lignin (ADL) and neutral detergent fibre (NDF) were determined according to Goering and Van Soest [19]. In vitro digestibility was determined using the Tilley and Terry method [20], as modified by Alexander and McGowan [21], with rumen fluid obtained from the local slaughterhouse (IAMA), as described by Borba [22].

2.3. In Vitro Gas Production

For in vitro gas production (GP), which simulates the fermentation process in the rumen and is used to assess the potential of food to produce greenhouse gases, each test was performed in triplicate. Samples were weighed and placed in the syringes in a convection oven at 37 °C for subsequent addition of the inoculum. For each inoculum, blank values were used to measure the proportion of total gas production attributable to the substrate in the inoculum, and these values were subtracted from the total to obtain the net GP. All treatments for each experiment were incubated simultaneously in all runs [23]. Buffer solutions and rumen inoculum were prepared as described by Menke and Steingass [24].

This gas production represents the kinetics of apparent rumen GP and is expressed by the McDonald [25] equation. Gas production profiles were obtained by fitting the data to the exponential equation of Ørskov and McDonald [26]:

$$p = a + b\,(1 - \exp^{-c\,t})$$

where p represents gas production at time t, a and b are constants in the exponential equation, $a + b$ is the total potential gas production (mL/g DM) and c is the rate constant. The fermentation constants a, b and c were calculated using curve-fitting techniques via the Neway software program (Rowett Research Institute, Aberdeen, UK), developed by Chen [27].

2.4. Determination of Gross Energy

For gross energy (GE), each sample was oven-dried, encapsulated (1 g approximately) and then subjected to combustion in an adiabatic mode by calorimeter bomb (IKA-WERKE C5003, Staufen, Germany). All determinations GE were performed in triplicate.

2.5. Statistical Analysis

The effect of different concentrations of NaOH on *M. acuminata* were statistically analysed by ANOVA, followed by a post hoc least significant difference test using IBM SPSS version 24 Statistics Program software (SPSS Inc. Chicago, IL, USA). For all analyses, a p value of <0.05 was considered statistically different.

3. Results

3.1. Chemical Composition, Nutritional Value and Energy Contents

In the present study, the effect of chemical treatment with the addition of sodium hydroxide (NaOH) in *M. acuminata*, for animal feed, was observed and then registered in Table 1.

Table 1. Chemical composition, nutritive and energetic values of *M. acuminata*.

Treatment		DM	100 g DM					DMD	GE
		(%)	CP	NDF	ADF	ADL	Ash	(%)	MJ/Kg DM
Control	Leaves	24.21 ^{a} (±4.42)	14.17 ^{a} (±1.56)	77.9 ^{a} (±4.3)	40.4 ^{a} (±4.7)	12.9 ^{a} (±2.9)	18.28 (±3.34)	21.0 ^{a} (±3.3)	15.4
	Pseudostem	6.38 ^{b} (±0.31)	7.52 ^{b} (±0.84)	55.3 ^{b} (±3.0)	30.6 ^{b} (±3.3)	4.6 ^{b} (±0.6)	21.48 (±3.04)	46.7 ^{b} (±3.4)	13.1
2% NaOH	Leaves	24.84 ^{a} (±1.1)	12.16 ^{a} (±0.12)	66.3 ^{a} (±0.7)	41.8 ^{a} (±2.3)	12.3 ^{a} (±0.5)	20 (±0.99)	20.0 ^{a} (±1.2)	16.5
	Pseudostem	6.99 ^{b} (±0.97)	7.68 ^{b} (±2.84)	49.2 ^{b} (±4.3)	30.1 ^{b} (±1.8)	4.7 ^{b} (±1.2)	24.54 (±3.46)	44.1 ^{b} (±4.8)	12.6
4% NaOH	Leaves	22.88 ^{a} (±1.96)	12.49 ^{a} (±0.86)	62.2 ^{a} (±3.5)	39 ^{a} (±1.0)	10.6 ^{a} (±0.7)	22.62 (±1.30)	24.8 ^{a} (±0.8)	15.3
	Pseudostem	6.78 ^{b} (±0.51)	6.02 ^{b} (±0.63)	48.8 ^{b} (±3.5)	29.7 ^{b} (±3.0)	4.6 ^{b} (±1.0)	26.11 (±1.19)	46.4 ^{b} (±3.2)	12.4
6% NaOH	Leaves	23.92 ^{a} (±1.45)	13.84 ^{a} (±1.98)	62 ^{a} (±0.4)	40.0 ^{a} (±2.2)	12.1 ^{a} (±0.2)	23.61 (±1.27)	31.1 ^{a} (±2.2)	15.2
	Pseudostem	7.36 ^{b} (±0.48)	5.43 ^{b} (±0.96)	44.2 ^{b} (±3.3)	27.2 ^{b} (±3.8)	3.2 ^{b} (±1.4)	26.83 (±2.05)	58.8 ^{b} (±1.8)	12.65
8% NaOH	Leaves	26.13 ^{a} (±0.83)	12.46 ^{a} (±1.07)	56.27 (±1.17)	37.6 ^{a} (±0.8)	10.1 ^{a} (±0.8)	25.71 (±1.03)	33.4 ^{a} (±2.6)	14.5
	Pseudostem	7.69 ^{b} (±0.63)	5.90 ^{b} (±0.68)	48.57 (±3.4)	29.9 ^{b} (±1.8)	3.5 ^{b} (±0.6)	30.99 (±2.69)	50.9 ^{b} (±4.3)	11.95

