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Soil compaction affects the silage quality of sunflower and Paiaguas palisadegrass (*Brachiaria brizantha*) grown on a Latosol in the Brazilian savanna

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Abstract

On the basis of the natural seasonality of pastures during the dry season, preservation of forage, especially silage, is necessary. However, the effects of soil compaction within sunflower and grass crop fields on the nutritional quality of the silage produced are unknown. Therefore, the aim of this study was to evaluate the fermentation and nutritional quality characteristics of sunflower silage under both monocropping and intercropping systems [with Paiaguas palisadegrass (*Brachiaria brizantha*)] under various degrees of soil compaction. A split-plot randomized complete block design was adopted. In the main plots, the treatments were bulk density values affected by the following traffic intensities: 0, 2, 10 or 30 passes of a tractor with tire wheels weighing 4.9 Mg. The subplots involved forage systems composed of sunflower as a monocrop or intercropped with Paiaguas palisadegrass. The fermentation, nutritional characteristics and *in vitro* digestibility of the silage were evaluated. Under the various aforementioned conditions, the agronomic characteristics of the forage were affected by increased soil compaction, resulting in changes in the fermentation and nutritional characteristics of the silage. The results showed that intercropping with Paiaguas palisadegrass and adequate proportions of sunflower allow good fermentation. This study recommends the adoption of practices that mitigate soil compaction and intercropping because of the increased forage productivity and the possibility of indirect renewal of the pasture.

Keywords: *Helianthus annuus*; *Brachiaria brizantha*; crop-livestock integration; soil physical quality; forage conservation.
Abbreviations: AA_acetic acid; ADF_acid detergent fiber; AOAC_Association of Official Analytical Chemists; BA_butyric acid; Bd_soil bulk density; CP_crude protein; DM_dry matter; EE_ether extract; IVDMD_*in vitro* dry matter digestibility; LA_lactic acid; MM_mineral matter; NDF_Neutral detergent fiber; NH_3_ammoniacal nitrogen; PA_propionic acid; SM_specific mass; syn_synonymous; TDN_ total digestible nutrients

Introduction

The adoption of agricultural production technology has positioned Brazil as among the most sustainable mitigators of global climate change and promoters of food security worldwide (Sá et al., 2017). Integrated crop systems are options for intensifying land use, especially for cultivation in succession to summer harvest, conducted via the simultaneous sowing of plots for the production of grains and forage (Guarnieri et al., 2019), silage (Costa et al., 2018) and/or biomass in no-tillage systems (Oliveira et al., 2019).

Among annual crop species used in integrated production systems, sunflower (*Helianthus annuus* L.) stands out (Santos et al., 2016; Cruvinel et al., 2017a). It has substantial agronomic importance because of its adaptation to tropical climates, short growth cycle, relatively high tolerance to water deficit and high nutritional value, which are mainly due to its energy and protein content (Tomich et al., 2003).

However, among the forage species suitable for integrated systems, the species of the *Brachiaria* [synonymous (syn.) *Urochloa* P. Beauv.] genus are the main ones cultivated in the Brazilian savanna. *Brachiaria brizantha* cv. BRS Paiaguas, which is a promising cultivar because of its agronomic characteristics, exhibits high productive potential and forage quality during the dry season (Euclides et al., 2016; Epifanio et al., 2019). However, given the natural seasonality of the production of this grass, the preservation of forage as silage becomes necessary. Therefore, sunflower intercropped with tropical forage species as a form of silage represents an interesting alternative for the production of high-quality forage, which in turn can maintain animal production throughout the year (Cruvinel et al., 2017b).

Sunflower plants, mainly grasses in general, have limitations in this context because of the low dry matter (DM) content at the time of cutting for silage (Possato Junior et al., 2013). Leonel et al. (2008) suggested delaying the harvest of annual crops to balance the levels of the cellular constituents of the silage, avoiding losses in the quality of the conserved forage. This can be done in integrated production systems where the forage production is harvested later (Costa et al., 2018).

In addition, little is known about the effects of soil physical properties on this oilseed species given the high machine traffic in the areas intended for the production of silage, especially during the cutting and transport of the forage (Düttmann et al., 2014). Notably, soil compaction affects the development of plant species in intercropping systems differentially, reducing the proportion of sunflower because of its high sensitivity to soil compaction Linhares et al. (2020). Once sunflower is affected by this compaction, the composition of the forage may influence the fermentation and nutritional characteristics of the resulting silage.

Therefore, the aim of this study was to evaluate the fermentation and nutritional characteristics of silage from sunflower either monocropped or intercropped with Paiaguas palisadegrass grown during the second cropping period in a Dystroferric Red Latosol subjected to compaction from the traffic of an agricultural tractor.

Results

Fermentation characteristics of the silage

The fermentation characteristics of the silage were influenced by the agronomic characteristics, productivity, and participatory development of the forage presented in Linhares et al. (2020). The analysis of the DM content revealed relatively high values for the sunflower silage (Figure 1A). In contrast, with respect to the silage of the forage from the intercropping system, the Paiaguas palisadegrass provided increased moisture, increasing the DM content within the range of soil bulk density (Bd) in which the sunflower plants could fully develop.

Figure 1A shows that the silage of the forage from the intercropping system presented a DM content of 350 to 388 g kg^{-1}, while the variation in the DM content of the forage from the monocropped sunflower was 380 to 452 g kg^{-1}. The specific mass (SM) was strongly influenced by soil compaction (Figure 1B), with greater variation in the monocropping system than in the intercropping system.

Figure 2A shows the loss of silage dry mass decreased more in the monocropped system than from the intercropping system (maximum of 13%). In addition, the loss of silage produced by the intercropping system was not affected by the Bd, showing a mean of 5%.

Figure 2B shows the change in pH in response to the production of organic acids. The pH values ranged from 4.21 to 4.65 and 4.40 for the sunflower silage from the monocropping and intercropping systems, respectively.

