The optimal plant density of maize for dairy cow forage production

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Abstract
Whole maize (Zea mays L.) plant (WMP) silage is an important feed for dairy cows. In northern China, yields and feed quality are adjusted by modifying the planting density. This paper is the result of a 2-yr field study aimed at determining the effects of plant density on maize silage yield and quality. Five planting densities (52,500, 60,000, 67,500, 75,000, and 82,500 plants ha−1) were used. The results showed that plant height and leaf area increased, while stem diameter, chlorophyll, and leaf area per plant decreased with increasing plant density. Both the biomass yield, expressed as the dry matter (DM) per ha, and the utilizable energy yield improved when the density was increased from 67,500 to 75,000 plants ha−1, but increasing the density further reduced these values. The highest observed DM were 17,734 kg ha−1 and 17,055 kg ha−1, and total net energy for lactation (NE_L) were 104.1 GJ ha−1 and 97.0 GJ ha−1 in 2017 and 2018, respectively. Feeding quality generally decreased with increasing plant density. The plant density which obtained the highest biomass yield was not the same as the plant density for optimizing feeding production. Compared with the highest predicted DM yields, the highest predicted total NE_L yields increased the grading index by 4–9%, which indicated an improvement in forage quality. Total NE_L yield is more efficient for the purpose of evaluating the productivity of WMP forage than biomass yield.

1 | INTRODUCTION
Maize (Zea mays L.) is a multi-purpose and high-yield crop that can be used for the production of human food and livestock forage, or as a raw material for industrial production (Mandić et al., 2015; Sun, 2017). Improving forage production is needed to expand the dairy industry (Feng, 2011; Sun, 2017). Maize, due to its high yield, high forage quality, and lower inputs, is widely used to produce silage (Cusicanqui & Lauer, 1999; Esfahani, Aminpanah, & Gandomani, 2014). The consumption of maize used as livestock forage increased from 85 million tons in 2000 to 157 million tons in 2018 (Jiang, 2018). In the dairy industry, whole maize plant (WMP) silage is a primary source of energy and fiber

Abbreviations: ADF, acid detergent fiber; CFa, crude fat; CFi, crude fiber; CP, crude protein; DM, dry matter; ED, energy digestibility; ET, evapotranspiration; GE, gross energy; GI, grading index; NDF, neutral detergent fiber; NE_L, net energy for lactation; NFE, nitrogen free extract; NUE, nitrogen use efficiency; RFV, relative feeding value; WMP, whole maize plant; WUE, water use efficiency.

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for dairy cows (Ferreira, Alfonso, Depino, & Alessandri, 2014).

Forage and silage quality can be modified by adjusting the plant density. Increasing maize plant density to appropriate rates increases dry matter (DM) yields (Fischer, Ramos, Monasterio, & Sayre, 2019). The forage yield of WMP is calculated from the biomass (dry matter) yield per plant and the plant density (Sun, 2017). Lower plant densities might produce a higher biomass per plant, but because of the reduced number of plants per unit area, the yield per unit land can be reduced (Shi et al., 2016; Zhang et al., 2018). Achieving an optimal maize production involves a tradeoff between the yield per plant and the number of maize plant per hectare. Increasing the plant density to an appropriate value could offset the reductions resulting from the competition between individual maize plants (Zhang et al., 2017). Increasing the plant density reduces the photosynthesis rate and dry matter accumulation per plant due to interplant competition, but it improves the light interception and the resource efficiency, thereby increasing biomass yield per unit area (Gao et al., 2017; Zhang et al., 2018). However, high plant densities exceeding the optimal rate result in a decrease in leaf area per plant and leaf chlorophyll content, limit assimilation, and a decrease in dry matter accumulation (Jia et al., 2018; Xu, 2018). Plant densities that maximize WMP forage production range widely from 45,000–125,000 plants ha$^{-1}$ in different regions (Karahan, 2014; Mandić et al., 2015; Stanton, Grombacher, Pinnisch, Mason, & Spaner, 2007). Optimizing plant population by establishing a better canopy structure is an effective way to obtain a high WMP forage yield.

Increasing the plant density may be negatively correlated to silage quality (Liu, Guo, Jia, & Yin, 2018; Mandić et al., 2015; Saponjic et al., 2014; Stanton et al., 2007; Sun, 2017; Wang et al., 2019). Using a higher plant density significantly reduces crude protein (CP), crude fat (CFa), and N free extract (NFE) content of WMP forage, but it increases its crude fiber (CFi), neutral-detergent fiber (NDF), and acid-detergent fiber (ADF) content, resulting in reduced palatability and energy digestibility (Dragičević et al., 2016; Mandić et al., 2015; Saponjic et al., 2014; Stanton et al., 2007). Lowering WMP forage quality decreases the production efficiency and feeding quality (Cusicanqui & Lauer, 1999; Dragičević et al., 2016; Stanton et al., 2007). As plant density increases, anabatic inter-plant competition decreases photosynthetic production assimilation, as well as energy and nutrients accumulation, which causes an increase in the weight of the vegetative organ (leaves and stem), but reduced grain proportion (Li, 2018; Sun, 2017). In turn, this leads to an increased CFi, ash, ADF, and NDF content, and reduces CP, CFa, and NFE content, thus reducing the WMP forage quality (Qiao et al., 2018; Yu, Chen, Bi, & Shao, 2018).

All in all, increasing the plant density to an appropriate level is an efficient way to improve WMP forage biomass yield, but it lowers WMP forage quality. Determining the optimal plant density involves a trade-off between WMP forage yield and its quality. Previous research on the effect of plant density on WMP forage production focused solely on either biomass yield or forage quality. However, to maximize the utilizable energy yield and productivity of WMP forage, biomass yield should be considered in conjunction with maize quality. Therefore, a 2-yr field study was carried out to (a) measure the effect of plant densities on forage maize plant growth (i.e., plant character, leaf area index, and leaf chlorophyll content), biomass yield, WMP forage quality, and forage feeding quality; (b) to determine the optimal plant density with respect to both the biomass yield and the WMP forage feeding quality; and (c) to confirm whether biomass yield or energy yield is more efficient for the purpose of evaluating the productivity of WMP forage.

