Chilean J. Agric. Anim. Sci. (2026) 42(2):169-186.
https://doi.org/10.29393/CHJAAS42-16LDAP40016

ISSN 0719-3890 online

LIQUID DAIRY MANURE IMPROVED THE SHORT-TERM PHYSICAL QUALITY OF AN ARGIUDOLL

Aline Martineli Batista[1a*], Eugenia Oggero[1b], Silvia Imhoff[1c], and Pablo Ghiberto[1d]

[1a] Instituto de Ciencias Agropecuarias del Litoral (ICiAgro Litoral), Universidad Nacional del Litoral, Consejo Nacional de Investigaciones Científicas y Técnicas (UNL-CONICET). Facultad de Ciencias Agrarias (FCA-UNL), Kreder 2805, CP: S3080HOF, Esperanza, Argentina / Embrapa Meio Ambiente, SP-340, km 127 - S/N, CEP: 13918-110, Jaguariúna - SP, Brazil
https://orcid.org/0000-0001-8173-6607
[1b] Instituto de Ciencias Agropecuarias del Litoral (ICiAgro Litoral), Universidad Nacional del Litoral, Consejo Nacional de Investigaciones Científicas y Técnicas (UNL-CONICET). Facultad de Ciencias Agrarias (FCA-UNL), Kreder 2805, CP: S3080HOF, Esperanza, Argentina
https://orcid.org/0009-0008-4295-7923
[1c] Instituto de Ciencias Agropecuarias del Litoral (ICiAgro Litoral), Universidad Nacional del Litoral, Consejo Nacional de Investigaciones Científicas y Técnicas (UNL-CONICET). Facultad de Ciencias Agrarias (FCA-UNL), Kreder 2805, CP: S3080HOF, Esperanza, Argentina
https://orcid.org/0000-0001-7330-9728
[1d] Instituto de Ciencias Agropecuarias del Litoral (ICiAgro Litoral), Universidad Nacional del Litoral, Consejo Nacional de Investigaciones Científicas y Técnicas (UNL-CONICET). Facultad de Ciencias Agrarias (FCA-UNL), Kreder 2805, CP: S3080HOF, Esperanza, Argentina
https://orcid.org/0000-0001-8039-5206
* Corresponding author: martineli.aline@gmail.com

ABSTRACT

The application of liquid dairy manure (LDM), which is an effluent generated in dairy production facilities from a mixture of feces, urine, milking-parlor wash water, and feed residues, can be a sustainable alternative to improve soil quality. This study aimed to determine the effect of different LDM doses on chemical and physical fertility indicators and overall quality of a silt loam Typic Argiudoll cultivated under no-till. The experiment was conducted using a randomized block design with three blocks and four treatments (LDM doses): D0, no application; D1, 60 m^3 ha^{-1}; D2, 120 m^3 ha^{-1}; and D3, 180 m^3 ha^{-1}. LDM was applied five days before sorghum planting, in November 2019. Chemical properties were evaluated 10 days later. Physical properties and aboveground biomass were assessed in March 2020. Global index of soil physical quality (GISPQ) and least limiting water range (LLWR) were also obtained as indicators of overall quality. Increasing LDM dose resulted in progressively lower soil bulk density (from 1.40 in D0 to 1.37 g cm^{-3} in D3), penetration resistance, effective stress, and higher organic matter (+29% from D0 to D3), biomass (up to +26%), nutrient concentrations and electrical conductivity (from 0.6 to 2.0 dS m^{-1}), while pH remained unaltered. GISPQ and LLWR reflected significant differences between D0 and D1 compared to D2 and D3. LDM doses D2 and D3 improved short-term soil structural quality, mainly due to their greater contribution of organic matter, supporting the hypothesis that appropriate LDM application rates can enhance soil physical quality in the short term despite the associated increase in soluble salts. The results suggest that LDM is a viable alternative for the sustainable management of agricultural systems and for reducing their negative environmental impact. However, the observed increase in

Received: December 3, 2025 Accepted: August 20, 2026

electrical conductivity indicates that soil salinity should be monitored to prevent potential long-term risks to crop yield.

Keywords: chemical properties, physical properties, global physical quality index, least limiting water range.

INTRODUCTION

The application of liquid dairy manure (LDM) to soil is gaining relevance in Argentina due to the intensification of dairy and beef production, the transition to confined systems, and the need for sustainable waste management (Lazzarini et al., 2019). In pastoral systems, some of the nutrients extracted from pastures by animals are returned to the soil via excreta (feces and urine), but a large proportion accumulates in milking facilities, corrals, and watering points. These residues, along with food scraps and wash water, constitute LDM, which is generally stored in lagoons near milking facilities, potentially causing contamination and sanitary issues (Alegbeleye et al., 2020; Pandey et al., 2024). These sanitary risks are commonly mitigated through storage or retention periods that allow partial pathogen die-off prior to land application, as well as by respecting minimum intervals between LDM application and crop harvest or grazing (Al-Wadaey et al., 2010; Richter et al., 2025).

Particularly in Santa Fe Province, Argentina, the decreasing number of dairy farms coupled with a constant cattle population has concentrated LDM production into fewer establishments (Lazzarini et al., 2019; SENASA, 2021), potentially creating localized pollution hotspots. Nevertheless, when properly managed, surface application is an effective strategy to reuse LDM, mitigating contamination risks while supplying organic matter (OM) and essential nutrients for plant growth (Whalen et al., 2019; Rayne and Aula, 2020). Previous studies have shown that LDM can enhance nutrient cycling, improve chemical and biological fertility, increase infiltration and water storage capacity, enrich soil organic matter (SOM), contribute to aggregate stability, and reduced bulk density (D_s) (Ghiberto et al., 2020; 2022; Rayne and Aula, 2021; Han et al., 2023). Such improvements are particularly relevant for the Santa Fe region, where productive soils are experiencing SOM loss, nutrient depletion, and physical degradation due to agricultural intensification (Montico et al., 2019; Alvarez et al., 2022; González et al., 2022).

Although the long-term benefits of manure application are well documented (e.g., Meng et al., 2019; Fu et al., 2022; Han et al., 2023; Sangotayo et al., 2023), short-term evaluations are notably scarce (Goldberg et al., 2020), particularly in the Pampas region (Ghiberto et al., 2020; 2022). Given the high soluble salt content of animal manure, which can increase the risk of soil structural degradation (Guo et al., 2018), short-term assessments are essential for identifying appropriate application rates that prevent structural degradation and for determining when positive effects on soil physical quality begin to emerge.

Understanding the short-term effects of varying LDM doses on soil physical properties will enhance LDM use as a nutrient source and soil amendment while reducing its contamination potential. Therefore, the hypothesis of this work is that, despite possible initial challenges related to soluble salt content, the proposed LDM doses will improve soil physical quality in the short-term, as reflected in fertility indicators, structural properties, and soil quality indices. Sorghum (*Sorghum bicolor* L. Moench) was used as the test crop because of its widespread use in regional forage and grain production systems and its recognized tolerance to moderate salinity and water deficit (Carcedo and Gambin, 2019; Guimarães et al., 2022), making it a suitable indicator species for evaluating the short-term agronomic response of soils amended with LDM. The objective of this work was to determine the effect of different LDM doses (60, 120, and 180 m^3 ha^{-1}) on chemical and physical indicators within the 0 to 0.15 m soil layer of a silt loam Typic Argiudoll after one crop cycle.

MATERIALS AND METHODS

Description of experimental conditions

The experiment was conducted on a dairy farm near Cavour, Santa Fe Province, Argentina (31º21’59” S; 61º00’28” W), in the region known as “Pampa Llana Santafesina”, which has flat relief. The climate is subhumid-humid mesothermal (c2b’3ra’), with an average annual temperature of 18.05°C and average annual precipitation of 967 mm. The soil, a Typic Argiudoll of the Rincón de Ávila series (Soil Survey Staff, 2014), has silt loam texture in the A horizon (0-0.20 m), a silty clay loam texture in the BA horizon (0.20-0.30 m), and silty clay texture in the Bt horizon (0.30-0.55 m). It has been managed under no-till with a ryegrass/sorghum-alfalfa rotation since 1995.