Among the organic acids, lactic acid (LA) was present at a relatively high concentration in the intercropping treatments, whereas the sunflower silage presented the greatest variation in this component, with both findings in accordance with a quadratic polynomial (Figure 3A). This behavior was opposite of that detected for the variation in DM content, with the minimum concentration occurring at a Bd of approximately 1.30 kg dm^{-3}. The concentration of acetic acid (AA) varied with increasing Bd and differentially between the evaluated cropping systems (Figure 3B). In addition, with a value of approximately 0.19%, propionic acid (PA) was not influenced by soil compaction in the intercropping system. With respect to the sunflower silage from the monocropping system, the value of PA was similar to that of the other organic acids, which showed a quadratic polynomial behavior (Figures 3C and 3D).

In terms of ammoniacal nitrogen (NH_3), shown as a percentage of the total nitrogen (N) in Figure 4A, the content increased linearly with increasing Bd until the content reached 5% for the silage from the intercropping system and when the content was below 3% for the silage from the sunflower monocropping system.

Nutritional quality of the silage

Figure 4B shows the direct quadratic relationship between soil compaction (Bd) and the content of the crude protein (CP) in the monocropping system, and the opposite was found for the silage from the intercropping system. The sunflower silage from the monocropping system had the greatest CP content (99 g kg^{-1}), and the sunflower and Paiaguas palisadegrass intercropping system had the lowest CP content (88 g kg^{-1}), which occurred at Bd values of 1.35 and 1.32 kg dm^{-3}, respectively.

Similarly, the ether extract (EE) was strongly affected by the forage composition of the silage. Figure 5A shows that, when produced from sunflower, the silage varied little. However, with respect to the silage from the intercropping system, the increase in Bd linearly reduced the EE by 50% within the range studied. In contrast, with a mean of 72 g kg^{-1}, the mineral matter (MM) of sunflower silage was not influenced by soil compaction (Figure 5B).

The neutral detergent fiber (NDF) content of the silage from the monocropped sunflower exhibit a quadratic behavior and presented a maximum of 526 g kg^{-1} close to the limiting Bd (Figure 6A). In contrast, when intercropped, the sunflower silage exhibited a direct linear relationship that was always superior to the monocropping silage. In addition, the acid detergent fiber (ADF) was influenced by soil compaction only (Figure 6B).

As a function of Bd, the *in vitro* dry matter digestibility (IVDMD) of the silage fit an inverse quadratic polynomial model, with the sunflower silage from the monocropping system having a greater IVDMD than the that from the intercropping system with Paiaguas palisadegrass (Figure 7A). However, both types of silage presented relatively low values (531 and 506 g kg^{-1} in the monocropping system and intercropping system, respectively) near the limiting Bd. The greatest digestibility occurred at the extremes of Bd (Figure 7A).

There was a greater total digestible nutrient (TDN) content in the sunflower silage from the monocropping system than from the intercropping system (Figure 7B). In contrast, in the intercropping system, there was a change in the behavior from quadratic to linear; the content decreased as the proportion of the Paiaguas palisadegrass increased.

Discussion

The DM content of the silage obtained in the intercropping system (approximately 350 g kg^{-1}) is considered optimal for the quality of the final product (Leonel et al., 2008) (Figure 1A). The high moisture content in perennial tropical forage at the time of harvesting for silage production, which limits the fermentation process (Santos and Zanine 2006), was balanced by the effects of intercropping with sunflower. The moisture content was high at the time of cutting, especially when the Bd was approximately 1.30 kg dm^{-3}.

At physiological maturity, sunflower plants have high moisture contents in certain parts, especially in the capitulum; this moisture diminishes after the plant matures, resulting in an increase in DM (Possatto Junior et al., 2013). Toruk et al. (2010) reported that increases in the DM content as sunflower matures are reflected in the nutritional and fermentation quality of the silage. The authors determined that the appropriate timing for silage is before the plant completes maturation.

The greatest variation in DM content (317 to 389 g kg^{-1}) detected in the monocropped sunflower silage (Figure 1A) confirms the results obtained by Possenti et al. (2005), who also found it difficult to determine the most appropriate time to collect sunflower for silage because of the morphological changes in the plants. Souza et al. (2005) investigated various parts of plants under conditions similar to those in the present study and recorded DM contents ranging from 820 to 860 g kg^{-1} in the achenes and contents ranging from 420 to 470 g kg^{-1} in the vegetative parts. These findings contribute to the elucidation of the relatively high DM content of sunflower at a Bd of approximately 1.30 kg dm^{-3}, a level of which is related to increased capitulum diameter and increased achene mass.

Another factor to consider is related to plant growth. A large leaf area (not evaluated here) effectively contributes to a loss of moisture during maturation and predisposes those plants to relatively high water loss through the plant tissue, accelerating the process of senescence and leading to rapid drying of the plant.

Considering the importance of forage moisture in the fermentation process of silage (Jobim et al., 2007), it should be emphasized that the behavior of the variables discussed is directly influenced by the variation in DM content, which is influenced by soil compaction during sunflower senescence.

The SM was strongly influenced by soil compaction (Figure 1B), reflecting the variation in the DM content of the forage as previously discussed. According to Tomich et al. (2004), this attribute is mainly responsible for silage compaction efficiency, with a strong negative correlation between the two variables.

Regardless of the forage system used, the SM content of the silage was greater than 300 kg m^{-3} when the DM content was within the ideal range for ensilage (below 350 g kg^{-1}) (Figures 1A and 1B). Under these conditions, the forage can be easily compacted for silage.

In contrast, the SM of the sunflower silage decreased with increasing DM content. Santos and Zanine (2006) noted that in silage with low moisture, damage from heating and mold tends to occur, leading to reductions in both weight and quality of the silage, among other problems. These losses are due to increased oxygenation in slightly compacted silage, causing increased respiration of plant cells and microorganisms, with the consequent degradation of water-soluble carbohydrates.

Figure 2A confirms these notions, given that the greatest loss of weight of ensiled mass occurred in the sunflower silage (13%) when the DM content was maximal (Figure 1A) when and the SM was low (Figure 1B).