### 2 MATERIALS AND METHODS

#### 2.1 Study site

Field experiments were conducted in 2017 and 2018 at the Shandong Agriculture University Farm Station in Taian, Shandong Province, China (E117°15′82″, N36°16′59″), which has a temperate continental sub-humid monsoon climate. Precipitation values were obtained from the Taian Meteorological Station, which is located at the Shandong Agriculture University Farm Station (Table 1). The soil at the study site is a clay loam, classified as fine, montmorillonitic, frigid Mollic Cryoboralf, with a slope of <1%. The soil’s physico-chemical properties are: pH 7.7, 1.68 g kg$^{-1}$ total N, 37.82 mg

### TABLE 1 Monthly precipitation amounts (mm) during the 2017 and 2018 summer maize growing seasons

| Year | June | July | Aug. | Sept. | Total |
|------|------|------|------|-------|-------|
| 2017 | 57.2 | 236.8 | 75.2 | 31.4 | 400.6 |
| 2018 | 85.7 | 36.7 | 264.6 | 74.8 | 461.8 |

*Precipitation amount with different growing stages, sowing–V6, V6–VT, and VT–R6 was 96.1, 224.7, and 79.8 mm in 2017, and 98.9, 119.4, and 243.5 mm in 2018.*
kg\(^{-1}\) NO\(_3^-\)–N, 4.25 mg kg\(^{-1}\) NH\(_4^-\)–N, 9.31 mg kg\(^{-1}\) available P, 89.63 mg kg\(^{-1}\) available K, 15.00 g kg\(^{-1}\) organic matter, 12.85% soil available water (field capacity minus permanent wilting point), and 1.25 g cm\(^{-3}\) soil bulk density.

### 2.2 Experimental design and management

Forage maize ‘Siyu 2’ (117-d growing period, semi-compact plant type, great resistance to stem rot and large spot, and harvest at dent stage when the moisture content of the whole stage reaches 66%), was used as experimental material. The prior crop was winter wheat (Triticum aestivum L.), rotary tillage with 20-cm depth was carried out for field preparation before sowing, and 220 N kg\(^{-1}\) N fertilizer (urea, 46.4% N) was applied as base fertilizer, which is the locally recommended rate for maize production (Shi et al., 2016). The experimental design was a randomized complete block design including five plant density treatments (52,500, 60,000, 67,500, 75,000, and 82,500 plants ha\(^{-1}\)) with three replications. Therefore, 15 plots (6 by 6 m), with 10 rows of maize in each plot (60-cm row spacing), were arranged randomly in three blocks. As measured along a row, plant spacing was 31.7, 27.8, 24.7, 22.2, or 20.2 cm, corresponding to a plant density of 52,500, 60,000, 67,500, 75,000, and 82,500 plants ha\(^{-1}\), respectively. Plots were kept free of weeds, insects, and diseases. In 2017 and 2018, the sowing dates were 10 June and 13 June, respectively.

### 2.3 Sampling and lab analysis

Prior to planting and fertilizing, soil samples were collected from the top 0- to 20-cm layer in each plot with an open-faced 6-cm diameter bucket probe (n = 5) and used to analyze the soil’s physicochemical properties. For the purpose of determining the soil’s moisture and NO\(_3^-\)–N content, additional soil samples were collected up to a depth of 100 cm (from five consecutive 20-cm sections) with a 3-cm tube probe before sowing and at the maize dent stage (40 d after silking). Fresh soil samples were analyzed for NO\(_3^-\)–N content (Alpkem, Clackamas, & Alpkem, 1986), and pH (1:1 soil/water; Warncke & Brown, 1998). Air-dried soil samples were sieved (0.5 mm) to analyze total N, total P, and organic matter content. The total N content was analyzed using the semimicro-Kjeldahl procedure (Bremner, 1996). The extractable P content was determined using the phosphomolybdate reduction method (Frank, Beegle, & Denning, 1998). The extractable K content was determined using an Atomic Absorption Spectrometer (ICE 3500, Thermo Fisher Scientific, Waltham, MA; Watson & Brown, 1998). The organic matter content was determined by the Walkley–Black method (Combs & Nathan, 1998). The soil moisture content was determined using an oven (105°C for 24 h). The bulk density was determined by analyzing a 5-cm diameter intact core (Blake & Hartge, 1986), and the field capacity was obtained using the Wilcox method (Marshall & Holmes, 1988).

When the maize grain reached the dent stage (20 Sept. 2017 and 20 Sept. 2018, 40 d after silking; Wiersma, Carter, Albrecht, & Coors, 1993), the plant height, ear height, stem diameter, and leaf area were measured (n = 10) using the methods proposed by Ren (2017). Ear leaves (n = 5) were collected to determine leaf chlorophyll using the method proposed by Kong (2008). For each treatment, five consecutive whole plants were sampled, weighed, chopped, and mixed evenly. One kg of mixed subsample was dried at 105°C for 30 min and then at 75°C for 7 d, and subsequently retained for quality analysis. The CP level was calculated by multiplying the total Kjeldahl N by 6.25 (Bremner & Breitenbeck, 1983). The CFa, CFi, and ash content were determined using the standard accredited methods (Wang, 2011). The NFE was calculated using the method proposed by Wang (2011), which was based on the dry matter, CP, CFa, CFi, and ash content. The NDF and ADF content was determined using the procedure proposed by Robertson and Van Soest (1981). The plant N accumulation was determined by multiplying the total N content by the biomass production (Bremner, 1996).

### 2.4 Cited equations

The relative feeding value (RFV), gross energy (GE), net energy for lactating (NE\(_L\)) cow (Bos taurus), total NE\(_L\), energy digestibility (ED), grading index (GI), evapotranspiration (ET), water use efficiency (WUE), and nitrogen use efficiency (NUE) are defined by following equations (Fang, 2004; Feng, 2006; Han, 2013; Jiang, et al., 2018; Ren, Dong, Zhao, Liu, & Zhang, 2017a; Ren, et al., 2017b; Zhang, 2003):

\[
RFV = (120/NDF)(88.9 - 0.779 ADF) \text{100%} \quad (1)
\]

where NDF (%) is the proportion of NDF in DM and ADF (%) is the proportion of ADF in DM.

\[
GE (MJ/kg DM) = 0.2393CP + 0.3975CFa + 0.2004CFi + 0.1688NFE. \quad (2)
\]

where CP (%) is the proportion of crude protein in DM, CFa (%) is the proportion of crude fat in DM, CFi is the proportion of crude fiber in DM, and NFE is the proportion of N free extract in DM.

\[
NE_L (MJ/kg DM) = (0.5501GE)(ED) - 0.3958 \quad (3)
\]
where GE is the gross energy, and ED is the energy digestibility.

$$\text{Total NE}_L (\text{GJ ha}^{-1}) = \text{NE}_L \text{DM}$$ (4)

where NE$_L$ is the net energy for lactating cow and DM is the dry matter content.

