COMPACTION PRESSURE AND DENSITY PROFILE IN PILE-TYPE SILOS

TAN, F.[1*] – DALMIS, I. S.[2]

[1]*Department of Biosystem Engineering, Faculty of Agriculture, University of Namık Kemal 59030 Tekırdag, Turkey*

[2]*Department of Mechanical Engineering, Corlu Faculty of Engineering, University of Namık Kemal, 5986 Corlu, Tekirdag, Turkey*

**Corresponding author*
e-mail: ftan@nku.edu.tr; phone: +90-282-250-2270; fax: +90-282-250-9929

(Received 11th Dec 2018; accepted 4th Feb 2019)

Abstract. The main aim of this study is to investigate the compaction pressure and density profile, and to determine the effectiveness of the compaction process applied to the pile-type silos. Chopped material was compacted into a pile-type silo. Pressure-sensing rubber globes were placed at the measuring points to determine the compaction pressure, during the silo filling. The compaction pressure and compaction time were acquired by the pressure measurement system. Data were stored by a recorder. The density measurements were made at pre-determined measurement points in each layer after the compaction process. The results showed that there was a significant relationship ($R^2 = 0.919$, $P < 0.01$) between the compaction pressure applied to silage and the density of silage under field condition. Pressure and density profile were found to be highly variable in the silo. The highest density (535.0 Kg m^{-3}) and pressure (0.46 bar) were at the bottom layer of the silo while the lowest density (206.6 Kg m^{-3}) and pressure (0.21 bar) were at the top layer of the silo.
Keywords: *silage, pile silo, pressure sensor, pressure measurement system, silage density*

Introduction

The compaction process is the most important process in silage making. This process is necessary to increase the density and remove oxygen from inside the silage as much as possible. Higher silage density and quality can be achieved by applying more compaction on the silage. It was indicated in the literature that the density of silage was variable in silage silos (Muck and Holmes, 2000; Roy et al., 2001; Tan et al., 2018). Latsch (2014) stated that the heterogeneous density occurring in silos was a major problem.

The efficiency of compaction is affected by the weight of equipment used (Darby and Jofriet, 1993; Muck et al., 2004), the layer thickness, the number of layers, the silo height (D’Amours and Savoie, 2005), the applied pressure (Savoie et al., 2004), the compression time (Roy et al., 2001), and the operator experience (Tan et al., 2018) while compaction pressure has an effect on silage fermentation (Tan et al., 2017). Toruk et al. (2010) reported that fermentation characteristics of the silage were positively affected by the increasing compaction pressure. Savoie et al. (2004) found that the density of corn silage was affected by pressure and layer thickness. In Turkey, the most common types of silos used for silage are the bunker silo and the pile-type silo. The use of pile-type silos is much more common in small livestock farms. However, determination of silage density and silage quality are significant problems for small livestock farms. Previous studies were generally conducted in laboratory conditions (Hoffman et al., 2013; Savoie et al., 2004), and studies to determine the compression

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/1702_27452754

pressure in the silo under the field conditions are limited. Therefore, this study aimed to determine the relationship between density and compaction pressure in pile-type silo under field conditions.

Materials and methods

Experimental conditions

The second crop of maize (Pioneer ® P2948W) was harvested at 32% dry matter (DM) on November 2nd, 2017. The chopped material was ensiled in the pile-type silo within a day. The mean particle length of the chopped material was 12 mm. A single tractor (John Deere 6230) was used to compact the silage material. A mass of the compaction tractor was 4.6 tons. The tractor had a pressure of 2 bar at the front tire (380/85R24) and pressure of 2.3 bar at the rear tire (420/85R38). The transversal way has been used by the tractor to pack the silo. The compaction pressure applied during the packing of the pile-type silo in small livestock farm was also recorded. The densities of the material were calculated in the samples taken from predetermined measuring points. Before filling silo, a sample of fresh material was put aside to determine the dry matter content by oven drying at 103 °C during 24 h according to standard S358.2 (ASAE, 2002).

Pile silo and measurement points

The pile-type silo was 4.5 m wide, 12 m long, and 1.6 m high (theoretical volume of 86.4 m^3). The silo was divided vertically into three regions (north-N, center-C and south-S), and horizontally into three positions (1, 2 and 3) and three layers (top, middle, bottom). The height of layers in the silo was equal. The height of each layer is approximately 0.4 m. *Figure 1* shows the pressure and density measurement points and the location of pressure sensors.