The forage conditions for silage discussed so far affect the entire fermentation process and are related to considerations made by Tomich et al. (2004) and Silva et al. (2011). According to these authors, anaerobic processes are critical for LA fermentation, which is responsible for the efficiency of the silage acidification process and can result in the inhibition of the prolonged action of unwanted bacteria during the process. Figure 2B shows that there is an association between this effect and the forage composition, in which the silage with low DM content, which is thus more compacted, exhibits a relatively fast fermentation rate and a relatively good production of organic acids responsible for reducing the pH.

Historically, pH values higher than 4.2 have been associated with poor silage (McDonald et al., 1991). However, Jobim et al. (2007) argued that pH allows only inferences in terms of the quality of fermentation, whose application is not suitable for materials that have high DM.

These values are within the range suggested by Tomich et al. (2003) as being suitable for ensiled forage of approximately 350 g kg^{-1} DM and corroborate the findings of Mello et al. (2006), who reported that, under these conditions, the pH becomes a characteristic of little importance because the development of acidity is inhibited by water deficiency and high osmotic pressure. In this context, taking into account that the pH values ranged from 4.21 to 4.65 and that the minimum DM content was approximately 320 g kg^{-1}, the silage should have good nutritional quality. In this situation, the abovementioned authors suggest that it is most appropriate to evaluate the concentration of organic acids, which are shown in Figure 3.

The LA values are well below the range of 6-10% recommended by Yan and Agnew (2004) (Figure 3A), whereas the AA levels are adequate (Figure 3B). In addition, PA and butyric acid (BA) are present at low concentrations (Figures 3C and 3D), though they are considered adequate.

Thus, the proportions of organic acids as indicators of good fermentation profiles (LA and AA) reinforce the arguments discussed in Linhares et al. (2020) and in the previous figures with respect to the effects of soil compaction in planning forage for food production during the second cropping period. The proportions obtained can be considered normal for sunflower silage and are consistent with the results obtained by Possenti et al. (2005) and Yildiz et al. (2010). However, concerning the data of Shingfield et al. (2003), these values may contribute to a low silage conservation capability; thus, caution is needed in its definition as plant material for ensilage.

These results shown in Figure 3A suggest that achenes are not the only components responsible for providing nutrients during the fermentation process, given that the largest proportion of Paiaguas palisadegrass resulted in increased contents of this acid. According to McDonald et al. (1991), water-soluble carbohydrates and sugars are the major substrates used by LA bacteria in fermentation, although other compounds can also be sources of substrates for fermentation of silage. In the present study, relatively high concentrations of organic acids, which are associated with a

Table 1. Soil chemical breakdown of the Dystroferric Red Latosol from the Brazilian savanna[1].

Ca	Mg	Al	H+Al	P	K	S	Zn	B	Cu	Mn	Mo	V[2]	m[3]	OM[4]	pH
----- $cmol_c$ dm^{-3} -----				--------------- mg dm^{-3} --------------								--- % ---		g kg^{-1}	
1.8	1.3	0.0	4.1	2.3	52	2.4	1.4	0.2	4.0	51.6	0.1	43.3	0.0	40	5.2

[1] 0.2 m depth; [2] V: base saturation; [3] m: aluminum saturation; [4] OM: organic matter. P: determined using the Mehlich test. The pH was measured in $CaCl_2$. The data are according to Linhares et al. (2020).

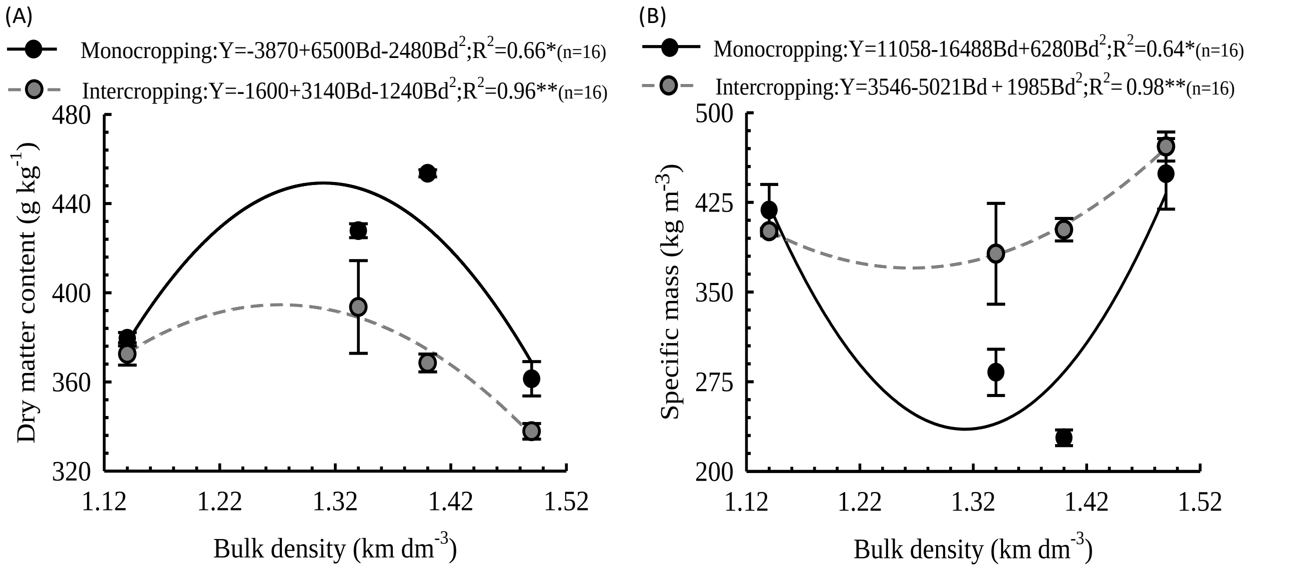

Fig 1. Dry matter (DM) content (A) and specific mass (SM) (B) of the sunflower silage from monocropping systems and intercropping systems (with Paiaguas palisadegrass) as a function of bulk density under different Latosol compaction levels in the Brazilian savanna.