The experiment was established in November 2019, five days before sowing sorghum at a seed density of 12 kg ha^{-1}, following the standard practice for forage/grain sorghum in the region (Carrasco et al., 2011). Dual-purpose sorghum was established under no-till (direct drilling), with 0.52 m row spacing, following a previous annual ryegrass (*Lolium multiflorum*) cover crop that had been mechanically grazed for dairy herd feeding. The experiment followed a randomized complete block design, with three replications and four treatments: D0, control with no LDM application (0 m^3 ha^{-1}); D1, low LDM dose (60 m^3 ha^{-1}); D2, medium LDM dose (120 m^3 ha^{-1}); and D3, high LDM dose (180 m^3 ha^{-1}). The experimental plots were 20 m long and 3 m wide, with a 2 m border surrounding each plot. No additional fertilizer was applied. Effective rainfall during the crop cycle was 418 mm, which was lower than the regional average of 595 mm. The trial was conducted under rainfed conditions, without supplemental irrigation.

The LDM was treated in a facultative lagoon (20 m wide × 40 m long × 2.5 m deep) on the farm, sized to provide a retention period of 120 days. A composite sample of the effluent was collected from the surface layer – within the aerobic zone and well above the bottom sediment and refrigerated. The samples were then sent to the laboratory to determine dry matter (DM) and the concentrations of essential nutrients, including nitrogen (N), phosphorus (P), calcium (Ca), magnesium (Mg), and potassium (K), as well as sodium (Na). Sodium was considered separately given its role as a potential indicator of salinity and sodicity risk rather than as a beneficial plant nutrient (Demo et al., 2025). Following Horwitz and Latimer (2007), total N and P concentrations were determined by spectrophotometry, whereas Ca, Mg, Na and K concentrations were determined by atomic absorption. The LDM (liquid fraction, homogenized by agitation before extraction) was applied as a liquid slurry and sprayed onto the plots using a 3-m-wide manure spreader three days before sowing sorghum. The amounts of DM, nutrients, and Na provided by treatments D1, D2, and D3 (Table 1) were calculated based on the concentrations of DM and nutrients in the effluent and the doses used in each treatment. Three effluent subsamples were additionally collected directly from the spreader for each plot to verify the applied volume. The LDM had a pH of 7.4 and an electrical conductivity (EC) of 7.32 dS m^{-1}.

Dry biomass production of sorghum

Harvesting was carried out at grain maturity (118 days after sowing). At this stage, one-square-meter samples of aboveground biomass (AGB) were collected from each plot and weighed to determine green biomass mass. Then, a subsample from each sample was placed in an oven at 60 °C until a constant weight was reached to determine dry AGB.

Soil chemical properties

Ten days after the LDM application, when the LDM had completely infiltrated into the soil and its consistency was suitable for sampling, disturbed soil samples were collected from depth of 0.00 to 0.15 m. This depth was selected because the wetted depth, calculated based on the highest dose (180 m^3 ha^{-1}) and the soil moisture content (0.20 cm^3 cm^{-3}), was 0.13 m. Therefore, the 0.00 to 0.15 m soil layer was considered the depth most directly influenced by LDM application and, importantly, the zone with the greatest crop root development (Adu et al., 2022). This depth is also agronomically relevant for assessing nutrient availability and root-related physical constraints, in accordance with the objectives of this study. Samples from the three field replicates of the same treatment were combined in equal proportions to form a single composite sample, following

Table 1. Amount of dry matter (DM) and nutrients provided by liquid dairy manure (LDM) in different doses.

Treatment	DM	N	P	Ca	Mg	K	Na
	kg ha^{-1}						
D1	4002	58	5	184	130	460	236
D2	8004	116	10	368	260	920	473
D3	12006	174	15	551	389	1381	709
LDM (effluent)[1]	g L^{-1}						
	66.7	0.97	0.08	3.07	2.16	7.67	3.94

[1]LDM (effluent): Estimated effluent concentration (amount applied ÷ volume applied). D1: low dose (60 m^3 ha^{-1}); D2: medium dose (120 m^3 ha^{-1}); D3: high dose (180 m^3 ha^{-1}); N: nitrogen; P: phosphorus; Ca: calcium; Mg: magnesium; Na: sodium; K: potassium. LDM pH: 7.4; LDM electrical conductivity (EC): 7.32 dS m^{-1}.

standard soil-sampling and sample-conditioning procedures (Pilatti et al., 2022; IRAM, 2009). The samples were then air-dried and sieved (< 2 mm) to measure the following properties, according to the procedures described in the Methodological Support System for Soil Analysis Laboratories (SAMLA, 2004): pH (1:2.5 ratio); EC of the saturation extract; organic carbon by the Walkley-Black method, subsequently converted to OM; exchangeable Na and K by flame photometry; exchangeable Ca and Mg by complexometric titration; cation exchange capacity (CEC) after extraction with ammonium acetate at pH 7.0 (Sumner and Miller, 2009); total nitrogen (Nt) by distillation using the Kjeldahl method; available P by the Bray and Kurtz (1945) method; and sulfur ($S\text{-}SO_4$) by turbidimetry.

Soil water retention curve

In March 2020, ten days after the sorghum harvest and four months after LDM application, undisturbed soil samples were collected from a depth of 0.05 to 0.10 m using cylinders (0.05 × 0.05 m). These samples were used to determine the soil water retention curve (SWRC) and the least limiting water range (LLWR).

Three undisturbed samples per plot were saturated by gradually raising the water table. The samples were weighed to determine the volumetric water content at saturation (θ_s), and then sequentially equilibrated at the following Ψ_m: -0.5, -1, -2, -3, -4, -5, -6, -7, -8, -9, -10 kPa on a handmade sand tension table (Lima and Silva, 2008); -33, -50, -100 kPa in pressure chambers (Soil Moisture Equipment Corp., Santa Barbara, CA) according to Klute (1986); and -300, -600, and -1500 kPa in a WP4-T (Decagon Devices, Inc., Pullman, WA, USA) according to Scanlon et al. (2002). Once the samples reached equilibrium at each Ψ_m, they were weighed. After the measurements were completed, the samples were oven-dried at 105°C to determine soil bulk density (D_s) (Blake and Hartge, 1986). Using this information, the volumetric water content (θ) was calculated to develop SWRCs. The data were fitted to the van Genuchten (1980) equation with the Mualem (1976) restriction (Equation 1, Supplementary Material) using the RETC Version 6.0 program (van Genuchten et al., 1998). The SWRCs were then compared with a regional reference curve (Ghiberto et al., 2015).

Pore distribution curve

The normalized frequency of the pore distribution curves (PDC) was calculated for each SWRC from the first derivative of the van Genuchten equation (1980) [$S_v(h)$] (Equation 2, Supplementary Material), assuming that the effective pore diameter (d_e) can be described by the capillarity equation (Libardi, 2018; Equation 3, Supplementary Material). The tangent slope at the SWRC inflection point [$S_{vi}(h)$] was then calculated (Equation 4, Supplementary Material). To make the curves comparable, the normalized pore distribution [$S^*(h)$] was obtained by dividing $S_v(h)$ by $S_{vi}(h)$ (Equation 5, Supplementary Material). The pore-size frequency curves (PSFCs) were compared using measures of central tendency, dispersion, skewness, and kurtosis. In addition, these curves were compared with the regional reference curve reported by Ghiberto et al. (2015).

Global index of soil physical quality

The global index of soil physical quality (GISPQ) proposed by Ghiberto et al. (2015) was calculated from the following attributes: OM, D_s, S index (S_{gi}) (Dexter, 2004), macropore domain porosity >300 μm (POR_p), total soil air capacity (AC_t), available water capacity (AWC), fraction of pores with a diameter less than 30 μm (θ_{10}/POR_t), and structural stability index (SI) (Reynolds et al., 2009; Equation 6, Supplementary Material). Each attribute was assigned a value between 0 (most limiting condition) and 1 (optimal condition), according to Table 2. The GISPQ was obtained by summing the values of the eight attributes. Thus, the maximum possible value was 8 (eight attributes with a value of 1), equivalent to 100%.

Table 2. Reference ranges of values used to calculate the global index of soil physical quality (GISPQ).

OM	D_s	POR_p	AC_t	AWC	θ_{10}/POR_t	SI	S_{gi}
g kg^{-1}	g cm^{-3}	----------	---------- m^3 m^{-3}	----------	----------	%	-
>50 (1)	<1.41 (1)	>0.07 (1)	>0.15 (1)	>0.2 (1)	0.6-0.7 (1)	>9.0 (1)	>0.05 (1)
50-30 (0.7)		0.07-0.04 (0.5)	0.15-0.10 (0.5)	0.15-0.2 (0.7)		7.0-9.0 (0.7)	0.035-0.05 (0.7)
30-20 (0.3)		<0.04 (0)	<0.1 (0)	0.1-0.15 (0.3)		7.0-5.0 (0.3)	0.02-0.035 (0.3)
<20 (0)				<0.1 (0)		<5.0 (0)	<0.02 (0)

Values in parentheses indicate the score assigned to each attribute. OM: organic matter; D_s: soil bulk density; POR_p: porosity in the macropore domain; AC_t: total air capacity; AWC: available water capacity; θ_{10}/POR_t: fraction of pores with a diameter less than 30 μm; SI: structural stability index; S_{gi}: S index.