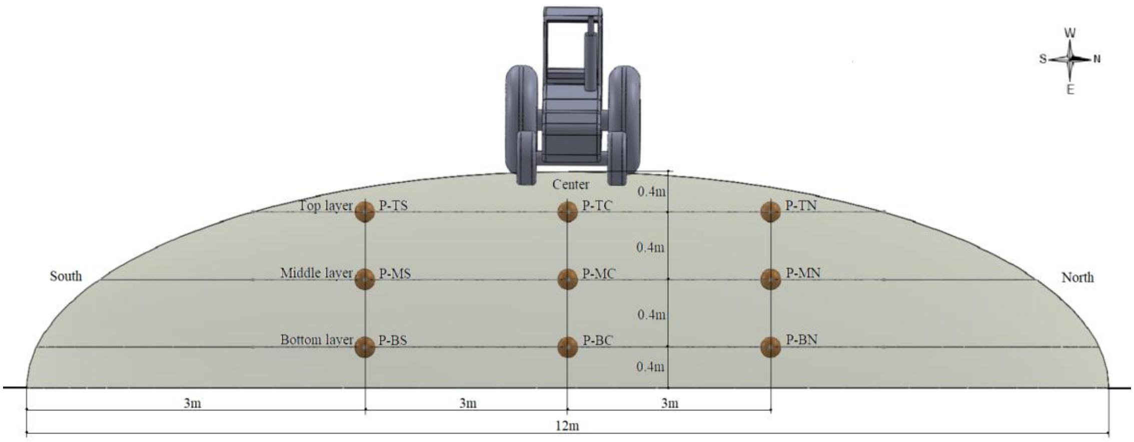

Figure 1. *Pressure measurement points in the pile silos*

Pressure measurement

The compaction pressure was acquired by the pressure measurement system. The measured pressure values were recorded by a data logger of the pressure measurement

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DOI: http://dx.doi.org/10.15666/aeer/1702_27452754

system throughout the entire process. Pressure values were recorded as one data per second (1 value/second). The lowest pressure (Min.), maximum pressure (Max.) and residual pressure (RP) values measured during the compaction process were evaluated. The residual pressure was the total pressure remaining on the material after the compaction process.

The pressure measurement system has mainly three units (*Figure2*). These are data collection and recording (1), pressure sensors (2), and pressure-sensing rubber globes (3).

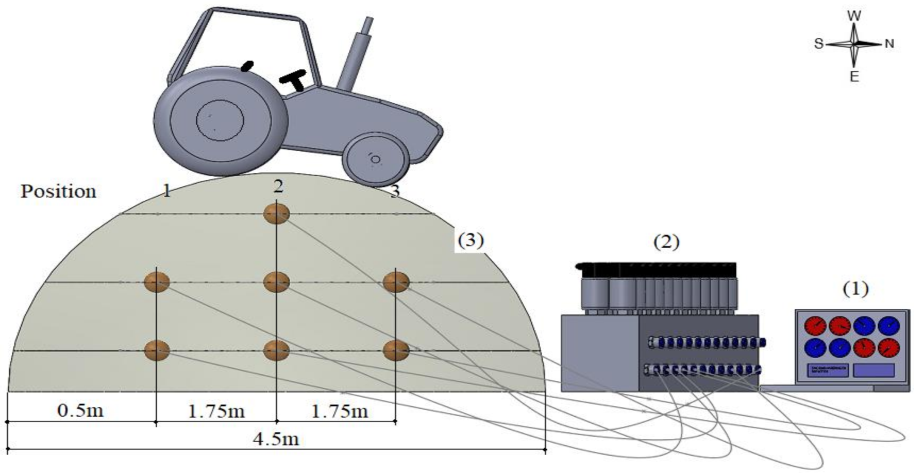

Figure 2. *Pressure measurement system; (1) data collection and recording, (2) pressure sensors, and (3) pressure sensing rubber globes*