Table 2. Physical properties of the Dystroferric Red Latosol from the Brazilian savanna.

Traffic intensity	Bulk density (kg dm^{-3})	Total porosity (dm^3 dm^{-3})
Absence of traffic	1.14±0.007	0.59±0.003
Two passes	1.34±0.006	0.52±0.002
Ten passes	1.40±0.007	0.50±0.002
Thirty passes	1.49±0.009	0.47±0.003

Note: Mean values for the 0-0.15 m layer (36 samples). The assessment is according to Linhares et al. (2020).

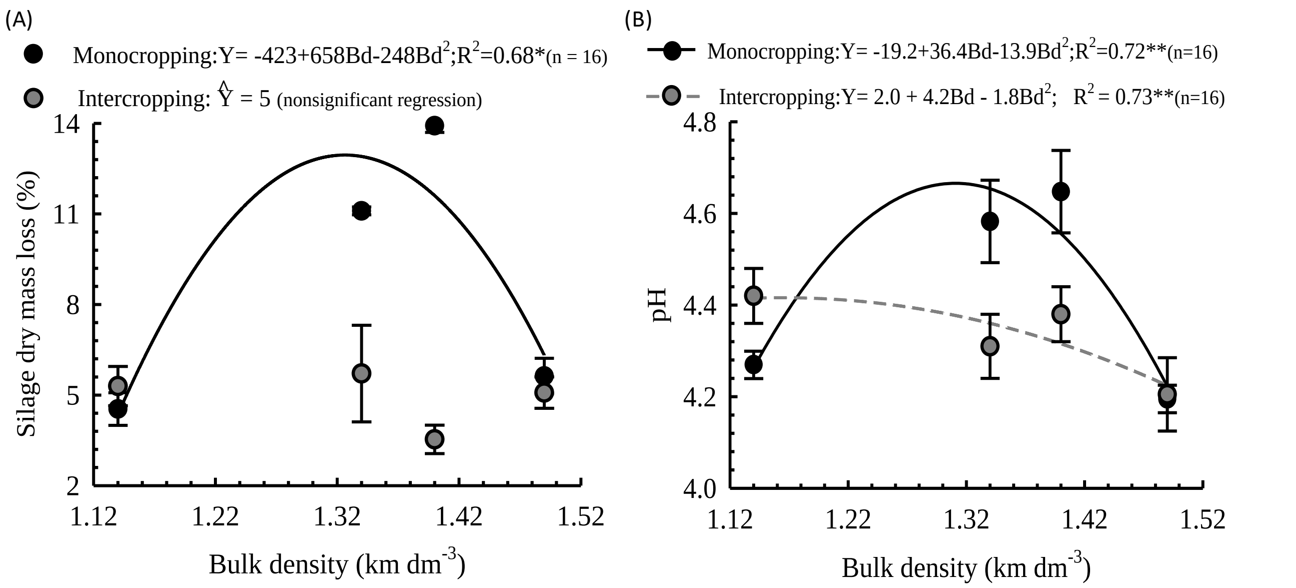

Fig 2. Loss of silage dry mass during fermentation (A) and the pH (B) of the sunflower silage from monocropping systems and intercropping systems (with Paiaguas palisadegrass) as a function of bulk density under different Latosol compaction levels in the Brazilian savanna.