For further details on the determination of the attributes considered, see Ghiberto et al. (2015).

Least limiting water range

Two undisturbed samples per plot were used to determine a second SWRC and penetration resistance (PR), and subsequently the LLWR. The samples were saturated by gradually raising the water table and equilibrated at the following Ψ_m: -3, -6, and -10 kPa on a tension table; -33, -100, and -500 kPa in pressure chambers (Klute, 1986); and -1500 kPa in a WP4-T (Scanlon et al., 2002). At equilibrium, each sample was weighed, and PR was measured using an electronic penetrometer with a 60° cone angle and a 4 mm base diameter. Finally, the samples were oven-dried at 105°C to determine D_s (Blake and Hartge, 1986) and calculate θ.

Using the θ and Ψ_m data, the SWRCs were fitted. In this case, the model proposed by Silva and Kay (1997) was used (Equation 7, Supplementary Material). In addition, the functional relationship among PR, θ, and D_s was determined by fitting the nonlinear model proposed by Busscher (1990) to the data. This model was used to determine the θ at which a PR value of 3 MPa is reached (θ_{PR}), considered restrictive for normal root growth in most crops (Boone and Veen, 1982). The θ at an air-filled porosity of 15% (θ_{AP}) was determined from D_s and particle density (D_p), considering an average value of 2.58 g cm^{-3} for the latter, representative of the study area (Pilatti and Imhoff, 2008; Equation 8, Supplementary Material). The LLWR was calculated according to Silva et al. (1994) for each measured D_s. The water contents corresponding to field capacity (θ_{FC}) and permanent wilting point (θ_{PWP}) were obtained for Ψ_m = -10 and -1500 kPa, respectively, from the model of Silva and Kay (1997). In addition, the critical soil bulk density (D_{sc}), at which the LLWR is 0, was determined.

Effective stress and PR-σ relationship

To understand the influence of PR on LLWR, effective stress (σ) was determined for unsaturated soils using the model proposed by Mullins and Panayiotopoulos (1984), which combines θ and Ψ_m (Equation 9, Supplementary Material). The relationship between σ and PR was fitted using a linear model (Equation 10, Supplementary Material) that considers cohesion parameters associated with aggregating substances and the effect of soil compaction (Vepraskas, 1984).

Statistical analysis

The comparison of the SWRC coefficients used to determine the pore-size distribution function (PSDF) and GISPQ was performed according to Glantz and Slinker (1990), using a significance level of 5% (α = 0.05). The GISPQ attributes and sorghum AGB production were subjected to analysis of variance (ANOVA), and when the differences were significant at the 5% level, Tukey's test was applied (α = 0.05). All statistical analyses were performed using R (R Core Team, 2023), and contrasts were set up using the R package 'emmeans' (Lenth, 2023).

Because chemical determinations were performed on a single composite sample per treatment, formal statistical comparisons (ANOVA/Tukey) among treatments were not conducted for these variables. The measured values were interpreted as descriptive treatment means, and treatment effects were assessed relative to the untreated control (D0).

RESULTS AND DISCUSSION

The application of LDM significantly increased ($p<0.05$) sorghum AGB production (Fig. 1). Compared with the control (D0), doses D1, D2 and D3 increased production by 5%, 20% and 26%, respectively, reaching a maximum of 23,437 kg ha^{-1}. Productivity responded positively to increasing LDM doses, as indicated by the positive linear relationship ($R^2 = 0.96$).

This result is consistent with previous studies in sorghum (Charlón et al., 2007; Gambaudo et al., 2014). Charlón et al. (2007) applied amounts of N similar to those used in the present study, using a treated, solid effluent. This suggests that the amount of nutrients supplied (Table 3), rather than the physical form of the effluent (liquid slurry in the present study versus treated solid effluent in Charlón et al., 2007) may be the main factor driving the biomass response. Nonetheless, an additional contribution from the OM added with LDM (Table 3) cannot be ruled out, since OM can indirectly improve nutrient availability and soil physical conditions (Han et al., 2023).

The low rainfall during the crop cycle (418 mm, 29.8% below the zonal average) may have negatively affected AGB (Moreira et al., 2023). However, the nutrients and OM supplied by the LDM (Table 3) had a positive effect on AGB. Further studies under different soil and precipitation conditions are needed to better understand the interactions between LDM, soil, and climate. Because the trial was conducted under rainfed conditions and evapotranspiration was not measured, the potential interaction with LDM-derived nutrient and water dynamics could not be quantified here and it is recommended as a focus for future research combining effluent application with direct evapotranspiration monitoring.

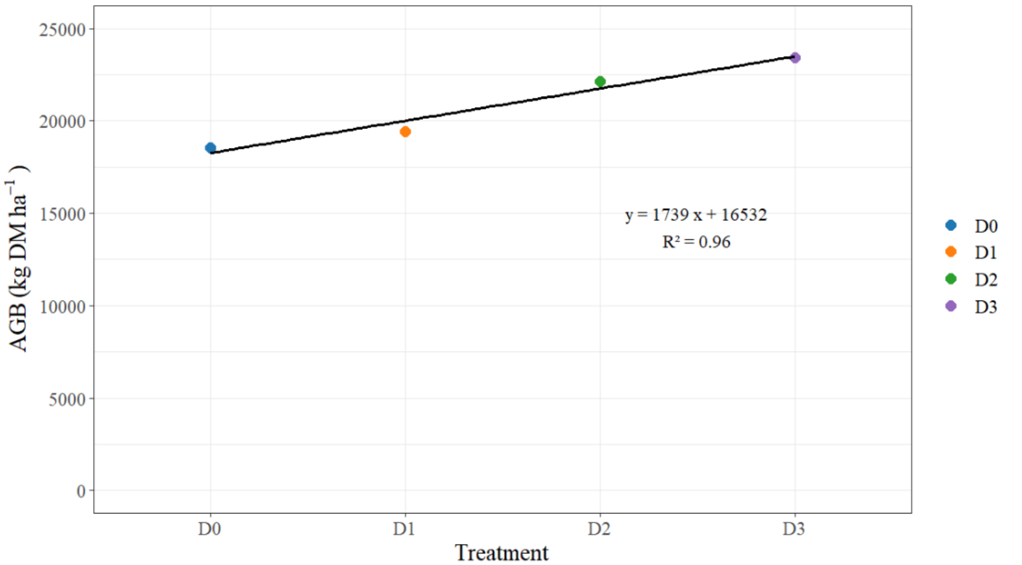

Fig. 1. Production of dry aboveground biomass (AGB) as a function of LDM treatments: D0, control without LDM application (0 m^3 ha^{-1}); D1, low LDM dose (60 m^3 ha^{-1}); D2, medium LDM dose (120 m^3 ha^{-1}); and D3, high LDM dose (180 m^3 ha^{-1}). Different letters indicate significant differences (Tukey's test, α = 0. LDM 05).

Table 3. Soil chemical properties of the Typic Argiudoll of the Rincón de Ávila soil series, evaluated at a depth of 0 to 0.15 m, 10 days after the application of different liquid dairy manure (LDM) doses.

	OM	N_t	P	S-SO_4		EC	Ca	Mg	Na	K	CEC
Treatment	g kg^{-1}				pH	dS m^{-1}	cmol$_c$ kg^{-1}				
D0	31.0	1.7	23.3	20.7	6.1	0.6	9.7	1.3	1.0	1.3	15.3
D1	32.3	1.8	25.0	22.3	6.2	1.1	9.8	1.3	1.2	1.7	15.6
D2	35.0	2.1	34.7	27.0	6.2	1.5	10.0	2.3	1.2	1.7	15.9
D3	39.7	2.4	40.3	31.0	6.2	2.0	10.7	2.3	1.3	2.0	16.7

D0: control dose (0 m^3 ha^{-1}); D1: low dose (60 m^3 ha^{-1}); D2: medium dose (120 m^3 ha^{-1}); D3: high dose (180 m^3 ha^{-1}); OM: organic matter; N_t: total nitrogen; P: phosphorus; S-SO_4: sulfur; EC: electrical conductivity; Ca: exchangeable calcium; Mg: exchangeable magnesium; Na: exchangeable sodium; K: exchangeable potassium; CEC: cation exchange capacity. Values are means from a single composite sample per treatment; no statistical comparison is presented for this table.