The pressure-sensing rubber globes (PS) were installed into the silo to characterize the general condition of the silo and to measure the pressure during the ensiling stage. Pressure measurements were done by 27 PS. The pressure sensors were connected to the PSs via hydraulic hoses (Turner and Raper, 2001; Tan et al., 2018). The sensors (MPS500 series) used in the system had a measurement range of 0-25 bar, 4-20 mA output signal and a temperature range from -40 °C to +125 °C. The sensors were connected to NI DAQ measurement and storage system. The data (NI cDAQ-9184) were stored in an MS Excel file on the computer by using a user interface created with a NI Labview software (Tan et al., 2018). In order to determine whether the output values of the pressure sensors used in the measurement system were correct and reliable, especially under the dynamic conditions, two different calibration curves were created (Dalmıs, 2006; Akıncı, 1994). The pressure distribution was analyzed as a function of the three position factors (region, position, and layer).

Density measurement

The density measurements were made at each pressure measurement point after the compaction on each layer during the ensiling stage. The density distribution was also analyzed as a function of the three position factors (region, position and layer). The density of the silage was determined by taking the cylinder volume into consideration. The silage samples taken with the cylindrical container were then weighed (*Eq. 1*). The volume and weight of the silage materials were then used to calculate the density of the silage in kg m^{-3}:

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$$\rho = \frac{m}{v} \quad \text{(Eq.1)}$$

where ρ is the ensiling material density, kg m^{-3}, m is the mass of the ensiling material filling, kg, and v is the cylinder volume, m^{-3} (Hoffmann et al., 2013; Wang, 2012).

Compaction time measurement

The compaction time was measured by the pressure measurement system. The measured time values were recorded by a data logger of the pressure measurement system throughout the entire process. The total compaction time measured during the compaction process was evaluated. The compaction time (hour/min) of packing tractor was recorded to estimate total compaction time on each layer.

Statistical analysis

In this study, to evaluate statistical significance between the compaction pressure and density in a pile-type silo, the data were analyzed by using the one-way ANOVA employing SPSS (version 18.0) software in a 3 x 3 x 3 factorial design. The minimum level of significance was 5%. Means were compared by the Tukey HDS test. A correlation test was performed among all parameters. The model statement included the effect of treatment, region, layer, position and interaction treatment (Eq.2).

The mathematical model used was;

$$y_{ijkl} = \mu + r_i + l_j + p_k + (rl)_{ij} + (rp)_{ik} + (lp)_{jk} + (rlp)_{ijk} + e_{ijkl} \quad \text{(Eq.2)}$$

in which y_{ijkl} = observed value of the variable that received the level of region i, layer j, position k, μ = overall mean; r_i = region effect, l_j = layer effect, p_k = position effect, interactions and e_{ijkl} = random error associated with each observation.

Results

The compaction pressure (a) and the density (b) measured in different layers according to the north-south regions of the silo are given in *Figure 3*. Compaction pressure and density values were increasing from the top layer to the bottom layer in all regions of the silo. The average values of the compaction pressure (a) and the density (b) measured in different layers according to the position are given in *Figure 4*.

The density of the silage and the residual pressure, the minimum and maximum compaction pressure measured in different layers during the ensiling stage are given in *Table 1*. When the values of compaction pressure between three layers were compared to each other, the top layer data were lower than the middle and the bottom layers. The bottom layer had the highest average compaction pressure compared to the other layers. Different results were obtained for the pressure. Compared to the other points, at the B-N_3 (0.46 bar) point, residual pressure was the highest, and at the T-S_1 (0.21 bar) point the lowest residual pressure was measured.

The applied compaction pressure varied from the northern (N) region of the silo to the southern (S) region. The highest pressure was measured in the northern region of the silo. B-$N_{1,2,3}$ were 16.67% and 24.77% higher than the C-$N_{1,2,3}$ and S-$N_{1,2,3}$, respectively. This indicates that the operator spent more time in the northern region of the pile-type silo than other regions. The effects of the compaction pressure have been