$$\text{ED} (\%) = 94.2808 - 61.5370 \left[ \frac{\text{NDF}}{100 - \text{ash}} \right]$$ (5)

where NDF (%) is the proportion of NDF in DM and ash (%) is the proportion of ash in DM.

$$\text{GI} (\text{MJ/kgDM}) = \left[ \frac{\text{NE}_L (120/\text{NDF}) \text{CP}}{\text{NDF}} \right]$$ (6)

where NDF (%) is the proportion of NDF in DM and CP (%) is the proportion of crude protein in DM.

$$\text{NUE (kg kg}^{-1} \text{N}) = \frac{\text{Y}}{\text{NU}}$$ (7)

where Y is the grain yield, and NU is the nitrogen uptake.

$$\text{ET} (\text{mm}) = \Delta W + \text{Irr} + \text{Pr} - (R + D)$$ (8)

where ET is evapotranspiration, ΔW is the soil water consumption with in the top 0–100-cm layer of soil, Irr is irrigation, Pr is growing season precipitation, R is runoff, and D is deep drainage. In the study, irrigation was 0 mm; R is taken to be 0 mm, due to the field slope being shallow (<1%), which prevented runoff; and D was taken to be 0 because the soil was very deep.

$$\text{WUE (kg mm}^{-1} \text{ha}^{-1}) = \frac{\text{GY}}{\text{ET}}$$ (9)

where GY is the grain yield or dry matter; ET is the evapotranspiration.

2.5 | Data analysis

To test for correlations between the observed data and plant density, an analysis of variance (ANOVA) approach implemented through SAS 8.1 was used. Differences between treatments were determined using Tukey tests (fixed range method; P < .05).

3 | RESULTS

3.1 | Maize plant characteristics

Plant density significantly affected leaf area, leaf area index, leaf chlorophyll content, plant height, ear height, and stem diameter (P < .05; Table 2). Across the various plant densities, the leaf areas ranged from 6425.7 to 7212.0 cm$^2$ plant$^{-1}$ in 2017, and from 6501.3–7827.3 cm$^2$ plant$^{-1}$ in 2018, while the leaf area index ranged from 4.0 to 5.3 in 2017, and from 4.1 to 5.4 in 2018 (Table 2). Leaf chlorophyll content was also influenced by plant density, ranging from 15.2 to 18.2% in 2017, and from 16.1 to 18.5% in 2018 (Table 2). The highest plant and ear heights were observed for the highest plant density (82,500 plants ha$^{-1}$), while the greatest stem diameter was observed for the lowest plant density (52,500 plants ha$^{-1}$; Table 2). When the plant density was increased from 52,500 to 82,500 plants ha$^{-1}$, the leaf area per plant and the leaf chlorophyll content were reduced by 16–17% and by 13–17%, respectively, but the leaf area index increased by more than 30%. Clearly, the plant and ear height are proportional to the plant density, but the stem diameter is inversely proportional to the plant density (Table 2). Except for the plant height, plant characteristics differed significantly between the two years during which the experiment was conducted (P < .05; Table 2).

3.2 | Biomass yield

Plant density had a significant effect on fresh matter, DM, and plant water content (P < .01; Table 3). Across the various plant density treatments applied, fresh matter ranged from 30,283 to 44,830 kg ha$^{-1}$ in 2017 and from 30,316 to 44,110 kg ha$^{-1}$ in 2018, while dry matter ranged from 12,699 to 17,734 kg ha$^{-1}$ in 2018, and from 12,601 to 17,055 kg ha$^{-1}$ in 2018 (Table 3). The greatest biomass yield for both fresh and dry matter was observed for 75,000 plants ha$^{-1}$ treatment, and the lowest biomass yield was obtained in the 52,500 plants ha$^{-1}$ treatment (Table 3). Increasing the plant population from 75,000 to 82,500 plants ha$^{-1}$ reduced biomass yields. The water content of WMP ranged from 58.1 to 62.1% in 2017 and from 58.4 to 62.7% in 2018. During the 2-yr experiment, the highest WMP water content was observed at the highest plant density of 82,500 plants ha$^{-1}$. The interannual difference was not significant for fresh matter and DM (P > .05) but was significant for plant water content (P < .05; Table 3). There was no significant interaction between Year and Treatment for fresh matter, DM, and plant water content (P > .05; Table 3).

3.3 | Forage quality of the whole maize plant

Forage quality items, that is, CP, CFa, CFi, NFE, ash, ADF, and NDF, had similar tendencies in both years. Plant density had a significant influence on both the proportion and yield
### Table 2: Maize leaf area, leaf area index, chlorophyll, plant height, ear height, and stem diameter in 2017 and 2018

| Plant density plants ha$^{-1}$ | Leaf area 2017 (cm$^2$ plant$^{-1}$) | Leaf area index 2017 (m$^2$ m$^{-2}$) | Chlorophyll content 2017 (%) | Plant height 2017 (cm) | Ear height 2017 (cm) | Stem diameter 2017 (mm) | Leaf area 2018 (cm$^2$ plant$^{-1}$) | Leaf area index 2018 (m$^2$ m$^{-2}$) | Chlorophyll content 2018 (%) | Plant height 2018 (cm) | Ear height 2018 (cm) | Stem diameter 2018 (mm) |
|-------------------------------|--------------------------------------|--------------------------------------|-------------------------------|------------------------|---------------------|------------------------|--------------------------------------|--------------------------------------|-------------------------------|------------------------|---------------------|------------------------|
| 52,500                        | 7,612.0a                            | 7,827.3a                            | 18.2a                         | 291.7d                 | 123.0d              | 3.6a                   | 7,612.0a                            | 7,827.3a                            | 18.2a                         | 291.7d                 | 123.0d              | 3.6a                   |
| 60,000                        | 7,398.3ab                           | 7,454.7b                            | 16.9b                         | 309.3c                 | 133.3c              | 3.2b                   | 7,398.3ab                           | 7,454.7b                            | 16.9b                         | 309.3c                 | 133.3c              | 3.2b                   |
| 67,500                        | 7,182.3bc                           | 7,329.0b                            | 16.7bc                        | 320.0bc                | 137.7bc             | 2.9c                   | 7,182.3bc                           | 7,329.0b                            | 16.7bc                        | 320.0bc                | 137.7bc             | 2.9c                   |
| 75,000                        | 6,906.3c                            | 7,049.7c                            | 15.7cd                        | 329.0ab                | 140.3b              | 2.7c                   | 6,906.3c                            | 7,049.7c                            | 15.7cd                        | 329.0ab                | 140.3b              | 2.7c                   |
| 82,500                        | 6,425.7d                            | 6,501.3d                            | 15.2d                         | 334.7a                 | 147.7a              | 2.5d                   | 6,425.7d                            | 6,501.3d                            | 15.2d                         | 334.7a                 | 147.7a              | 2.5d                   |

*Means within a column in the same growing season followed by the different letter are not significantly different at $p < .05$. Year $P$-value, Treat $P$-value, Year $\times$ Treat $P$-value.