LDM application increased OM by 29% from D0 to D3 (Table 3), with associated increases in P (79%), N_t (41%), S-SO_4 (50%). CEC increased by 9%, while the contributions of Ca, Mg, Na and K to CEC were small (0.8; 5.3; 1.3 and 3.5%, respectively), with Mg and K predominating. These results agree with previous reports showing increased OM and nutrients availability after LDM application (Cavalcante et al., 2019, Rayne and Aula, 2020; Han et al., 2023). EC increased with LDM dose, while pH remained unchanged due to the soil's buffering capacity (Jansen van Rensburg et al., 2009). The EC rise was associated with the added cations, especially K, as also observed in other studies (Rayne and Aula, 2020; Han et al., 2023).

An increase in monovalent cations, especially Na, may cause rapid soil disaggregation and decrease infiltration rates and hydraulic conductivity due to their highly dispersive characteristics (Farahani et al., 2018). This highlights the need to know the effluent chemical composition and the soil properties prior to LDM application to determine the appropriate application rates. Monitoring is also important to understand the EC and pH evolution, and avoid excessive accumulation of nutrients, such as P and N, which can cause environmental pollution at certain levels (Ozlu and Kumar, 2018). For instance, EC increased by a factor of 1.36 from D1 to D2, 1.82 from D1 to D3, and 3.33 from D0 to D3 (Table 3), reflecting a dose-dependent salinization trend that reinforces the need for continuous EC monitoring to prevent long-term risks to soil and crop productivity. Additionally, given the combined effects of evaporation and leaching on solute movement, monitoring Na concentrations at various soil depths over time is recommended to better track its redistribution and potential long-term accumulation risk under LDM application (Öztürk and Özkan, 2004; Dong et al., 2026).

The SWRCs (Fig. 2), and the van Genuchten fitting parameters did not differ (p>0.05) among LDM doses (Table 4), indicating that LDM did not alter soil water retention capacity during the evaluated sorghum crop cycle. Parameter α, which is related to the average pore size and the air entry point, and the parameters m and n, associated with the pore size distribution (Farooq et al., 2024; Usowicz et al., 2024), were also unaffected, confirming no short-term changes in pore distribution.

However, SWRCs differed markedly from the regional reference curve (Fig. 2). The α parameter of the reference was 12.9 times greater than the average value across treatments (Table 4), indicating later air entry due to smaller macropores, a common characteristic of fine-textured or poorly structured soils (Schwenk et al., 2023). Likewise, the larger n and m in the treatments (1.12 and 1.54 times greater than those in the reference, respectively) suggest faster water release as Ψ_m decreases, consistent with the higher D_s (1.40 to 1.37 g cm^{-3}) compared to the reference (1.24 g cm^{-3}) (Ghiberto et al., 2015).

Given the similarity among SWRCs (Fig. 2 and Table 4), PDCs were also very similar, with only a slight rightward shift in D3 toward the reference curve (Fig. 3). Despite this slight trend, all treatment curves differed from the regional reference curve. Measures of central tendency and shape confirmed the predominance of small pores: wide distributions (SD > 16), leptokurtic behavior (skewness < -0.3), with values concentrated around the mean compared to a log-normal distribution (kurtosis = 1.11 to 1.50). The predominance of these small pores may cause aeration and water drainage problems in the soil (Du et al., 2023; Silva et al., 2022), leading to aeration problems for soil organisms and roots (Miretti et al., 2011).

In all treatments, means (0.8 to 0.9 μm), medians (1.2 to 1.5 μm), and modes (3.0 to 4.0

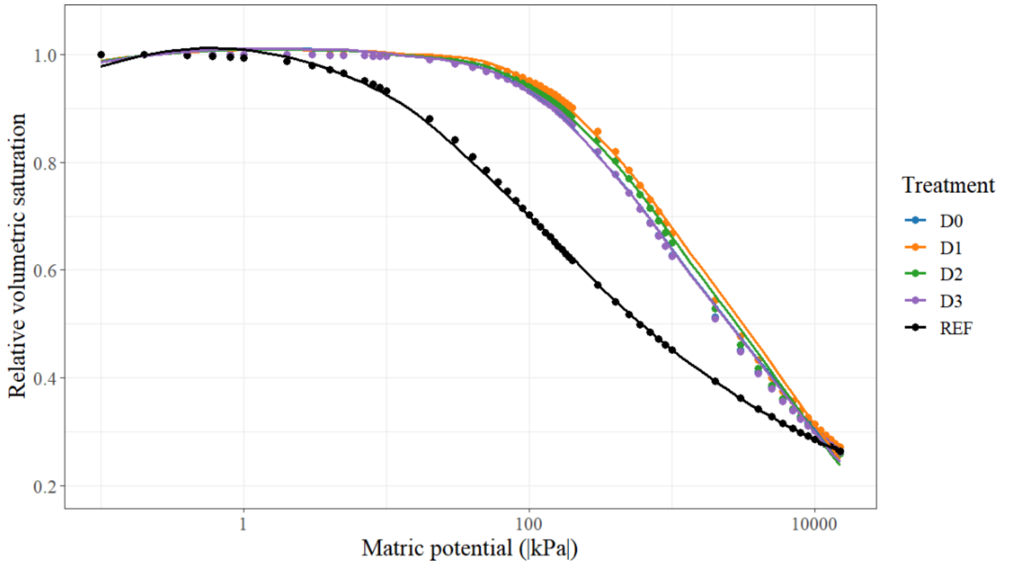

Fig. 2. Soil water retention curves (SWRC) corresponding to a Typic Argiudoll of the Rincon de Ávila soil series, evaluated at a depth of 0.05 to 0.10 m, after application of different liquid dairy manure (LDM) doses: D0, control dose (0 m^3 ha^{-1}); D1, low dose (60 m^3 ha^{-1}); D2, medium dose (120 m^3 ha^{-1}); and D3, high dose (180 m^3 ha^{-1}). The reference curve (REF) estimated by Ghiberto et al. (2015) is also presented.

Table 4. Adjustment parameters of the soil water retention curves (SWRC) for a Typic Argiudoll of the Rincón de Ávila soil series, evaluated at a depth of 0.05 to 0.10 m, after application of different liquid dairy manure (LDM) doses and of the reference curve (REF, Ghiberto et al., 2015).

Trat.	α (cm^{-1})	n	m
D0	0.0044 a	1.3279 a	0.2462 a
D1	0.0032 a	1.3563 a	0.2620 a
D2	0.0042 a	1.3516 a	0.2591 a
D3	0.0046 a	1.3348 a	0.2499 a
REF	0.0530	1.1988	0.1658

Different letters indicate significant statistical differences (Tukey, α = 0.05). D0, control dose (0 m^3 ha^{-1}); D1: low dose (60 m^3 ha^{-1}); D2: medium dose (120 m^3 ha^{-1}); D3: high dose (180 m^3 ha^{-1}).