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
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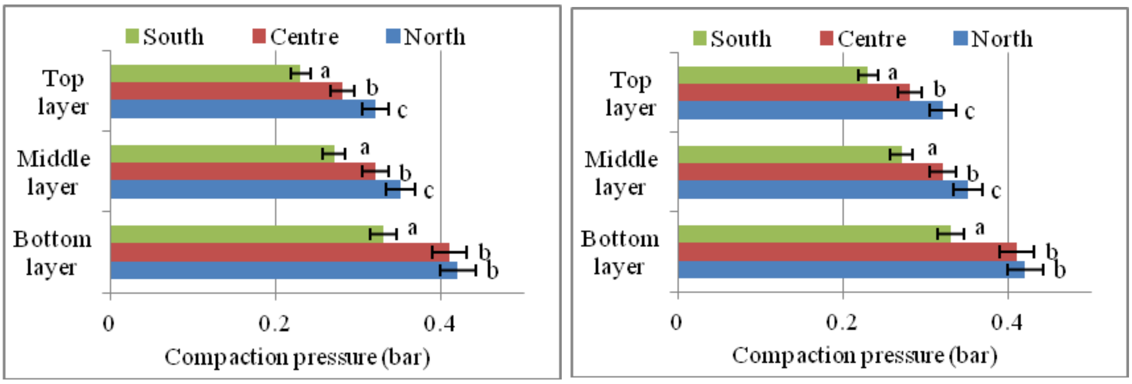
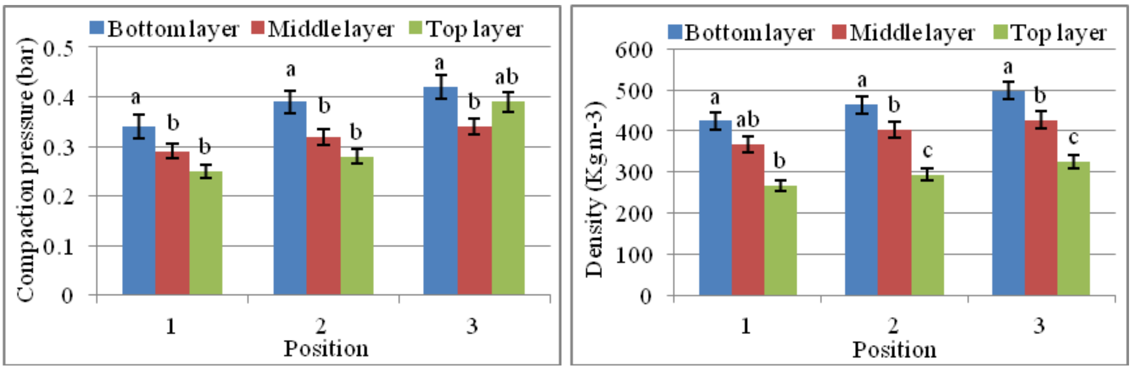
found statistically significant in the region and position (P < 0.05). The lowest mean compaction pressure was at position-1 (0.29 bar), and the highest compaction pressure was at position-3 (0.35 bar), which was 16.72% higher than the one at position-1.



a **b**

Figure 3. *The compression pressure (a) and density (b) measured in different layers according to the regions. Column with different letters within regions are statistically significant at P = 0.05 (n = 9)*



a **b**

Figure 4. *The compaction pressure measured (a) and density (b) in different layers according to the positions (positions 1, 2 and 3 have been shown in Figure 2). Column with different letters within regions are statistically significant at P = 0.05 (n = 9)*

The density of fresh matter increased from top to bottom in the pile-type silo. The bottom layer had the highest average fresh matter density compared to other layers. The average silage density of the top layer was the lowest and bottom layer had the highest silage density among the three layers. The compaction pressure applied to the silo is not equal which causes density differences. For this reason, the compaction time in the top layer of the silos should be higher than the other layers. The highest density was measured in the N-region of the silo. There was a difference among the regions according to the densities. B-$N_{1,2,3}$ were 15. 85% and 37.73% higher than the M-$N_{1,2,3}$ and S-$N_{1,2,3}$, respectively. The fresh matter density measured at position-3 of the silo in all layers was much higher than position-1 and position-2 of the silo. The effects of the density and the compaction pressure on the regions, layers, and positions are shown in *Table 2*.