DM—Dry Matter; CP—Crude Protein; NDF—Neutral Detergent Fibre; ADF—Acid Detergent Fibre; ADL—Acid Detergent Lignin; DMD—in vitro Dry Matter Digestibility; GE—Gross Energy. ^{a,b} different superscript within the same column indicates significant differences, $p \leq 0.05$.

In terms of DM, our results showed that leaves and pseudo-stems are significantly different in every treatment. When we compared the leaves and stems in different treatments, we noticed a slight increase in the values throughout the treatments, even though there

were no significant differences, with the highest value in the 8% treatment (26.13 ± 0.83 in leaves and 7.69 ± 0.63 in pseudostem). As for CP, it also showed significant differences between the leaves and the pseudostems in all treatments, with leaves always showing the highest results. It also shows a small decrease when the treatment with NaOH is applied. NDF values showed significant differences between leaves and pseudostems, but their values decrease during the treatment with NaOH (8%), which gives the lower values, when compared to the lower treatment (2%) (77.9 ± 4.3 in leaves and 55.3 ± 3 in pseudostems, 56.27 ± 1.17 in leaves and 48.57 ± 3.4 in pseudostems at 2% and 8%, respectively). About ADF and ADL, they also showed significant differences between leaves and pseudostems throughout all treatments, with the values decreasing as we increased the NaOH concentration. Ash showed no statistically significant differences among treatments ($p > 0.05$). DMD showed significant differences between leaves and pseudostems, with pseudostems always showing higher values. We should point out that the two highest treatments, 6% and 8%, are the ones that give us the highest digestibility values in both leaves and pseudostems.

Gross energy reveals higher values in leaves in each treatment, even in the control group, when compared with pseudostems.

3.2. In Vitro Gas Production

Table 2 shows the cumulative gas production affected by replacing ruminant feed with *Musa* spp. treated with different concentrations of NaOH.

Table 2. Effect on cumulative gas production (ml 200 mg^{-1} DM) and gas kinetics of NaOH treatment on *M. acuminata*.