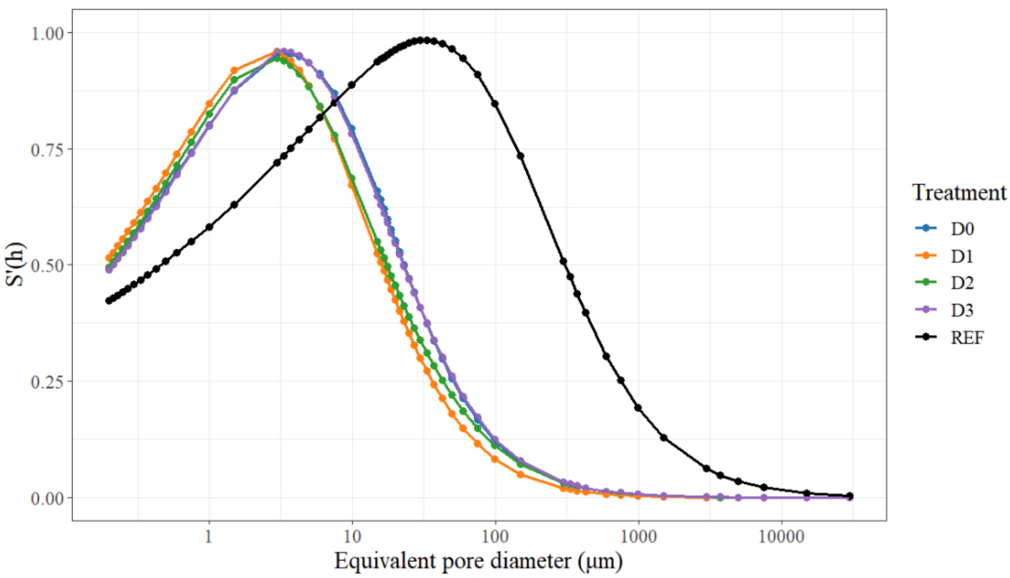

Fig. 3. Normalized frequency of pore distribution curves (PDC) corresponding to a Typic Argiudoll of the Rincon de Ávila soil series, evaluated at a depth of 0.05 to 0.10 m, after application of different liquid dairy manure (LDM) doses: D0, control dose (0 m^3 ha^{-1}); D1, low dose (60 m^3 ha^{-1}); D2, medium dose (120 m^3 ha^{-1}); D3, high dose (180 m^3 ha^{-1}). The reference curve (REF) estimated by Ghiberto et al. (2015) is also presented.

µm), were below the reference ranges (1.2 to 3.0; 3.4 to 6.8; and 31.0 to 39.0 *µm*, respectively). The low magnitude of these measures suggests limitations in soil physical quality (Osooli et al., 2025). This finding is consistent with the SWRCs (Fig. 2), because, at the same Ψ_m, the treatments showed higher θ than the reference, which is directly linked to the PDCs (Fig. 3).

The primary factor affecting water retention and soil aggregate stability in soils of similar texture is OM (Lal, 2020; Giustiniani et al., 2024). This is consistent with the 29% increase in OM observed from D0 to D3 (Table 3). Because OM increased even after a single LDM application cycle, long-term effects on the soil physical and hydraulic properties can be expected (Yan et al., 2023). Continuous monitoring will help determine when such effects become detectable.

Average values of GISPQ attributes and the index itself are shown in Table 5. D_s decreased ($p<0.05$) in D3, likely due to its higher OM content (Table 2), as consistently reported for Argiudolls and Hapludolls of the Pampas region (Ghiberto et al., 2015; Imhoff et al., 2016; Rodríguez et al., 2025), as well as in other soils globally (Fu et al., 2022; Han et al., 2023).

Table 5. Average values of the attributes used to calculate the global index of soil physical quality (GISPQ) and GISPQ evaluated at a depth of 0 to 0.15 m for different liquid dairy manure (LDM) doses applied on a Typic Argiudoll, Rincon de Ávila soil series.

	MO	D_s	PORp	AC_t	AWD	θ_{10}/POR_t	SI		
	g kg^{-1}	g cm^{-3}	m^3 m^{-3}				%	S_{gi}	GISPQ
D0	31.0 c	1.40 a	0.035 b	0.061 b	0.233 b	0.9 a	3.5 c	0.038 c	31.9 b
D1	32.3 c	1.40 a	0.030 c	0.050 c	0.249 a	1.0 a	3.6 c	0.040 b	31.6 b
D2	35.0 b	1.39 a	0.026 c	0.053 c	0.248 a	0.9 a	3.8 b	0.041 ab	35.2 ab
D3	39.7 a	1.37 b	0.039 a	0.065 a	0.243 a	0.9 a	4.3 a	0.042 a	38.9 a

D0: control dose (0 m^3 ha^{-1}); D1: low dose (60 m^3 ha^{-1}); D2: medium dose (120 m^3 ha^{-1}); D3: high dose (180 m^3 ha^{-1}). OM: organic matter; D_s: soil bulk density; POR_p: porosity in the macropore domain; AC_t: total air capacity; AWD: available water capacity; θ_{10}/POR_t: pore fraction with a diameter less than 30 μm; SI: structural stability index; S_{gi}: S index. Different letters indicate significant statistical differences (Tukey, α = 0.05).

All D_s values were below the Proctor- estimated D_s for typical Argiudolls from the same study region (1.58 and 1.62 g cm^{-3}; Masola et al., 2020). However, using the regional threshold of 1.40 g cm^{-3} for Argiudolls and Hapludolls in the Santa Fe province with comparable clay content (Imhoff et al., 2016), only D2 and D3 were below this value (Table 5), suggesting possible root limitations in D0 and D1. This root-growth limitation in D0 and D1 is consistent with their lower aboveground biomass production relative to D2 and D3 (Fig. 1), supporting a mechanistic link between soil physical constraints and the observed differences in sorghum yield.

Although POR_p values remained below the critical 0.04 m^3 m^{-3} (Reynolds et al., 2009), its increase in D3 indicates an early positive trend in microporosity, associated with the improvements in OM and D_s, that may become more pronounced with repeated LDM applications (Meng et al., 2019; Sangotayo et al., 2023). AC_t values (Table 5), which correspond to pores with diameter greater than 30 μm, were low and consistent with the previous results. However, AC_t increased ($p<0.05$) in D3 compared to D0, suggesting improvements in aeration capacity.

The predominance of small pores (Fig. 2 and 3) was also reflected in high θ_{10}/POR_t, values, which indicate a high volume of pores retaining water at a Ψ_m of -10 kPa. Optimal θ_{10}/POR_t values are between 0.6 and 0.7 (Reynolds et al., 2002), which implies that the values measured in this study were almost 30% higher than the optimal ones. These results also indicate potential aeration constraints (Pragg et al., 2024), and a potentially greater susceptibility to denitrification under excessive moisture (Micucci et al., 2023), as inferred from the θ_{10}/POR_t values in Table 5 rather than from direct measurements.

SI increased with LDM dose (Table 5), though values remained below 5%, indicating soil structural degradation (Reynolds et al., 2009), which is typical of these soils. This condition is related to the soil's high silt, low sand, and non-expansive clay content, as well as historical OM and Ca depletion due to long-term land use (Imhoff et al., 2018; Alvarez et al., 2022; González et al., 2022). Since OM and Ca promote soil aggregation (Safar and Whalen, 2023; Pessoa et al., 2024), the increase in SI with LDM is consistent with its contributions.

S_{gi} also increased with LDM dose (Table 5). Dexter (2004) proposed this indicator as a measure of soil microstructure that controls key processes, such as water and air flow. This author proposed a value of 0.035 as a critical threshold, verifying that lower values were obtained in soils with compaction problems, sodicity, or low hydraulic conductivity (i.e., indicative of low structural quality) at the 0 to 0.15 m depth evaluated here. Because S_{gi} is positively related to OM and inversely to D_s (Fernández et al., 2021), these results align with the observed changes.

Based on GISPQ values, the overall soil physical quality increased with LDM dose (Table 5). However, all treatments were classified as soils with problems with aeration and water percolation (AC_t <15% and POR_p <4%; Ghiberto et al., 2015). However, LDM did not deteriorate porosity, contrary to other amendments such as Na-rich irrigation water (Pilatti et al., 2006; Imhoff et al., 2010), and the observed early improvements indicate potential long-term benefits.

SWRC parameters from Silva and Kay (1997) and the parameters from Busscher (1990) (Table S1 and S2, Supplementary Material), confirmed that θ reduced PR, whereas D_s increased PR. The negative sign of parameter e indicates the magnitude by which θ decreases as Ψ_m decreases (i.e, becomes more negative). Increasing D_s

increased θ_{PR} and reduced θ_{AP} across treatments (Fig. 4), without affecting θ_{FC} or θ_{PWP}, indicating that available water content (θ_{FC} - θ_{PWP}) remained unchanged, consistent with results reported for similar soils (Safadoust et al., 2014).

θ_{PR} limited LLWR from D_s ~ 1.27 g cm^{-3} in D0, D2, and D3, and from 1.32 g cm^{-3} in D1. Its effects were more severe in D0 and D1, as indicated by steeper slopes (Fig. 4), corroborating the beneficial effect of LDM on PR. This indicates that above these values the crop growth will be affected by the high soil PR before its θ reaches the permanent wilting point (PWP). Such limitations are common in compacted agricultural soils (Fernández et al., 2017; Iglesias et al., 2021), where high PR may restrict root elongation and reduce water and nutrient absorption, ultimately decreasing crop yields (Bengough et al., 2011).