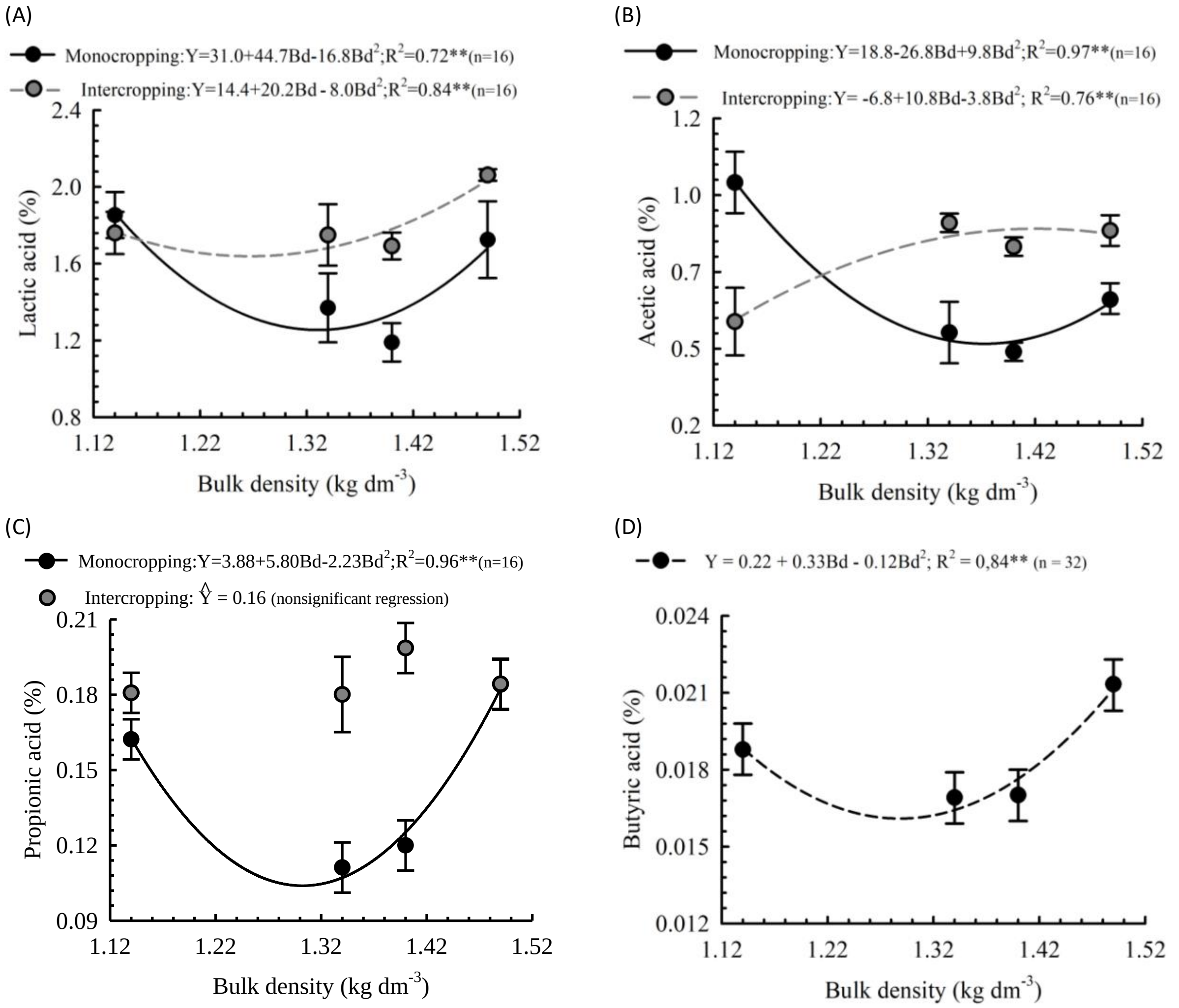

Fig 3. Percentage of lactic acid (LA) (A), acetic acid (AA) (B), propionic acid (PA) (C) and butyric acid (BA) (D) in the sunflower silage from monocropping systems and intercropping systems (with Paiaguas palisadegrass) as a function of bulk density under different Latosol compaction levels in the Brazilian savanna. ns: nonsignificant regression analysis of variance (ANOVA).

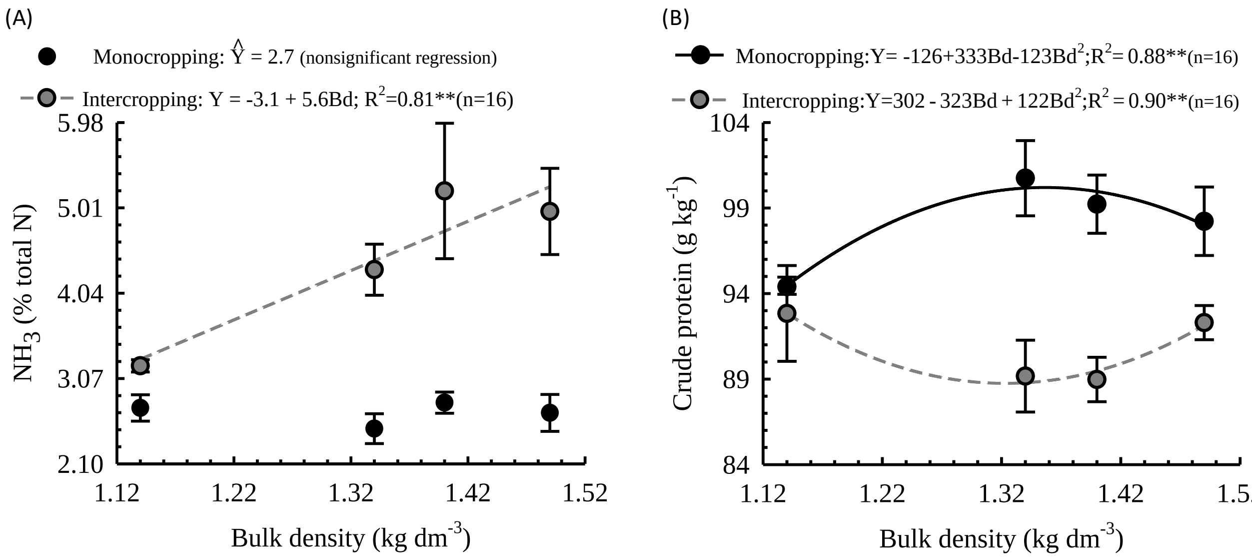

Fig 4. Ammoniacal nitrogen (NH_3) percentage (A) and crude protein (CP) content (B) of sunflower silage from monocropping systems and intercropping systems (with Paiaguas palisadegrass) as a function of bulk density under different Latosol compaction levels in the Brazilian savanna. ns: nonsignificant regression analysis of variance (ANOVA).

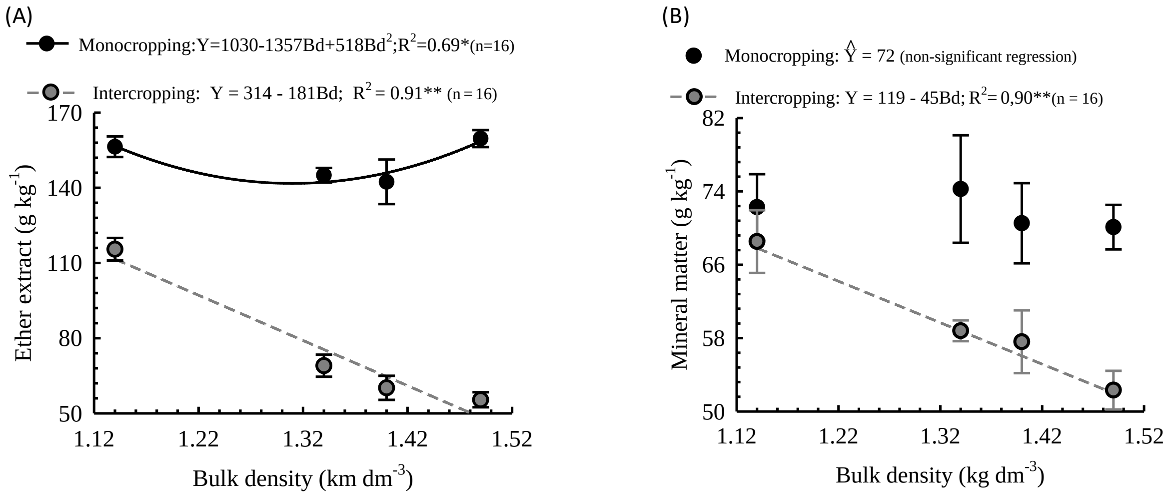

Fig 5. Ether extract (EE) content (A) and mineral matter (MM) content (B) of sunflower silage from monocropping systems and intercropping systems (with Paiaguas palisadegrass) as a function of bulk density under different Latosol compaction levels in the Brazilian savanna. ns: nonsignificant regression analysis of variance (ANOVA).