Treatment		Incubation Time (h)							Gas Kinetic Parameters			Lag Time (h)
		4	8	12	24	48	72	96	a	b	c	
Control	Leaves	1.28	1.68	2.07	3.18	5.21	6.98	8.53	0.87	18.62	0.0055	0.0
	Pseudostems	−0.16	1.67	3.42	8.20	15.99	21.95	26.52	0.00	44.18	0.0111	4.4
2% NaOH	Leaves	1.27	1.63	1.99	3.03	5.02	6.89	8.66	0.91	37.26	0.0025	0.0
	Pseudostems	0.58	2.10	3.51	7.20	12.78	16.79	19.87	0.18	45.94	0.0114	2.7
4% NaOH	Leaves	0.82	1.54	2.23	4.15	7.38	9.95	12.02	0.13	24.59	0.0087	0.2
	Pseudostems	0.55	4.80	8.44	16.50	24.75	28.01	29.32	0.00	30.20	0.0397	3.6
6% NaOH	Leaves	1.61	2.75	3.84	6.76	11.38	14.73	17.17	0.43	23.27	0.0133	0.1
	Pseudostems	0.54	4.76	8.32	15.98	23.41	26.19	27.26	0.00	28.00	0.0419	3.6
8% NaOH	Leaves	1.65	2.63	3.53	5.88	9.26	11.44	12.86	0.60	14.98	0.0186	0.0
	Pseudostems	−0.08	2.86	5.51	12.02	20.52	25.42	28.43	0.00	37.21	0.0247	4.2

a = gas production from the immediately soluble fraction (mL 200 mg^{-1} DM); b = gas production from the insoluble fraction (ml 200 mg^{-1} DM); c = gas production rate constants for the insoluble fraction (mL h^{-1}).

The in vitro gas production technique simulates the rumen fermentation process. It has been used to evaluate the potential gas production of foods. The volume of gas produced throughout the simulation (96 h) varied from 0.1 mL to nearly 30 mL (29.32 mL) 200 mg^{-1} DM.

It is worth highlighting that the pseudostems always produced more gas when compared to the leaves in any of the treatments, and it is in the higher concentrations of NaOH that these values stand out.

During the first hours of incubation, the differences in gas produced are minimal. However, at 24 h of incubation, large differences are noted in the treatments with 4%, 6% and 8% NaOH compared with the control group and 2% NaOH.

The interception value (a) from the soluble fractions was always highest in leaves, being the higher value in 2% NaOH. In the parameter (b), which stands for the fermentation of the insoluble fractions, the highest values were presented in pseudostems.

When we observed the lag time (hr), we could see that *M. acuminata* leaves supplemented with 2% NaOH and 8% were the first to begin their fermentation (immediately after placing the sample to incubate), when compared to the others.

4. Discussion

To minimise problems and reduce feed costs, the use of crop residues is a good option. They are easy to find, can be used as a feed source and hopefully reduce environmental pollution. A high percentage of banana trees are considered waste in the field, with approximately 60–80 tonnes/ha/year of banana pseudostems produced [28]. The use of banana waste is very limited in the world. Pseudostems are usually left to rot on farms to replenish some of the nutrients in the soil. They have a low nutritional value and a high water content, about 93.4%, but based on DM, the nutritional value of CP is 6.5% and the nutritional value of lipid is 1.5% [29]. These findings are in accordance with our study, since the pseudostems presented lower values when compared with leaves. CP contents of pseudostems are below 8%, which is required for optimal rumen function and intake. Although leaves contain more CP than pseudostems, their digestibility is lower, probably due to their higher lignin content [30].

The tests carried out aim to understand if the treatment with sodium hydroxide (NaOH) improves the digestibility of the *M. acuminata* and if nutritional characteristics are altered. It is important to know the best concentration of NaOH to treat this plant, which has a big production in the Azores.

In a comparative study between different treatments (NH_3, urea, NaOH and $Ca(OH)_2$) on the nutritional value of forage, they concluded that NaOH and $Ca(OH)_2$ are more efficient in reducing the cell wall and increasing the digestibility of treated roughage than NH_3 and urea [31].