θ_{AP} was the upper LLWR limit for all treatments and became restrictive at D_s ~ 1.27 g cm^{-3} (Fig. 4), indicating aeration constraints even near θ_{FC}. The limitation due to θ_{AP} increased with D_s. This pattern matches the physical characteristics highlighted earlier (Fig. 2 and 3; Table 5) and also reflects the dominance of small pores. In soils with similar texture, compaction, reflected in this study by the measured increase in D_s and PR (Table 5; Fig. 4 and 5), tends to induce aeration limitations at lower D_s (Imhoff et al., 2016), unlike clayey soils where θ_{AP} becomes a limiting factor at lower D_s (Moura et al., 2021).

Average LLWR values (i.e., 50% of the calculated LLWR values fall above and below these values) were 0.03, 0.06, 0.09, and 0.10 cm^3 cm^{-3} for D0, D1, D2, and D3, respectively, with D0 showing the poorest condition, and D2 and D3 the best. Higher OM in D3 (Table 2) supports its wider LLWR, consistent with the findings of Imhoff et al. (2016). The smallest LLWR range implies a greater probability that plants will suffer stress conditions during their growth cycle, especially in production systems without irrigation (Silva and Kay, 1997).

D_{sc} values were ~ 1.45 g cm^{-3} for D0 and D1 and were not reached within the measured D_s range for D2 and D3 (Fig. 4). Projected values (1.48 g cm^{-3} for D2 and 1.49 g cm^{-3} for D3) suggest better structural quality in D2 and D3 (Reichert et al., 2009). As D_s approaches D_{sc}, PR increases sharply, restricting root growth and reducing yield (Bengough et al., 2011), reinforcing the better physical environment in D2 and D3.

Treatments with higher LDM doses (D2 and D3) showed higher θ at a given Ψ_m, resulting in lower σ values. A positive linear PR-σ relationship was observed (Fig. 5). D2 and D3 differed from D0 and D1 by exhibiting higher parameter a and lower parameter b (Equation 10, Supplementary

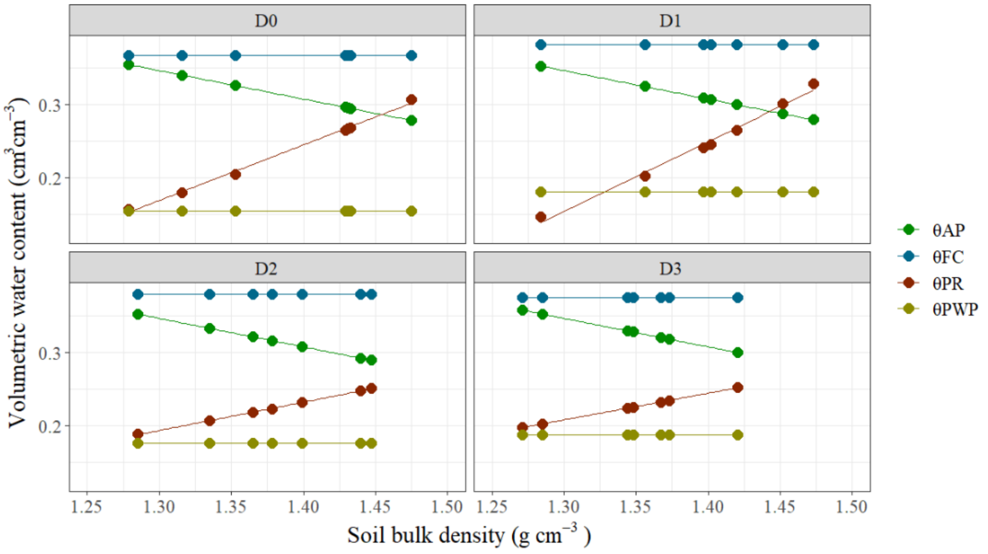

Fig. 4. Volumetric water content (θ) variation in the soil as a function of soil bulk density (D_s) for critical values of aeration porosity (AP), field capacity (FC), soil penetration resistance (PR) and permanent wilting point (PWP) corresponding to a Typic Argiudoll, Rincon de Ávila soil series, evaluated at a depth of 0.05 to 0.10 m, after application of different liquid dairy manure (LDM) doses: D0, control dose (0 m^3 ha^{-1}); D1, low dose (60 m^3 ha^{-1}); D2, medium dose (120 m^3 ha^{-1}); and D3, high dose (180 m^3 ha^{-1}).

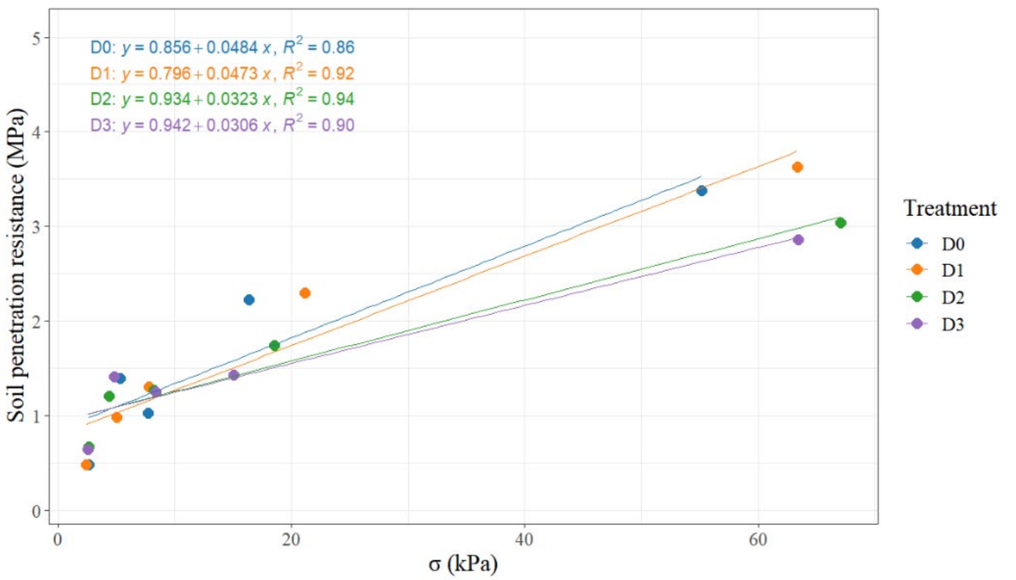

Fig. 5. Soil penetration resistance (PR) as a function of effective stress (σ) corresponding to a Typic Argiudoll, Rincon de Ávila soil series, evaluated at a depth of 0.05 to 0.10 m, after application of different liquid dairy manure (LDM) doses: D0, control dose (0 m^3 ha^{-1}); D1, low dose (60 m^3 ha^{-1}); D2, medium dose (120 m^3 ha^{-1}); and D3, high dose (180 m^3 ha^{-1}).

Material), indicating smaller PR increases per unit *σ*. This reflects increased cohesive forces (parameter a) due to the added OM and reduced frictional resistance between both the soil particles and the penetrometer (or root) and the adhesive forces between soil particles and water (meniscus effect; parameter b) due to D_s reduction and improved aggregation.

These results indicate that OM and D_s were the most influential properties affecting the PR-*σ* relationship. As a result, roots in D2 and D3 would face less mechanical resistance at a given *σ*, allowing greater soil exploration and improved access to water and nutrients. The positive results of LDM identified by PR-*σ* and LLWR are consistent with the highest GISPQ in D2 and, especially, in D3, and help explain the higher AGB production in D3 (Fig. 1). Taken together, the results indicate that higher LDM doses (D2 and D3) positively modified the soil physical environment.

Taken together, the results point to a coherent, dose-dependent improvement in soil chemical and physical conditions. Some methodological limitations should nonetheless be acknowledged. Because chemical properties were assessed using a single composite sample per treatment, formal statistical testing could not be applied to these variables, representing a limitation of this short–term assessment. Likewise, the assessment was restricted to the 0 to 0.15 m soil layer. Evaluating deeper horizons and hydraulic conductivity is recommended to determine the influence of LDM at greater depths.

CONCLUSIONS

This study demonstrates the positive short-term (four-month) effects of liquid dairy manure (LDM) application on a Typic Argiudoll (Rincón de Ávila series) and on sorghum above-ground biomass production. LDM increased soil organic matter (+29%), extractable P (+79%), and total N (+41%) (D0 to D3), while reducing bulk density (from 1.40 to 1.37 g cm^{-3} in D3), mechanical strength, and effective stress. Electrical conductivity also increased (0.6 to 2.0 dS m^{-1}), indicating a salinity risk that should be monitored over successive applications, particularly since the capacity of the crop to buffer this increase has not been established. These changes improved integrated indicators of soil structural quality (global index of soil physical quality and least limiting water range), particularly at the highest doses (D2 and D3). Overall, these results indicate that LDM use is a promising amendment for improving soil quality and supporting sustainable agricultural management. However, further evaluations are needed to confirm the persistence of these effects in the long-term, especially under conditions of poor water quality, which may alter LDM composition and its agronomic performance.