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Table 1. *Compaction pressure values (min., max., mean and residual) and density measured during the ensiling stage according to layers, regions (north-N, center-C and south-S) and positions (1, 2 and 3)*

MP	**Min. (bar)**	**Max. (bar)**	**Ave. (bar)**	**RP (bar)**	**Density (Kg FM m^{-3})**
Bottom layer (B) Compacting time 3:42 (h/min)					
B-S_1	0.002	0.452	0.227	0.30	384.4
B-S_2	0.002	0.477	0.239	0.33	402.9
B-S_3	0.003	0.518	0.260	0.36	435.6
B-C_1	0.003	0.468	0.235	0.34	395.9
B-C_2	0.003	0.515	0.259	0.43	478.1
B-C_3	0.004	0.599	0.301	0.45	520.9
B-N_1	0.003	0.550	0.276	0.38	492.2
B-N_2	0.004	0.620	0.312	0.42	510.2
B-N_3	0.004	0.726	0.365	0.46	535.0
	0.0031	0.547	0.275	0.383	461.7
Middle layer (M) Compacting time 2:53 (h/min)					
M-S_1	0.001	0.387	0.194	0.26	322.6
M-S_2	0.001	0.410	0.205	0.28	351.1
M-S_3	0.001	0.435	0.218	0.29	389.1
M-C_1	0.001	0.410	0.205	0.29	370.8
M-C_2	0.002	0.435	0.218	0.32	419.8
M-C_3	0.002	0.461	0.231	0.36	444.2
M-N_1	0.003	0.480	0.242	0.32	408.9
M-N_2	0.003	0.513	0.258	0.36	436.4
M-N_3	0.003	0.657	0.330	0.38	448.5
	0.0018	0.465	0.233	0.317	399.0
Top layer (T) Compacting time 2:05 (h/min)					
T-S_1	0.001	0.358	0.179	0.21	206.6
T-S_2	0.001	0.366	0.183	0.24	245.6
T-S_3	0.001	0.370	0.185	0.25	297.8
T-C_1	0.001	0.392	0.196	0.26	290.9
T-C_2	0.001	0.410	0.205	0.28	324.0
T-C_3	0.001	0.435	0.218	0.30	330.3
T-N_1	0.001	0.420	0.210	0.29	302.3
T-N_2	0.002	0.482	0.242	0.32	310.0
T-N_3	0.002	0.568	0.285	0.34	345.1
	0.0012	0.422	0.212	0.279	294.7
Total compacting time 8:40 (hours/min)					

MP: the measurement point defined for density and pressure; Min.: the lowest pressure value measured at the specified point; Max.: the highest pressure value measured at the specified point; RP: the residual pressure on the material after compression

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The density was the lowest at T-S_1 position with 206.6 Kg m^{-3} and the highest at T-N_3 position with 345.1 Kg m^{-3}. The main reason for this is that there was a shelter near the right side of the silo. This was a problem for the quality of the compaction process. The density also increased with the increasing pressure. The densities obtained in our study were similar to several studies in the literature. In the present study, the density in the regions ranged from 337.32 Kg m^{-3} to 420.98 Kg m^{-3} (*Table 2*).

The highest density and pressure changes were calculated between the layers, which are 36.16% and 27.15%, respectively. The lowest density and pressure changes were calculated between the positions, which are 15.27% and 16.72%, respectively. The density and residual pressure in the northern and center region of the silos were higher than the southern region of the silos. The layers had significant effects on the density and pressure ($P < 0.05$). The highest values were measured at the bottom layer. In the present study, the density of the pile-type silo ranged from 294.77 Kg FM m^{-3} to 461.7 Kg FM m^{-3}. The compaction time was the lowest at the top layer and the highest at the bottom layer. The positions had also significant effects on the density and pressure (*Table 2*). The average residual compaction pressure on the material after compaction in the pile-type silo was calculated as 0.33 ± 0.62 bar, and the average density was calculated as 385.178 Kg m^{-3}.

Table 2. *The effects of density and compaction pressure on the regions, layers and positions*

Regions	D	RP	Layers	D	RP	Positions	D	RP
North	420.98^{a}	0.362^{a}	BL	461.71^{a}	0.383^{a}	1	352.77^{a}	0.294^{a}
Centre	397.22^{a}	0.338^{a}	ML	399.05^{b}	0.317^{b}	2	386.45^{ab}	0.331^{ab}
South	337.32^{b}	0.279^{b}	TL	294.77^{c}	0.279^{c}	3	416.30^{b}	0.353^{b}
RP				$R^2 = 0.989$				
Region*Layers				F = 9.412			P < 0.05	
Region*Position				F = 7.765			P < 0.05	
Layers*Positions				F = 17.353			P < 0.05	
Region*Layers*Positions				F = 5.397			P < 0.05	
D				$R^2 = 0.996$				
Region*Layers				F = 32.147			P < 0.05	
Region*Position				F = 31.291			P < 0.05	
Layers *Positions				F = 4.919			P < 0.05	
Region*Layers*Positions				F = 20.426			P < 0.05	

*Mean values in the same column with the same superscript do not differ significantly at ($P < 0.05$)
D: Density; RP: is the residual pressure on the material after compression

The correlations amongst all parameters are shown in *Table 3*. The correlation results showed that the fresh matter density of the silages and the compaction pressure were strongly ($R^2 = 0.919$, $P < 0.01$) correlated (*Table 3*).