Dietary fibre is an important component of feed, influencing intake and digestibility. The cell wall component can be quantified by the determination of NDF, which consists of cellulose, hemicellulose and lignin. Concerning NDF values, they showed significant differences between leaves and pseudostems. A similar decrease is also reported by Pereira Filho [8], indicating that the use of 2% and 8% NaOH in the black jurema hay provided a decrease in the NDF content. The main effect of NaOH on cell wall components is characterised by the alkaline hydrolysis of the ester-type covalent bonds between lignin and structural carbohydrates [32]; in this way, solubilisation of hemicellulose [12,33] and phenolic compounds occurs [34] with a consequent decrease in the NDF content, facilitating the decomposition of cellulose and hemicellulose by microorganisms in the rumen. In general, in all the studies evaluated that referred to the action of NaOH on the cell wall components, the results were similar.

ADF refers to the part of the plant cell wall made up of lignin and cellulose. Lignin is indigestible, and cellulose is partially digestible, depending on its lignification. The ADF content is important because it relates to the animal's ability to digest the feed. Many studies show that using NaOH in fibrous foods does not reduce [35] or increase [36] the ADF content. In the work by Nolte [37], there was a reduction in the ADF of wheat straw after treatment with an alkaline solution. However, Sundstol and Coxworth [38] stated that the effect of chemical treatment on ADF concentration does not present consistent results.

Since they are negatively correlated, a high NDF content can be a limiting factor in DM intake [39]. Fibre intake generally leads to rumen filling and satiety before the ruminant has maximised its caloric intake, resulting in reduced nutrient levels. Consequently, increasing the fibre content can lead to a decrease in feed intake and thus a decrease in animal production. Equally important is the ADF content, as it is related to the animal's ability to digest the feed. In terms of ADF content, the banana leaf can be classified as low-quality feed, the pseudostem as medium-quality feed and the peel as high-quality feed [40].

Regarding ash, there was an increase in the percentage with the treatment but not statistically different. This increase was also shown in other studies [41]. Such results would be expected since the mineral residue left by the NaOH significantly increases the inorganic matter and, consequently, the ash.

Digestibility values of *M. acuminata* were not similar when we compared the different by-products. The pseudostems presented higher values compared to the leaves, and it gets higher with the increment of NaOH concentration, and this is supported by other

authors, who stated that the increase in DMD of NaOH-treated diets was due to the greater exposure of cell wall components, increasing the susceptibility of structural carbohydrates to digestion [36].

Pereira Filho [42] observed a significant increase ($p < 0.05$) of the DMD of the black jurema hay as the content of NaOH used in chemical treatment increased.

Chaudhry [36] pointed out that, normally, the DMS of forage treated with alkaline solution shows a positive linear relationship with increasing concentrations of NaOH up to 8%. It is important to note that NaOH has been widely used in combination with other alkaline compounds and/or physical treatment, as it is one of the most efficient chemical products for the lignification of cell wall compounds. The increase in DMS of NaOH-treated forage was due to increased exposure of cell wall components, increasing the susceptibility of structural HCs to digestibility as well as the removal of phenolic compounds, reducing the protein complexity and improving the in vitro digestibility of DM [43], which can affect the ruminal degradability of NDF and CP, mainly in plants rich in tannin [42].

Relative to energy, the values were higher in leaves than in pseudostems in all treatments, in line with other results published [44], where the author stated that leaves have higher energy values than pseudostems.

The rumen fermentation process was simulated using the in vitro gas production technique, which has been used to assess the gas production potential of feed. It was found that treatment with NaOH resulted in a decrease in gas production, especially at 8%, which could be a positive point in reducing enteric gas and therefore a positive aspect in the fight against climate change.

In leaves, NaOH treatments increase gas production, indicating that the higher the NaOH concentration (up to 6%), the higher the gas production. In pseudostems, NaOH treatments increase a, but the control already shows significant gas production, possibly due to the higher lignocellulose content of the pseudostems, which is made more accessible by the treatment.

The rate constant b tends to increase with NaOH treatment, especially for pseudostems. Thus, the value of b was 45.94 for pseudostems treated with 2% NaOH, and b for leaves was 37.26 also treated with 2% NaOH, indicating faster fermentation. However, leaves treated with 8% NaOH showed a decrease in the rate constant (b = 14.98), indicating that excessive NaOH may interfere with the optimal fermentation rate.