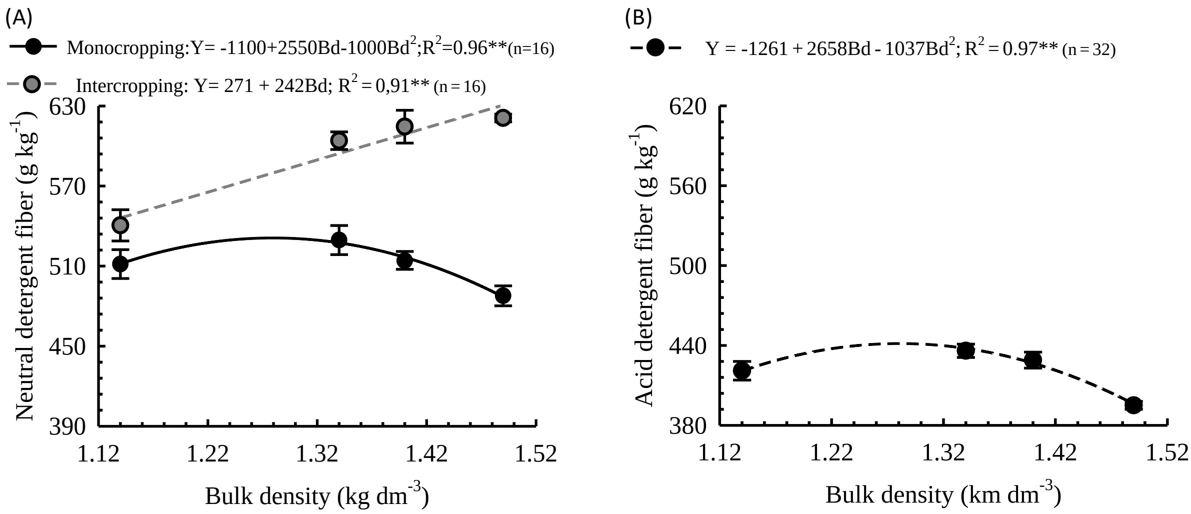

Fig 6. Neutral detergent fiber (NDF) content (A) and acid detergent fiber (ADF) content (B) of sunflower silage from monocropping systems and intercropping systems (with Paiaguas palisadegrass) as a function of bulk density under different Latosol compaction levels in the Brazilian savanna.

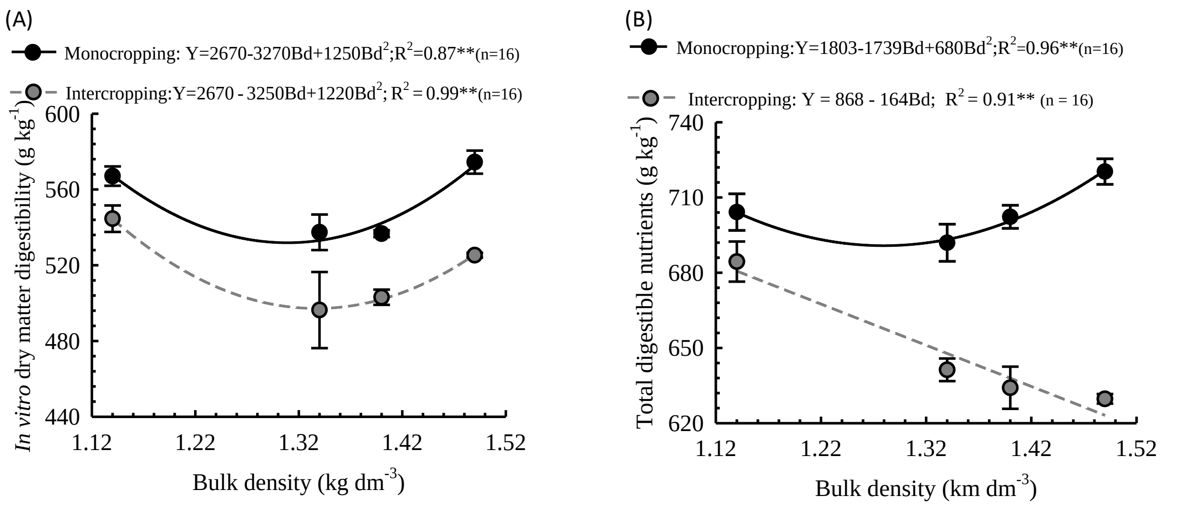

Fig 7. *In vitro* dry matter digestibility (IVDMD) (A) and estimates of total digestible nutrient (TDN) (B) contents of sunflower silage from monocropping systems and intercropping systems (with Paiaguas palisadegrass) as a function of bulk density under different Latosol compaction levels in the Brazilian savanna.

relatively high proportion of grass, a forage that is rich in hemicellulose, were observed.

This effect most likely also contributed to the increase in AA. In the silage from the intercropping system (Figure 3B), this increase is directly proportional to the increase in the proportion of Paiaguas palisadegrass in the total mass; this relationship presented in Linhares et al. (2020).

BA has been noted as limiting the quality of silage because it reflects the extent of clostridial activity. Thus, this acid is related to the negative aspects of fermentation responsible for reducing acceptability and intake (Tomich et al., 2004). In the present study, the concentrations are close to zero and indicate a correct and efficient fermentation of the silage, regardless of the soil compaction level, forage system, and pH of the silage.

The NH_3 content was below 8% in all treatments (Figure 4A), which is recommended by Tomich et al. (2004) as an indicator of the absence of degradation of plant proteins. As such, the high efficiency of the fermentation process, evidenced by the low values of this attribute, is associated with the low activity of the bacteria involved, as shown in the analysis in Figure 3D. In contrast, NH_3 development was expected to be highly correlated with pH; however, in this study, the data did not show this correlation (Figures 2 and 4).