The density of the silage in the pile-type silo was positively affected by the increasing compaction pressure. The pressure and density of the silage showed positive correlations with the regions and positions, whereas they were negatively correlated with the thickness of the increased layers. This indicates that the thickness of the layers, the compaction times reserved for the layers, and the movement of the compaction equipment is important in silo management.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
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Table 3. *Correlations between all parameters*

	Density	Pressure	Region	Layers	Position
Density	1	0.919**	0.411**	-0.821**	0.312**
Pressure	0.919**	1	0.549**	-0.684**	0.388**

**Correlation is significant at the 0.01 level (2-tailed)

Discussion

In our study, the density and pressure values in some regions of the silo are higher than the other regions. However, according to Latsch (2014), there are no significant differences between the bulk density in compact areas. In position 1, compacting time was found a bit longer than in position 2 and 3. In the present study, compaction time was the lowest at the top layer and the highest at the bottom layer. This indicates that the operator spent more compaction time in some layers than the other ones. Similar results were reported by Latsch (2014), Tan et al. (2018), and Muck et al. (2004).

There is no literature on compression pressure measurement in the ensiling process performed under field conditions. Compaction efficiency has been described in relation to silage density in many studies. In this study, the compression pressures and silage density measured in the field conditions have been explained together. As a result of the study, it was observed that the densities related to the measured pressure values were consistent with the literature. As a result, it was seen that the compaction pressure applied in the pile-type silo meets the recommended density values in the literature.

In the present study, the density of the pile-type silo ranged from 294.77 Kg FM m^{-3} to 461.7 Kg FM m^{-3}, which are similar to those found by Muck and Holmes (2000) and Roy (2001). These values are higher than the ones (205.03-376.43 Kg m^{-3}) expressed by Norell et al. (2013) and (129-302 Kg m^{-3}) expressed by Oelberg et al. (2006). These results can be explained by the fact that they are not average value.

In our study, it was determined that the silo density and pressure increased from the top layer to the bottom one. This can be explained by the increase in the layer thickness and the weight of the mass. Huhnke (1995), Muck and Holmes (2000), D'Amours and Savoie (2005), and Oelberg et al. (2005) also observed that the density at the top of the silo was lower than the density measured at the bottom. However, the data about the compaction pressure were not determined in the literature. D'Amours and Savoie (2005) reported that the density in the silo was quite variable and was affected by the pressure. According to Tan et al. (2017), the highest compaction pressure measured in the bunker silo is 0.34 bar. In our study, the measured residual pressure was 0.46 bar, which was higher than the value reported by Tan et al. (2017). Although average residual pressure was 0.33 bar, the maximum pressure measured instantaneously was0.726 bar during the ensiling.

There was a strong and positive relationship between the silage density and the compaction pressure applied to the corn silage in a pile-type silo. The results showed a positive correlation with regions and position, whereas they were negatively correlated with increasing layers thickness. According to Tan et al. (2017), there was a relationship between the compaction pressure applied to silage and temperature. The relations between density and pressure were not reported in those studies conducted in field conditions in the previous studies.

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Conclusion

Pressure and density values in the silo were found to be quite variable for regions, positions and layers. The differences could be largely explained by different compaction times and tractor mass for regions, the way used by the tractor to pack the silo for positions and the increasing material mass for layers. At small farms, very heavy compaction equipment is not available. For this reason, it may be advisable to make more compaction time for packing or more passages on a thinner layer to achieve high density in these farms.

Results indicated that it is important to select areas that will not restrict tractor movements when locating the silo. This situation causes differences in silo compaction pressures due to restrictions on tractor movements. The effects of measured exact regional compaction time on the quality of silage and silage compaction pressure can be worked for future works.

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