A higher c-value reflects faster gas production in the early stages. The pseudostems with 6% NaOH had a high c-value of 0.0419, indicating rapid early gas production. This shows that NaOH effectively degrades the recalcitrant fibres in the pseudostems and promotes microbial fermentation in the early stages.

In most treatments, the lag time for leaves was minimal or non-existent, indicating that microbial colonisation and fermentation began immediately. However, the 4% NaOH treatment showed a slight delay of 0.2 h, possibly due to overtreatment affecting initial microbial activity.

The control pseudostems had a longer lag time of 4.4 h, which was shortened by NaOH treatment. The 2% NaOH treatment shortened the lag time to 2.7 h, suggesting that NaOH accelerates the microbial fermentation process by improving the accessibility of the fibres. However, the lag time for pseudostems does not appear to improve linearly with higher NaOH concentrations, as shown by the 4.2 h for 8% NaOH, indicating a threshold effect.

The addition of NaOH treatment promoted less gas production and greater fibre degradation. This fact probably reflects a higher efficiency of the microorganisms in degrading the substrate and better nutrients' utilisation with lower loss of carbon in the gas form (CO_2 and CH_4). With delignification, cell content substrates may become more available to microorganisms, reducing cell wall fermentation [45].

Lignin degradation can release various phenolic compounds. These compounds could inhibit the cellulolytic and methanogenic microorganisms, which could help explain the reduction in methane emissions with chemical treatments [46].

Probably there was a larger availability of substrates, readily available to be absorbed by ruminal microorganisms. Furthermore, substrates generated by fibre hydrolysis caused by NaOH could favour the fermentation of propionate-producing microorganisms and could not favour the fermentation of acetate-producing microorganisms, and with that, methanogenesis.

Hydrogen and carbon derived from the fermentation of glucose to acetate are the main substrates for methane. On the other hand, to methanogenesis, the fermentation of glucose to propionate does not contribute to carbon and hydrogen, in addition to using free hydrogen for its production, being considered a hydrogen drip.

In this context, Meeske [47] showed a decrease in the production of acetate and an increase in the production of propionate in wheat straw treated with NaOH. Moreover, NaOH may have contributed to buffering the medium, and it could reduce the amount of available hydrogen for methanogenic microorganisms and, consequently, reduce the amount of methane.

A similar result was obtained by Shetty [48], who observed reduced methane production when adding up to 5% NaOH to rice straw. According to the authors, this was attributed to the increase of sodium ions concentration. Sodium is a well-known process inhibitor in anaerobic systems. It inhibits methanogenic micro-organisms by increasing the osmotic pressure or completely dehydrating the micro-organisms [49].

In Teixeira [50], their study also reveals that NaOH at 8% would work in *A. donax*, since it decreased the fibrous part of the plant. So, increasing the nutritional values with NaOH made it a better source of fibre for animal feed.

Some authors stated that the inclusion of 50 per cent of banana residues can promote an improvement in rumen fermentation in grass-based diets. However, despite the good presented using this by-product in animal feed, its use has restrictions that must be observed [51]. Non-conventional feed as fibre sources, must continue to be studied to improve their nutritional value, either through chemical treatments or through physical and biological treatments, for the purpose of introducing them into cattle feed, minimising the importation of fibres, helping to reduce the ecological footprint.

The traditional sources of fibre used by Azorean farmers are gaining new importance, which calls for urgent research into their viability in terms of production and the nutritional value.

5. Conclusions

The banana industry generates many residues that can be used in various processes, with a focus on implementing a circular economy. With the possibility of including several alternative food sources and quantifying animal responses in terms of economic production, chemical treatments with NaOH were carried out on *M. acuminata*. After analysing the results, we found that, regarding the different concentrations of NaOH, the best treatments would be 6 and 8%, for being the treatments that presented better variations in the reduction of NDF contents and increased digestibility values. It suggests that this by-product can be used in animal feed, which is a favourable strategy to improve the feed efficiency of ruminants. As a follow-up to this article, we are carrying out tests to start the feeding phase, including a study with silage.

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