### Table 3: Maize fresh matter, dry matter, and plant water content in 2017 and 2018

| Plant density plants ha$^{-1}$ | Fresh matter 2017 (kg ha$^{-1}$) | Fresh matter 2018 (kg ha$^{-1}$) | Dry matter 2017 (kg ha$^{-1}$) | Dry matter 2018 (kg ha$^{-1}$) | Plant water content 2017 (%) | Plant water content 2018 (%) |
|--------------------------------|-----------------------------------|-----------------------------------|--------------------------------|--------------------------------|-----------------------------|-----------------------------|
| 52,500                        | 30,283c                           | 30,316c                           | 12,699c                        | 12,601c                        | 58.1c                       | 58.4c                       |
| 60,000                        | 32,753c                           | 32,106c                           | 13,498c                        | 13,158c                        | 58.8c                       | 59.0c                       |
| 67,500                        | 39,235b                           | 39,935b                           | 15,813b                        | 15,869b                        | 59.7bc                      | 60.3bc                      |
| 75,000                        | 44,830a                           | 44,110a                           | 17,734a                        | 17,055a                        | 60.4b                       | 61.3b                       |
| 82,500                        | 42,047ab                          | 42,940ab                          | 15,931b                        | 16,009b                        | 62.1a                       | 62.7a                       |

*Means within a column followed by the different letter are not significantly different at $p < .05$. Year $P$-value, Treat $P$-value, Year $\times$ Treat $P$-value.

of CP, CFa, CFi, NFE, ash, ADF, and NDF ($P < .05$; Table 4). When plant density was increased from 52,500 to 82,500 plants ha$^{-1}$, the CP, CFa, and NFE content was reduced by 17–18%, 10–13%, and 7–8%, respectively, while the CFi, ash, ADF, and NDF content increased 25–26%, 28–43%, 12–16%, and 10–11%, respectively (Table 4). Increasing the plant density reduced the CP, CFa, and NFE content, but improved the CFi, ash, ADF, and NDF content. With increasing plant density, the yields of CP, CFa, CFi, NFE, ash, ADF, and NDF increased initially, then peaked at 75,000 plants ha$^{-1}$, and decreased slightly thereafter (CP, CFa, and NFE) or remained stable (CFi, ash, ADF, and NDF). The highest yield for CP, CFa, and NFE was observed for a plant density of 75,000 plants ha$^{-1}$, while the highest yields for CFi, ash, ADF, and NDF was found for plant densities of 75,000 and 82,500 plants ha$^{-1}$ (Table 4). The interannual differences varied across forage quality aspects. Significant interannual difference was determined for the content of CFi, NFE, ADF, and NDF, and the yield of CFi and NFE ($P < .05$), but not for other aspects ($P > .05$; Table 4). The interaction between Year and Treatment was only observed for the ADF and NDF content ($P < .05$; Table 4).

#### 3.4 Feeding characters of the whole maize plant

The feeding characteristic of forage maize, including GE, ED, NE$_L$, RFV, and GI, were significantly influenced by the plant density in the two growing seasons during which the experiment was conducted ($P < .05$; Table 5). In both years, GE, ED, NE$_L$, RFV, and GI were highest for a plant density of...
**Table 4** Crude protein, crude fat, crude fiber, N free extract, ash, acid detergent fiber (ADF), and neutral detergent fiber (NDF) for the whole maize plant in 2017 and 2018

|            | Plant density plants ha\(^{-1}\) | Crude Protein kg ha\(^{-1}\) | % DM\(^{\text{a}}\) | Crude Fat kg ha\(^{-1}\) | % DM\(^{\text{a}}\) | Crude Fiber kg ha\(^{-1}\) | % DM\(^{\text{a}}\) | N Free Extract kg ha\(^{-1}\) | % DM\(^{\text{a}}\) | Ash kg ha\(^{-1}\) | % DM\(^{\text{a}}\) | ADF kg ha\(^{-1}\) | % DM\(^{\text{a}}\) | NDF kg ha\(^{-1}\) | % DM\(^{\text{a}}\) |
|------------|----------------------------------|-----------------------------|---------------------|--------------------------|---------------------|-----------------------------|---------------------|----------------------------|---------------------|----------------|-----------------|----------------|----------------|----------------|----------------|
| **2017**   |                                  |                             |                     |                          |                     |                             |                     |                            |                     |                 |                 |                 |                 |                 |                 |
| 52,500     | 1.143.0b\(^{\text{b}}\)         | 9.0a                        | 4.94.5c             | 3.9a                     | 2.414.6c            | 19.0d                      | 8.107.2c            | 63.9a                     | 3.95d               | 2.414.6c         | 19.0d            | 5.748.6c        | 24.2d          | 5.748.6c        | 24.2d          |
| 60,000     | 1.180.5b                         | 8.7a                        | 5.13.3c             | 3.8ab                    | 2.718.5c            | 20.1cd                     | 8.474.3c            | 62.8ab                    | 6.11.0c             | 4.5bc             | 3.308.7c        | 24.5cd          | 6.305.1c        | 46.7c          |
| 67,500     | 1.371.2a                         | 8.7a                        | 5.89.9ab            | 3.7bc                    | 3.369.0b            | 21.3bc                     | 9.722.4ab           | 61.5bc                    | 7.60.1b             | 4.8b              | 3.948.4b        | 25.0c           | 7.476.5b        | 47.3bc         |
| 75,000     | 1.449.5a                         | 8.2b                        | 6.39.4a             | 3.6c                     | 3.938.0a            | 22.2ab                     | 10.758.2a           | 60.7cd                    | 9.48.6a             | 5.4a              | 4.587.3a        | 25.9b           | 8.529.5a        | 48.1b          |
| 82,500     | 1.214.1b                         | 7.6c                        | 5.44.7b             | 3.4d                     | 3.786.2a            | 23.8a                     | 9.502.5b             | 59.6d                     | 8.83.4ab             | 5.5a              | 4.327.5ab       | 27.2a           | 7.917.3ab       | 49.7a          |
| 2018       |                                  |                             |                     |                          |                     |                             |                     |                            |                     |                 |                 |                 |                 |                 |                 |
| 52,500     | 1.141.3b                         | 9.1a                        | 4.89.2c             | 3.9a                     | 2.516.4c            | 20.0d                     | 7.955.8c             | 63.1a                     | 4.982.2d            | 4.0d              | 3.031.6d        | 24.1c           | 5.911.8c        | 46.9d          |
| 60,000     | 1.166.1b                         | 8.9b                        | 5.01.0c             | 3.8a                     | 2.806.8c            | 21.3c                     | 8.093.2c             | 61.5b                     | 5.91.1c             | 4.5c              | 3.376.6c        | 25.7b           | 6.253.7c        | 47.5cd         |
| 67,500     | 1.345.9a                         | 8.5bc                       | 5.90.4ab            | 3.7ab                    | 3.665.6b            | 23.1b                     | 9.492.9b             | 59.8c                     | 7.74.4b             | 4.9bc             | 4.095.3b        | 25.8b           | 7.705.3b        | 48.6c          |
| 75,000     | 1.394.5a                         | 8.2c                        | 6.23.7a             | 3.7ab                    | 4.062.5a            | 23.8b                     | 10.072.9a            | 59.1cd                    | 9.01.7a             | 5.3ab             | 4.458.3a        | 26.1b           | 8.532.1a        | 50.0b          |
| 82,500     | 1.201.2b                         | 7.5d                        | 5.52.4b             | 3.5b                     | 4.015.8a            | 25.1a                     | 9.328.3b             | 58.3d                     | 9.11.5a             | 5.7a              | 4.461.3a        | 27.9a           | 8.359.0a        | 52.2a          |
| **Year (P-value)** | .09 | .59 | .52 | .70 | .01 | .00 | .00 | .00 | .00 | .20 | .55 | .50 | .00 | .11 | .00 |
| **Treat (P-value)** | .00 | .00 | .00 | .00 | .00 | .00 | .00 | .00 | .00 | .00 | .00 | .00 | .00 | .00 | .00 |
| **Year × Treat (P-value)** | .71 | .42 | .87 | .96 | .73 | .75 | .59 | .49 | .10 | .19 | .41 | .02 | .51 | .05 | .05 |