Overall, the silage presented positive characteristics regarding the main undesirable factors, such as the production of BA and the formation of NH_3, but also presented low amounts of desirable factors, especially LA. This behavior of silage may be associated with the relatively low content of soluble carbohydrates in both crops under the ensiling conditions assessed in this study.

In addition, the total variation of only 6% in the CP content of the sunflower silage from the monocropping system reflects the protein fraction of the achenes, which in turn was constant within the sunflower forage. In contrast, the reduction in the sunflower proportion with increasing soil compaction in the intercropping system (Linhares et al., 2020) also reduces the CP because of the dilution effect caused under these conditions.

Associated with this partitioning, the first part of this study shows that, under shaded conditions, changes in Paiaguas palisadegrass morphology are associated with low nutritional quality, especially the elongation of stems and a small proportion of leaves (Linhares et al., 2020). However, without light restrictions, Paiaguas palisadegrass stands out because of its high biomass production. Its leaf laminae have a high CP content and high nutritional potential beneficial to performance animals (Euclides et al., 2016). Thus, under limitations imposed on sunflower by soil compaction, the grass regains its quality, resulting in increases in the protein content of the silage from the intercropping system.

Regardless of the forage system, the CP of the silage exceeded the minimum contents of 70 g kg^{-1} necessary for effective rumen microbial fermentation (Van Soest 1994) (Figure 7). This content is lower than that reported by Oliveira et al. (2010) but is similar to that reported by Toruk et al. (2010) and Martin et al. (2014).

The minimum EE obtained in the sunflower silage from the monocropping system was 141 g kg^{-1} when the was 1.31 kg dm^{-3} (Figure 5A). With respect to the silage from the intercropping system, the results are due to the low EE content associated with the predominance of the grass when soil physical quality decreased and reflects the oil dilution effect in the production of biomass and achenes, corroborating the results of Souza et al. (2005).

The EE content in silage provides a higher energy density and utilization efficiency (Mello et al., 2006). In contrast, according to those authors, the EE content in ruminant diets in most situations must be below 70 g kg^{-1} (on a DM basis) to prevent jeopardizing the rumen microbial activity in the regulation of fiber fermentation, digestibility, and passage rate.

Oliveira et al. (2010) noted the need for the association of sunflower with other forage in ruminant diets. At the point of maximum DM productivity in the intercropping system discussed in the first part of the study (Bd = 1.29 kg dm^{-3}, according to Linhares et al. (2020), the EE content was approximately 80 g kg^{-1}, which is close to the recommended value. Thus, the importance of intercropping aimed at the balance between productivity and the nutritional quality of the silage becomes evident.

The lack of appreciable effects of Bd on the MM content of the sunflower silage (Figure 5B) again reinforces that the reduction in sunflower plants due to soil compaction occurred proportionally in all plant parts. The dilution effect of the ensiled mass at the expense of the proportional increase in Paiaguas palisadegrass can also be observed on the basis of the MM analysis. The linear reduction within the Bd range studied was approximately 25%.

Sunflower silage is considered a food rich in MM, and the results obtained in the present study are similar to those reported by Martin et al. (2014). According to those authors, approximately 99% of MM consists of plant macronutrients, especially calcium, potassium, N, magnesium, and phosphorus. Therefore, the importance of proper fertilization when working with crops intended for silage is evident [according to results of the chemical analysis of the soil (Table 1) and the fertilizers applied (Linhares et al., 2020)].

Quantitative and qualitative analyses of the fiber fraction in forages are also important for assessing their nutritional capacity. The contents of NDF (Figure 6A) and ADF (Figure 6B) are close to those obtained by Jayme et al. (2007) when ensiled at the same phenological stage. The results also suggest that the forage composition of the ensiled mass, especially the proportions discussed in the first part of the study and the DM content (Figure 1A), affects the changes in the fiber fraction analyzed.

The NDF content of the silage obtained from cropping systems varied with increasing Bd but remained at high levels under all evaluated soil structure conditions, which is due to the relatively high content of this fibrous component in tropical forages, especially those produced during the dry season (Maia et al., 2014). The lack of variation in ADF values between cropping systems evaluated, despite being altered according to soil compaction, occurred because the ADF represents a secondary structural component that is characteristic of plant maturity, especially in sunflower. In the intercropping system, the ADF is associated with grass stem elongation in search of light, a behavior discussed in the first part of this study. The low proportion of leaves results in decreased nutritional quality, and these factors may be responsible for the ADF increase in both silage compositions because the maximum value (442 g kg^{-1}) is near the limiting Bd (1.28 km dm^{-3}), which was also observed in the changes in the morphological development of the crop species under these conditions.

The behavior of the IVDMD values was the opposite of that of the ADF content (Figure 6B). According to Mello et al. (2006), this fraction is strongly negatively correlated with digestibility. However, given that there was no difference between the forage systems, the higher digestibility of the monocropped sunflower silage compared with the intercropped sunflower silage may be related in part to the relatively low content of the NDF (Figure 6A), which is in line with the results of Jayme et al. (2007).

Although changes in digestibility have been reported, the systems presented values considered adequate (520-630 g kg^{-1}) and normal (<520 g kg^{-1}). These results are consistent with those reported by Souza et al. (2005), who worked with sunflower plants at different physiological maturity levels.

The greatest digestibility occurred at the Bd extremes (Figure 7A) and may be associated with the interactions among the factors that lead to changes in the morphological components of the plants, especially stem elongation and a reduced the leaf/stem ratio, which is consistent with the report of Silva and Nascimento Júnior (2007).

Moreover, the largest DM content (Figure 1A) possibly corresponds to the greatest physiological maturation and, consequently, to low digestibility, corroborating the findings of Toruk et al. (2010). Another factor that may occur is related to the silage SM, in which increased silage compaction reduces the loss of ensiled mass, especially the fraction that is relatively more digestible.