ACKNOWLEDGMENTS

We would like to thank the Universidad Nacional del Litoral (Esperanza, Santa Fe province, Argentina) for the funding provided through the CAI+D 330/16 project that made this study possible.

Author contributions

Aline M. Batista: Visualization, Writing – original draft. Eugenia Oggero: Formal analysis, Visualization, Writing – original draft. Silvia Imhoff: Conceptualization, Methodology, Investigation, Formal analysis, Validation, Writing – review & editing, Supervision. Pablo Ghiberto: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Visualization, Validation, Writing – review & editing, Supervision, Funding acquisition, Project administration. All co-authors reviewed the final version and approved the manuscript before submission.

Declaration on the use of generative AI

No generative Artificial Intelligence tools were used in the preparation of the text, tables, or figures of this manuscript.

LITERATURE CITED

Adu, M.O., P.A. Asare, D.O. Yawson, K.K. Amoah, K. Atiah, M.K. Duah, and A. Graham. 2022. Root system traits contribute to variability and plasticity in response to phosphorus fertilization in field-grown sorghum [*Sorghum bicolor* (L.) Moench] cultivars. Plant Phenomics 2022:0002. https://doi.org/10.34133/plantphenomics.0002

Alegbeleye, O.O., and A.S. Sant'Ana. 2020. Manure-borne pathogens as an important source of water contamination: An update on the dynamics of pathogen survival/transport as well as practical risk mitigation strategies. International Journal of Hygiene and Environmental Health 227:113524. https://doi.org/10.1016/j.ijheh.2020.113524

Alvarez, R., A. Gimenez, M. Caffaro, F. Pagnanini, D. Gangi, and G. Berhongaray. 2022. Land use effects on soil organic carbon fractions in the Pampas of Argentina determined via inverse analysis of carbon mineralization data. Communications in Soil Science and Plant Analysis 53:2094-2104. https://doi.org/10.1080/00103624.2022.2070629

Al-Wadaey, A., S.C. Wortmann, A.C. Shapiro, G.T. Franti, and E.D. Eisenhauer. 2010. Manure application setback effect on phosphorus and sediment in runoff. Journal of Soil Science and Environmental Management 1(5):92-98. http://www.academicjournals.org/JSSEM

Bengough, A.G., B.M. McKenzie, P.D. Hallett, and T.A. Valentine. 2011. Root elongation, water stress, and mechanical impedance: a review of limiting stresses and beneficial root tip traits. Journal of Experimental Botany 62(1):59-68. https://doi.org/10.1093/jxb/erq350

Blake, G.R., and K.H. Hartge. 1986. Bulk density. p. 363-375. In A. Klute (ed.). Methods of soil analysis. Part 1. Physical and mineralogical methods. 2nd ed. Soil Science Society of America, Madison, Wisconsin, USA.

Boone, F.R., and B.W. Veen. 1982. The influence of mechanical resistance and phosphate supply on morphology and function of maize roots. Netherlands Journal of Agricultural Science 30:179-192.

Bray, R.H., and L.T. Kurtz. 1945. Determination of total, organic, and available forms of phosphorus in soils. Soil Science 59:39-46.

Busscher, W.J. 1990. Adjustment of flat-tipped penetrometer resistance data to a common water content. Transactions of the ASAE 33(2):519-524. https://doi.org/10.13031/2013.31360

Carcedo, A.J., and B.L. Gambin. 2019. Sorghum drought and heat stress patterns across the Argentinean temperate central region. Field Crops Research 241:107552. https://doi.org/10.1016/j.fcr.2019.06.009

Carrasco, N., M. Zamora, A.A. Melin, A. Bolletta, J. Marinissen, R. Gigón, H. Forján, S. Lagrange, P. Campos, L. Manso, and M. Cicchino. 2011. Manual de sorgo. Instituto Nacional de Tecnología Agropecuaria (INTA), 1ª ed., 105 p. Available at Accessed on Aug. 11, 2026.

Cavalcante, J.S., Favaretto, N., Dieckow, J., Cherobim, V.F., and Barth, G. 2019. Long-term surface application of dairy liquid manure to soil under no-till improves carbon and nitrogen stocks. European Journal of Soil Science, 71(6):1132-1143. https://doi.org/10.1111/ejss.12920

Charlón, V., L. Romero, L. Cuatrin, y M. Taverna. 2007. Utilización de residuos del tambo en un cultivo de sorgo forrajero para silaje. Revista Argentina de Producción Animal 27:216-217.

Demo, A.H., M.K. Gemeda, D.R. Abdo, T.N. Guluma, and D.B. Adugna. 2025. Impact of soil salinity, sodicity, and irrigation water salinity on crop production and coping mechanism in areas of dryland farming. Agrosystems, Geosciences & Environment 8(1):e70072. https://doi.org/10.1002/agg2.70072

Dexter, A.R. 2004. Soil physical quality: Part I. Theory, effects of soil texture, density, and organic matter, and effects on root growth. Geoderma 120(3-4):201-214. https://doi.org/10.1016/j.geoderma.2003.09.004

Dong, L., W. Yang, Q. Wang, W. Tao, and C. Ma. 2026. Hydrological feedback of evaporation-driven salt crystallization in soils: The effect of pore structure and ion composition. Geoderma, 469:117826. https://doi.org/10.1016/j.geoderma.2026.117826

Du, Y., S. Guo, R. Wang, X. Song, and X. Ju. 2023. Soil pore structure mediates the effects of soil oxygen on the dynamics of greenhouse gases during wetting–drying phases. Science of the Total Environment 895:165192. https://doi.org/10.1016/j.scitotenv.2023.165192

Farahani, E., H. Emami, T. Keller, A. Fotovat, and R. Khorassani. 2018. Impact of monovalent cations on soil structure. Part I. Results of an Iranian Soil. International Agrophysics 32(1):57-67. https://doi.org/10.1515/intag-2016-0091

Farooq, U., W. Gorczewska-Langner, and A. Szymkiewicz. 2024. Water retention curves of sandy soils obtained from direct measurements, particle size distribution, and infiltration experiments. Vadose Zone Journal 23(4):e20364. https://doi.org/10.1002/vzj2.20364

Fernández, R., V. Belmonte, A. Quiroga, C. Lobartini, and E. Noellemeyer. 2021. Land-use change affects soil hydro-physical properties in Mollisols of semiarid Central Argentina. Geoderma Regional 25:e00394. https://doi.org/10.1016/j.geodrs.2021.e00394

Fernández, R., A. Quiroga, C. Lobartini y E. Noellemeyer. 2017. Determinación del least limiting water range en Ustoles de la región semiárida pampeana. Ciencia del Suelo 35(2):215-227.

Fu, Y., L.W. de Jonge, P. Moldrup, M. Paradelo, and E. Arthur. 2022. Improvements in soil physical properties after long-term manure addition depend on soil and crop type. Geoderma 425:116062. https://doi.org/10.1016/j.geoderma.2022.116062

Gambaudo, S., S. Imhoff, M.E. Carrizo, M. Marzetti y S. Racca. 2014. Uso de efluentes líquidos de tambo para mejorar la productividad de cultivos anuales y la fertilidad del suelo. Ciencia del Suelo 32(2):197-208.

Ghiberto, P.J., J. Baudracco, P. Heffner, and S. Imhoff. 2022. Farm dairy effluent application on an Argiudoll cultivated with alfalfa (*Medicago* sativa L.): biomass production and persistence. Chilean Journal of Agricultural & Animal Sciences 38(3):354-362. https://doi.org/10.29393/CHJAA38-33DPKT10033

Ghiberto, P.J., S. Imhoff, F. Genero, and A. Heymo. 2020. Soil chemical changes and nutrient leaching losses following application of a farm-dairy effluent. Agrochimica 64(4):331-346. https://doi.org/10.12871/00021857202042

Ghiberto, P.J., S. Imhoff, P.L. Libardi, Á.P. Silva, C.A. Tormena, and M.A. Pilatti. 2015. Soil physical quality of Mollisols quantified by a global index. Scientia Agricola 72:167-174. https://doi.org/10.1590/0103-9016-2013-0414

Giustiniani, E., F. Behrends Kraemer, and L.A. Garibaldi. 2024. Crop sequence intensification: meta-analysis of soil organic carbon and aggregate stability in Argentina. European Journal of Soil Science 75(2):e13485. https://doi.org/10.1111/ejss.13485

Glantz, S.A., and B.K. Slinker. 1990. Primer of applied regression and analysis of variance. McGraw-Hill, New York, USA. 777 p.