\(^{\text{a}}\)DM, dry matter.

\(^{\text{b}}\)Means within a column in the same growing season followed by the different letter are not significantly different at \(p < .05\).
Forage gross energy (GE), energy digestibility (ED), net energy for lactation (NE\textsubscript{L}), relative feeding value (RFV) and grading index (GI) for the whole maize plant in 2017 and 2018. DM, dry matter

| Plant density plants ha\(^{-1}\) | GE MJ kg\(^{-1}\) DM\(^{-1}\) | ED % | NE\textsubscript{L} MJ kg\(^{-1}\) DM\(^{-1}\) | Total NE\textsubscript{L} GJ ha\(^{-1}\) | RFV | GI MJ kg\(^{-1}\) DM\(^{-1}\) |
|-------------------------------|------------------|-----|-----------------|-----------------|-----|------------------|
| 2017                          |                  |     |                 |                 |     |                  |
| 52,500 plants ha\(^{-1}\)     | 18.3a            | 65.2a | 6.2a            | 78.3d           | 144.0a | 3.3a            |
| 60,000 plants ha\(^{-1}\)     | 18.2ab           | 64.2b | 6.0b            | 81.6cd          | 139.0b | 2.9b            |
| 67,500 plants ha\(^{-1}\)     | 18.2b            | 63.7bc | 6.0b            | 94.6ab          | 136.6b | 2.8b            |
| 75,000 plants ha\(^{-1}\)     | 18.1c            | 63.0c  | 5.9c            | 104.1a          | 132.9c | 2.5c            |
| 82,500 plants ha\(^{-1}\)     | 18.0c            | 61.9d  | 5.7d            | 91.4bc          | 126.8d | 2.1d            |
| 2018                          |                  |     |                 |                 |     |                  |
| 52,500 plants ha\(^{-1}\)     | 18.4a            | 64.2a  | 6.1a            | 76.8c           | 139.1a | 3.0a            |
| 60,000 plants ha\(^{-1}\)     | 18.3ab           | 63.7ab | 6.0a            | 79.1c           | 134.9b | 2.8b            |
| 67,500 plants ha\(^{-1}\)     | 18.2bc           | 62.9b  | 5.9b            | 93.8ab          | 131.8b | 2.6c            |
| 75,000 plants ha\(^{-1}\)     | 18.2c            | 61.8c  | 5.8c            | 97.0a           | 127.5c | 2.3d            |
| 82,500 plants ha\(^{-1}\)     | 18.0d            | 60.2d  | 5.6d            | 89.3b           | 119.7d | 1.8e            |

Year (\(P\)-value) .00 .00 .00 .03 .00 .00
Treat (\(P\)-value) .00 .00 .00 .00 .00 .00
Year \times Treat (\(P\)-value) .37 .03 .04 .48 .41 .20

*Means within a column in the same growing season followed by the different letter are not significantly different at \(p < .05\).

52,500 plants ha\(^{-1}\), and lowest for a plant density of 82,500 plants ha\(^{-1}\). Increasing plant density consistently reduced GE, ED, NE\textsubscript{L}, RFV, and GI (Table 5). The total NE\textsubscript{L} ranged from 78.3 to 104.1 GJ ha\(^{-1}\) in 2017, and from 76.8 to 97.0 GJ ha\(^{-1}\) in 2018 (Table 5). When plant density was increased, the total NE\textsubscript{L} initially increased, then peaked for plant densities of 67,500 and 75,000 plants ha\(^{-1}\) and decreased for a plant density of 82,500 plants ha\(^{-1}\). The total NE\textsubscript{L} for a plant density of 75,000 plants ha\(^{-1}\) was about 4–10% higher than that for a plant density of 67,500 plants ha\(^{-1}\), but no significant difference was detected. The feeding characteristics of WMP forage differed significantly between the two years (\(P > .05\); Table 5). For the same plant density, the GI of WMP forage in 2017 was 4–16% higher than in 2018. A significant interaction between Year and Treatment was detected for ED and NE\textsubscript{L} (\(P < .05\)), but not for GE, RFV, and GI (\(P > .05\); Table 5).