In corroboration of the IVDMD results, in the report by Chandler (1990), there was a greater TDN content in the monocropped sunflower compared with the intercropped sunflower (Figure 7B). In addition, the sunflower silage presented percentages close to those found by Oliveira et al. (2010), who reported its qualitative potential, including its superiority to that of both corn and sorghum. In contrast, in the intercropping system, the increased proportion of the grass in the silage resulted in TDN values that decreased linearly with increasing Bd. These results are due to the lower TDN content in *Brachiaria* forages (Perim et al., 2014).

These results are in accordance with those of Mello et al. (2006), who reported that, with respect to the IVDMD, sunflower plants are similar to the major grasses (corn, sorghum) but stand out in terms of TDNs because the former have lower NDF contents and higher EE contents. In this context, this data shows that both systems produced good-quality silage. However, notably, under conditions of limiting Bd, the TDN content was only 5% lower in the intercropping system than in the monocropping system but was compensated by its productive superiority; these results are presented and discussed in the first part of this study (Linhares et al., 2020). Several studies have demonstrated the benefits of producing silage from intercropping systems, as shown in studies by Ribeiro et al. (2017) in sorghum intercropped with *B. brizantha*; by Cruvinel et al. (2017b) in sunflower intercropped with Paiaguas palisadegrass; and by Costa et al. (2018) in millet intercropped with Paiaguas palisadegrass in different forage systems. In general, our results show that the nutritional quality of the silage from the intercropping system can also be considered satisfactory. With respect to these issues, although the silage of sunflower intercropped with Paiaguas palisadegrass has a lower nutritional quality than that of the monocropping system, this decrease is compensated by the increased productivity of the total forage and by the indirect renewal of the pasture, providing quality food.

Materials and Methods

Experimental area characterization

The study was conducted in the field at the Federal Institute of Education, Science and Technology Goiano, Campus Rio Verde, located in the southwestern region of the state of Goias state, Brazil. The forage was produced on a Dystroferric Red Latosol. Its physical and chemical properties are presented in Table 1.

A split-plot randomized complete block design with four replications was adopted in conjunction with plots that were 12.0 m long and 6.0 m wide. The main plots consisted of increased degrees of soil compaction (assessed via Bd) caused by traffic from an agricultural John Deere 6605 tractor with a 4.9 Mg load; to create the compaction, the tractor made zero, two, ten, or thirty passes over the same place. In the subplots, sunflower (*H. annuus* L.) (Charrua hybrid) was grown solely as a monocrop at a population density of 40,000 plants ha^{-1}, and sunflower and Paiaguas palisadegrass (*B. brizantha* cv. BRS Paiaguas) were grown in an intercropping system under 10 plants linear m^{-1}.

In all the subplots, after the crops were sown, nine undisturbed soil samples within 0-0.15 m were collected in volumetric rings using an Uhland sampler for Bd treatment quantification in response to soil compaction characterization caused by tractor traffic (Table 2).

The growth of the plants was monitored by their increase in biomass, and the plants were ensiled when the DM content was approximately 350 g kg^{-1}, which occurred at 112 days after sowing. The forage was cut at a height of 0.2 m in 4.0 m^2 and was sent to be chopped into pieces that were 10 to 20 mm in length by a stationary forage harvester machine, and a portion of the material (0.5 kg) was sampled to obtain the DM content of the ensiled material.The forage was homogenized and compacted in experimental polyvinyl chloride (PVC) silos (0.1 m in diameter and 0.5 m in length). The silos were then weighed and stored at room temperature, which offered protection from rain and sunlight, for fermentation.

Fermentation and bromatological analysis

After 65 days of fermentation, the silos were weighed for the assessment of losses of silage, which were obtained by quantifying the dry mass before and after storage. The SM of the silage was considered the ratio between the forage mass and the silo volume. These calculations were performed according to the methods of Jobim et al. (2007). After the silos were opened, the central portion was homogenized and divided into two samples for fermentation and chemical analysis. To determine the pH and NH_3, the samples were thawed for juice extraction and were prepared according to the method described by Tabacco et al. (2009). The aqueous extracts were subsequently prepared for the determination of organic acids (LA, AA, PA, and BA) via high-performance liquid chromatography in conjunction with an ultraviolet detector at a wavelength of 210 nm, according to the Association of Official Analytical Chemists (AOAC) (AOAC, 1990). The other samples, which were approximately 0.5 kg each, were placed in a forced-ventilation oven at 55ºC for 72 hours to determine the predried matter content. The samples were then ground in a “Wiley” type knife mill that had a sieve diameter of 1 mm.

A chemical analysis was performed to determine the DM, MM, and CP contents by determining the total N using the micro-Kjeldahl technique and a fixed conversion factor (6.25). The EE was determined according to methods of the AOAC (AOAC, 1990); the NDF, Mertens (2002); and the ADF, the AOAC (AOAC, 1990).

For the IVDMD, we adopted the technique described by Tilley and Terry (1963), which was adapted for artificial rumen developed by ANKOM® via a Daisy incubator from ANKOM Technology.

Total digestible nutrients concentration was estimated by the equation proposed by Chandler (1990) as follow: $TDN = 105.2 - 0.68NDF$.

Statistical analysis

The results of the fermentation and nutritional characteristics of the silage as a function of Bd were subjected to analysis of variance (ANOVA), and regression models as a function of Bd were constructed via SigmaPlot 11.0 software (Jandel Scientific) when significant results ($p<0.05$) were obtained.

Conclusions

The productivity and composition of the ensiled mass were affected by soil compaction, resulting in fermentation changes that also affected the nutritional characteristics of the silage. The relatively high DM content of the sunflower harvested under conditions of maximum productivity, balanced by relatively high moisture content of the Paiaguas palisadegrass in the intercropping system, ensured good silage fermentation. The adoption of intercropping is recommended for increased productivity of forage systems, which, despite a slightly reduced silage quality, enables the indirect renewal of pasture after the forage is harvested, providing good-quality forage to animals during the second cropping period and/or the formation of biomass for no-tillage systems.

Conflicts of interest

The authors declare that no financial or other competing conflicts of interest exist.

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