### 3.5 Nitrogen and water use

The plant density significantly affected N uptake, NUE, ET, and WUE (\(P < .05\); Table 6). Across all plant density treatments, N uptake varied from 188.5 to 244.0 kg N ha\(^{-1}\) in 2017, and from 186.9 to 238.8 kg N ha\(^{-1}\) in 2018 (Table 6). When plant density was increased, N uptake was increased significantly, but then remained stable for plant densities between 75,000 and 82,500 plants ha\(^{-1}\) in 2017, and for plant densities between 67,500 and 82,500 plants ha\(^{-1}\) in 2018 (Table 6). The lowest NUE was observed for a plant density of 60,000 plants ha\(^{-1}\), while the highest NUE was observed for plant densities of 67,500, 75,000, and 82,500 plants ha\(^{-1}\) (Table 6).

For all treatments, ET ranged from 369.3 to 395.0 mm in 2017, and ranged from 415.5 to 426.8 mm in 2018 (Table 6). For the same plant density, ET in 2018 was 8–13% higher than in 2017. A higher plant density tended to increase ET in both growing seasons. The lowest WUE was observed on 52,500 and 60,000 plants ha\(^{-1}\). The highest WUE was observed for plant densities of 67,500 and 75,000 plants ha\(^{-1}\) in 2017, and for 75,000 plants ha\(^{-1}\) in 2018 (Table 6). With increasing plants density, WUE increased from 52,500 to 75,000 plants ha\(^{-1}\), but decreased at the highest plant density of 82,500 plant ha\(^{-1}\). No significant interannual difference was found for N uptake or NUE (\(P > .05\)), but significant

### TABLE 6 Plant intensity, dry matter (DM), total net energy for lactation (NE\textsubscript{L}), and grading index (GI) at the maximum predicted DM yield or maximum predicted total NE\textsubscript{L} yield

| Plant density, plants ha\(^{-1}\) | Maximum predicted DM yield | Maximum predicted total NE\textsubscript{L} yield |
|---------------------------------|-----------------|-----------------|
| 2017                            | 2018            | 2017            | 2018            |
| 77,511                          | 79,368          | 74,750          | 74,664          |
| 16,636                          | 16,455          | 16,582          | 16,322          |
| 97.2                            | 92.9            | 97.6            | 93.8            |
| 2.36                            | 2.04            | 2.46            | 2.22            |
differences were found for ET and WUE \((P < .05; \text{Table 6})\). The interaction between Year and Treat was only determined for ET \((P < .05; \text{Table 6})\).

### 3.6 Optimizing the plant density for productivity

The observed data was fitted to a statistical model to evaluate the effect of plant density on DM biomass yield, total NE\(_L\), and GI. The regression equations for maize DM yield, total NE\(_L\), and GI in 2017 and 2018 were achieved as shown in Equations (10–15):

\[
Y = -0.00000711x^2 + 1.1022x - 26080 \quad (10)
\]

\[
Y = -0.00000601x^2 + 0.9540x - 21403 \quad (11)
\]

\[
Y = -0.000000452x^2 + 0.0067574x - 154.97 \quad (12)
\]

\[
Y = -0.000000400x^2 + 0.0059731x - 129.19 \quad (13)
\]

\[
Y = -0.000356x + 5.1195 \quad (14)
\]

\[
Y = -0.000387x + 5.1090 \quad (15)
\]

where \(Y\) is the estimated DM biomass yield (Equations 10–11 for 2017–2018), total NE\(_L\) (Equations 10–11 for 2017–2018), or GI (Equations 10–11 for 2017–2018), and \(x\) is the plant density. The \(r^2\) values for Equations 10–15 are as follows: .7682 (10), .8445 (11), .6860 (12), .7538 (13), .9422 (14), .9666 (15).

The regression Equations (10–15) proved effective for predicting the effect of plant density on DM biomass yield, total NE\(_L\), and GI for the two years during which the experiment was conducted, as indicated by the \(r^2\) values in the regression equations ranging from .69 to .84 \((P < .01)\). The response line for the effect of the plant density on DM biomass yield and total NE\(_L\) shows similar parabolic tendencies (Figures 1, 2). With increasing plant density, both DM biomass yield and total NE\(_L\) increased, peaked, and then decreased (Figure 2). According to the Equations 10 and 11, the predicted maximum DM biomass yield was 16,636 kg ha\(^{-1}\) in 2017 for a plant density of 77,511 plants ha\(^{-1}\), and 16,455 kg ha\(^{-1}\) in 2018 for a plant density of 79,368 plants ha\(^{-1}\). According to Equations 12 and 13, the predicted maximum total NE\(_L\) was 97.6 GJ ha\(^{-1}\) in 2017 for a plant density of 74,750 plants ha\(^{-1}\), and 93.8 GJ ha\(^{-1}\) in 2018 for a plant density of 74,664 plants ha\(^{-1}\). For the two years, the optimal plant density with

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**FIGURE 1** Biomass yield (dry matter) regression depending on maize plant density in 2017 and 2018

**FIGURE 2** Total net energy for lactation (NE\(_L\)) regression depending on maize plant density in 2017 and 2018
highest total NE_L was 4–6% lower than the plant density with the greatest DM biomass yield (Table 7). Compared with the plant density that maximized the biomass yield, the optimal plant density for the highest total NE_L reduced the DM yield by about 1%, but increased the total NE_L and GI by about 1% and 4–9%, respectively (Table 7).

4 | DISCUSSION

Maize production is a function of the biomass per plant and the plant density. Increasing the plant density is used as an efficient management tool for improving maize production (Yan et al., 2017). Increasing yield by increasing plant density hinges on the mechanism that a higher plant density improves light interception and photosynthetic accumulation per hectare (Jia et al., 2018; Zhang et al., 2018). However, even with sufficient water and nutrients, light can limit yields (Amanullah & Shad, 2009; Wang et al., 2019). Our study confirms the intensification of inter-plant competition due to increased plant density. With increasing plant density, plant ear height increased significantly (Table 2), which agrees with Karaşahin (2014), Mandić et al. (2015), and Wang et al. (2019). This suggested that maize plants grow higher to obtain more light as a means to combat low-light stress within a maize population (Mandić et al., 2015). A great plant height limits the extent of the plant stem diameter, and causes maize plants to become slender, so that assimilation and dry matter accumulation might be affected (Wang et al., 2019). Inter-plant competition for resources was increased for high plant densities, and maize photosynthesis was reduced, ultimately causing a reduction in plant stem diameter (Liu et al., 2018; Qiao et al., 2018). Increasing the plant density reduced leaf chlorophyll content and leaf area per plant (Table 2), resulting in a reduced photosynthesis rate. Wang et al. (2019) reported that increasing the plant density reduces the stay-green ability of silage maize, thereby decreasing photosynthesis levels and yield per plant. Notwithstanding these findings, our study showed that increasing the plant density significantly increases the leaf area index (Table 3). An increased leaf area index achieves more light interception and photosynthetic assimilation per unit land area, thus increasing maize biomass yield (Andrade et al., 1999; Jia et al., 2018; Xu, 2018).

According to our results, the biomass yield related to fresh and dry matter shows an upward trend as plant density increases. However, when plant density increased from 75,000 to 82,500 plants ha\(^{-1}\), the biomass yield neither increased nor decreased (Table 3). This limiting effect on the biomass yield should be attributed to the intense inter-plant competition (Jia et al., 2018; Zhang et al., 2018). When the plant density exceeds optimal value, intraspecific competition passively affects the transformation and assimilation of nutrients, thereby limiting any gains in crop productivity, and resulting in reduced yield (Boomsma, Santini, Tollenaar, & Vyn, 2009; Ferreira et al., 2014; Qiang et al., 2019). Furthermore, with increasing plant density, the plant water content increases and the proportion of dry matter decreases (Table 3), in agreement with Dragičević et al. (2016), Qiao et al. (2018) and Saponjic et al. (2014). This suggested that intensive plant density causes delayed maturity, as well as a reduced matter concentration and dry matter yield at harvest time (Baron, Najda, & Stevenson, 2006; Stanton et al., 2007; Wang et al., 2019). A similar phenomenon was shown by our regression equations (Figures 1, 2). In both years, the regression equations show that the biomass yield for dry matter had a parabolic tendency as plant density increased.

### Table 7

Maize N uptake, nitrogen use efficiency (NUE), evapotranspiration (ET), and water use efficiency (WUE) in 2017 and 2018

| Plant density plants ha\(^{-1}\) | N uptake kg N ha\(^{-1}\) | NUE kg kg\(^{-1}\) N\(^{-1}\) | ET mm | WUE kg ha\(^{-1}\) mm\(^{-1}\) |
|-------------------------------|-----------------|-----------------|------|-----------------|
| 2017                          |                 |                 |      |                 |
| 52,500                        | 188.5d          | 67.3bc          | 369.3c| 34.4d           |
| 60,000                        | 211.5c          | 63.8c           | 375.6c| 35.9cd          |
| 67,500                        | 226.2b          | 69.9ab          | 384.3b| 41.1ab          |
| 75,000                        | 244.0a          | 72.7a           | 388.4ab| 45.7a           |
| 82,500                        | 230.5ab         | 69.1ab          | 395.0a| 40.3bc          |
| 2018                          |                 |                 |      |                 |
| 52,500                        | 186.9c          | 67.4b           | 416.5c| 30.3c           |
| 60,000                        | 213.2b          | 61.7c           | 415.5c| 31.7c           |
| 67,500                        | 229.1a          | 69.3ab          | 419.1bc| 37.9b           |
| 75,000                        | 238.8a          | 70.3ab          | 422.9ab| 39.7a           |
| 82,500                        | 224.3ab         | 71.4a           | 426.8a| 37.5b           |
| Year (P-value)                | .42             | .33             | .00  | .00             |
| Treat (P-value)               | .00             | .00             | .00  | .00             |
| Year × Treat (P-value)        | .55             | .08             | .00  | .45             |

*Means within a column in the same growing season followed by the different letter are not significantly different at p < .05.*
(Figure 1). The predicted maximum biomass yields were 16,636 kg ha\(^{-1}\) in 2017 for a plant density of 77,511 plants ha\(^{-1}\), and 16,455 kg ha\(^{-1}\) in 2018 for a plant density of 79,368 plants ha\(^{-1}\). Saponjic et al. (2014) reported that the biomass yield was maximized at 68,000–74,000 plants ha\(^{-1}\) in various soil types, and that intensive plant densities tended to reduce maize biomass yield slightly. Optimal plant densities for biomass yield varied widely from 45,000–125,000 plants ha\(^{-1}\), depending on the growing region (Stanton et al., 2007).

In the present study, the concept behind increasing the plant density was to improve WMP forage yield. As plant density increased, the leaf area per unit land area increased, which results in more water consumption and an increased ET (Jia et al., 2018; Ogola, 1999). The rainfall at the study site ranged from 400.6 to 461.8 mm (Table 1), which meets the physiological needs of maize. In our study, increasing ET generally increased the WUE (Table 4). For plant densities higher than 75,000 plants ha\(^{-1}\), increasing the plant density still increased the ET, but the higher water consumption could not contribute to a higher biomass yield.

Our results showed that increasing the plant density increased the N uptake, but the N uptake did not increased for densities higher than 75,000 plants ha\(^{-1}\). An intensive plant density might lead to N deficiency and low assimilation efficiency, especially at the milking stage, which limits the N uptake (Han et al., 2016). Over the two years of our study, a plant density of 75,000 plants ha\(^{-1}\) achieved the highest biomass yield, N uptake, NUE, and WUE.

Plant density is an important factor not only for WMP forage yield, but also for WMP forage quality (Dragičević et al., 2016; Gallego-Giraldo et al., 2016; Wang et al., 2019). Crude protein, CFa, NFE, CFi, ash, ADF, and NDF are important factors for WMP forage quality, and their proportions are related to the production efficiency of WMP forage. High quality WMP silage requires a high CP, CFa, and NFE, but a low CFi is needed to improve digestibility and absorption by animals (Liu et al., 2018). Increasing the CP, CFa, and NFE, which constitute the major sources of energy and nutrition, improves the forage digestibility coefficient (Feng, 2006; Wang, 2011). Crude fiber, ADF, and NDF are beneficial for animal digestibility and nutrition uptake, but have a passive co-relationship with the forage digestibility coefficient (Wang, 2011). Increasing plant density increased the CFi, ADF, and NDF, which reduced its palatability for dairy cows (Qiao et al., 2018). In our results, with increasing plant density, the proportion of CP, CFa, and NFE decreases, but the proportion of CFi, ash, ADF, and NDF increases (Table 5). Therefore, a lower plant density improves WMP forage quality, while a higher plant density reduced forage quality. Similar findings were reported by Ferreira et al. (2014), Gallego-Giraldo et al. (2016), Saponjic et al. (2014), and Stanton et al. (2007). One of the reasons why plant density affects WMP forage quality is that plant density affects the assimilate distribution in the leaves, stem, and grain. In comparison of the leaves and stem, grain contains more CP, CFa, and NFE, but less CFi, ash, ADF, and NDF, so that increasing the proportion of grain in WMP forage reduces the WMP forage quality (Qiao et al., 2018). Mandić et al. (2015) and Wei et al. (2019) stated that a more intensive plant density results in a decreasing number of kernels per row, a lower number of grains per ear, a lower grain weight per ear, and a lower 1,000-grain weight, meaning that the grain proportion is reduced. Therefore, increasing plant density changes the ratio of vegetative organs to grains, thus reducing the forage quality (Kong, 2008; Li, 2018; Yu et al., 2018). Another reason is that a high plant population could decrease the leaf chlorophyll content (Table 2), reduce the enzymatic activity of photosynthesis and assimilation, and accelerate plant aging (Han et al., 2016; Yan et al., 2017; Yin et al., 2019; Wang et al., 2019). These passive effects reduce the production of CP, CFa, and NFE, but increase the proportion of CFi, ash, ADF, and NDF, thus diminishing forage quality (Qiao et al., 2018; Wang et al., 2019). However, the yield tendencies of quality items did not match with those of the proportion of quality items, but with biomass yield in our results. With increasing plant density, the CP, CFa, CFi, NFE, ash, ADF, and NDF yields initially increase, then peak at 75,000 plants ha\(^{-1}\), and finally decrease slightly (i.e., CP, CFa, and NFE) or not at all (i.e., CFi, ash, ADF, and NDF; Table 5). Therefore, biomass was the major contributor to CP, CFa, CFi, NFE, ash, ADF, and NDF yields.

Plant density has a significant influence on the feeding characteristics of WMP forage. Feng (2011) indicated that GE, ED, NE\(_L\), RFV, and GI are negatively co-related to maize plant density. In our study, when plant density increased, GE, ED, NE\(_L\), RFV, and GI were significantly reduced, meaning that increasing the plant density diminished WMP forage feeding quality (Table 6). Increasing plant density generally increased biomass yield, but reduced both forage and feeding quality, which is in agreement with Boomsma et al. (2009), Ferreira et al. (2014), and Wang et al. (2019). Therefore, the plant density which obtained the highest biomass yield was not the same as the plant density for optimizing feeding production. The results are contrary to the perception that the maximum biomass yield can be considered as a proxy for feed quality (Dragičević et al., 2016; Ferreira et al., 2014; Saponjic et al., 2014). Therefore, we propose that the total NE\(_L\) should be considered when estimating utilizable energy yield for dairy cows. In our study, the total NE\(_L\) ranged from 78.3 to 104.1 and from 76.8 to 97.0 GJ ha\(^{-1}\) in 2017 and 2018, respectively (Table 6). As plant density increased, the total NE\(_L\) peaked at 67,500 and 75,000 plants ha\(^{-1}\). Increasing the population to 82,500 plants ha\(^{-1}\) did not improve total NE\(_L\) (Table 6). The predicted maximum total NE\(_L\) was 97.6 GJ ha\(^{-1}\) in 2017 for a plant density of 74,750 plants ha\(^{-1}\), and 93.8 GJ ha\(^{-1}\) in 2018 for a plant density of 74,664 plants ha\(^{-1}\). Additionally, lowering the seeding rate from 82,500
to 75,000 plants ha⁻¹ reduced seeding costs and saved water and N. Furthermore, using a lower plant density improved the GI of WMP forage by 4–9%. This confirms that the plant density that achieves the highest total NE_L also slightly increases the utilisable energy yield and greatly improves the quality of WMP forage, as compared with the plant density that achieves the highest biomass yield. Using the total NE_L, which is a utilisable energy yield, to evaluate the productivity of WMP forage is more efficient and precise than using the biomass yield.

The results of our study indicate a significant inter-annual variance in forage yield and quality, which might be attributed to the rainfall distribution across different growth stages. More rainfall after the VT stage in maize growth in 2018 kept the soil moisture at a high level up to the harvest, and may have retarded plant senescence (Han et al., 2016; Li et al., 2017), which resulted in increases in leaf chlorophyll content and plant water content as compared with 2017 (Table 1). However, that does not contribute to the WUE or maize yield improvements. The interannual variance with respect to the observed biomass yield was not significant, but the predicted maximum biomass for 2017 was only 1% greater than that for 2018. The rainfall distribution, however, did not significantly affect the maize biomass yield, but it did affect WMP forage quality. For the same plant density, the GI of WMP forage in 2017 was 4–16% higher than in 2018 (Table 5). The improvement in WMP forage quality should be attributed to grain yield increase. Maize grain yield is linearly related to rainfall between the V6 and VT stages (Han, 2013; Schmidt, Sripada, Beegle, Rotz, & Hong, 2011). More rainfall between the V6 and VT stages could increase dry matter accumulation before tasseling, and thus improve pollen activity and pollination rate, which then increases the number of grains per ear and grain yield (Li et al., 2017; Song, Dai, Zhang, Huang, & Gu, 1998; Wang et al., 2018). Although the rainfall during the maize growth season in 2018 was 15% higher than in 2017, the rainfall between the V6 and VT stages in 2017 was twice the amount in 2018, resulting in a higher WUE and grain yield in 2017 (Table 3, 7). Increasing the grain yield increased the NFE, that is, starch and sugar, in WMP forage, which improved the WMP forage quality (Feng, 2006). The mean content and yield of NFE in 2017 were 2 and 4% higher than in 2018, respectively (Table 4). Therefore, an increased grain yield for WMP forage was an important factor with respect to the WMP forage quality.

5 | CONCLUSIONS

Increasing the plant density to appropriate levels increases the WMP forage yield but lowers the forage quality and feeding efficiency of WMP. When plant density increases, WMP forage yield and total NE_L increased, peaked, and then decreased. An excessive plant density reduces the biomass yield and the total NE_L. The predicted maximum total NE_L was 97.6 GJ ha⁻¹ in 2017 for a plant density of 74,750 plant ha⁻¹, and 93.8 GJ ha⁻¹ in 2018 with a plant density of 74,664 plants ha⁻¹. In comparison with the plant density that achieved the greatest biomass yield, the plant density that achieved the highest total NE_L decreased biomass yield by 4–6%, but increased the total NE_L and GI by about 1 and 4–9%, respectively, which improved the WMP forage quality. When evaluating the optimal plant density, it should be considered that the plant density that achieved the maximum total NE_L was more effective than the plant density with maximum WMP forage yield. The recommended plant density for the production of WMP forage (‘Siyu 2’) was 74,750 and 74,664 plants ha⁻¹ in 2017 and 2018, respectively.

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