Goldberg, N., U. Nachshon, E. Argaman, and M. Ben-Hur. 2020. Short-term effects of livestock manures on soil structure stability, runoff and soil erosion in semi-arid soils under simulated rainfall. Geosciences 10(6):213. https://doi.org/10.3390/geosciences10060213

González, L.H., G. Neffen, V. Benedetto, M. Sánchez Miñarro, A. García, R. Biasatti, P. Rimoldi, C. Alesio, and D. Paiz. 2022. Natural landscape of the Pampa Region in Santa Fe Province, Argentina: environmental resilience and opportunity for changing the agri-food paradigm. In Biodiversity islands: strategies for conservation in human-dominated environments. p. 353-386. Springer International Publishing, Cham, Switzerland. https://doi.org/10.1007/978-3-030-92234-4_14

Guimarães, M.J., W.L. Simões, A.M. Salviano, A.R.D. Oliveira, J.S.D. Silva, J.R. Barros, and L. Willadino. 2022. Management for grain sorghum cultivation under saline water irrigation. Revista Brasileira de Engenharia Agrícola e Ambiental 26(11):755-762. https://doi.org/10.1590/1807-1929/agriambi.v26n11p755-762

Guo, Z.C., Z.B. Zhang, H. Zhou, M.T. Rahman, D.Z. Wang, X.S. Guo, L.J. Li, and X.H. Peng. 2018. Long-term animal manure application promoted biological binding agents but not soil aggregation in a Vertisol. Soil and Tillage Research 180:232-237. https://doi.org/10.1016/j.still.2018.03.007

Han, Z., W. He, H. Shi, Ch. Wang, Ch. Liu, and Y. Feng. 2023. Effects of the integrated use of dairy cow manure on soil properties and biological fertility. Sustainability 15:11693. https://doi.org/10.3390/su151511693

Horwitz, W., and G.W. Latimer. 2007. Official methods of analysis of AOAC international. 18th Edition. AOAC International, USA.

Iglesias, J.O., J.A. Galantini, A. Vallejos y S. Imhoff. 2021. Least limiting water range en un Argiudol del SO de la provincia de Buenos Aires con dos sistemas de labranzas. Ciencia del Suelo 39(2):253-267.

Imhoff, S., P.J. Ghiberto, A. Grioni, and J.P. Gay. 2010. Porosity characterization of Argiudolls under different management systems in the Argentine Flat Pampa. Geoderma 158(3-4):268-274. https://doi.org/10.1016/j.geoderma.2010.05.005

Imhoff, S., M.A. Pilatti, M.E. Carrizo, M.J. Masola, R.P. Marano y O. Felli. 2018. Compactación en suelos del centro y norte de Santa Fe. p. 153-179. En P. Imbelloni y C. Alvarez (eds.). Compactaciones naturales y antrópicas en suelos argentinos. Asociación Argentina de Ciencia del Suelo, Buenos Aires, Argentina.

Imhoff, S., A.P. Silva, P.J. Ghiberto, C.A. Tormena, M.A. Pilatti, and P.L. Libardi. 2016. Physical quality indicators and mechanical behavior of agricultural soils of Argentina. PLoS One 11(4):e0153827. https://doi.org/10.1371/journal.pone.0153827

IRAM. 2009. Calidad ambiental - Calidad del suelo. Pretratamiento de muestras de suelo de uso agropecuario para análisis físicos y químicos con secado en estufa. Instituto Argentino de Normalización y Certificación (IRAM)/SAGyP 29578. Available at https://iramcoleccion.org.ar/norma.aspx?ID=8538. Accessed on Aug. 11, 2026.

Jansen van Rensburg, H.G., A.S. Claassens, and D.J. Beukes. 2009. Relationships between soil buffer capacity and selected soil properties in a resource-poor farming area in the Mpumalanga Province of South Africa. South African Journal of Plant and Soil 26(4):237-243. https://doi.org/10.1080/02571862.2009.10639961

Klute, A. 1986. Water retention: laboratory methods. p. 635-662. In A. Klute (ed.). Methods of soil analysis. Part 1. Physical and mineralogical methods. Soil Science Society of America, Madison, Wisconsin, USA. https://doi.org/10.2136/sssabookser5.1.2ed.c26

Lal, R. 2020. Soil organic matter and water retention. Agronomy Journal 112(5):3265-3277. https://doi.org/10.1002/agj2.20282

Lazzarini, B., J. Baudracco, G. Tuñon, L. Gastaldi, N. Lyons, H. Quattrochi, and N. Lopez-Villalobos. 2019. Milk production from dairy cows in Argentina: current state and perspectives for the future. Applied Animal Science 35(4):426-432. https://doi.org/10.15232/aas.2019-01842

Lenth, R.V. 2023. Package 'emmeans': Estimated Marginal Means, aka Least-Squares Means. R package version 1.8.8. https://cran.r-project.org/package=emmeans

Libardi, P.L. 2018. Dinâmica da água no solo. 3ª ed. Editora da Universidade de São Paulo, São Paulo, Brasil. 352 p.

Lima, H.V., and A.P. Silva. 2008. Sand tension table: procedures for construction and validation. Revista Brasileira de Ciência do Solo 32(5):2209-2214. https://doi.org/10.1590/S0100-06832008000500041

Masola, M.J., C.A. Alesso, M.E. Carrizo, G. Berhongaray, G.F. Botta, R. Horn, and S. Imhoff. 2020. Advantages of the one-wheeled tramline for multiple machinery widths method on sunflower (*Helianthus annus* L.) and maize (*Zea mays* L.) responses in the Argentinean Flat Pampas. Soil and Tillage Research 196:104462. https://doi.org/10.1016/j.still.2019.104462

Meng, Q., X. Ma, J. Zhang, and Z. Yu. 2019. The long-term effects of cattle manure application to agricultural soils as a natural-based solution to combat salinization. Catena 175:193-202. https://doi.org/10.1016/j.catena.2018.12.022

Micucci, G., F. Sgouridis, N.P. McNamara, S. Krause, I. Lynch, F. Roos, R. Well, and S. Ullah. 2023. The 15N-gas flux method for quantifying denitrification in soil: current progress and future directions. Soil Biology and Biochemistry 184:109108. https://doi.org/10.1016/j.soilbio.2023.109108

Miretti, M.C., S. Imhoff, Á.P. Silva, and R. Lavado. 2011. Soil structure degradation in patches of alfalfa fields. Scientia Agricola 67:604-610. https://doi.org/10.1590/S0103-90162010000500015

Montico, S., N. Di Leo, B. Bonel y J. Denoia. 2019. Cambios del uso de la tierra en la cuenca del arroyo Ludueña, Santa Fe: impacto en la sostenibilidad y en los servicios ecosistémicos. Cuadernos del CURIHAM 25:31-39. https://doi.org/10.35305/curiham.v25i0.115

Moreira, V.S., L.A. Candido, M.C. Mota, G. Webler, E.D.P. Oliveira, and D.R. Roberti. 2023. Impacts of climate change on water fluxes and soybean growth in southern Brazil. Revista Ciência Agronômica 54:e20228398. https://doi.org/10.5935/1806-6690.20230014

Moura, M.S., B.M. Silva, P.K. Mota, E. Borghi, A.V. de Resende, S.F. Acuña-Guzman, G.S.S. Araújo, L.C. Silva, and N. Curi. 2021. Soil management and diverse crop rotation can mitigate early-stage no-till compaction and improve least limiting water range in a Ferralsol. Agricultural Water Management 243:106523. https://doi.org/10.1016/j.agwat.2020.106523

Mualem, Y. 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resources Research 12(3):513-522. https://doi.org/10.1029/WR012i003p00513

Mullins, C.E., and K.P. Panayiotopoulos. 1984. The strength of unsaturated mixtures of sand and kaolin and the concept of effective stress. Soil Science 35:459-468. https://doi.org/10.1111/j.1365-2389.1984.tb00303.x

Osooli, H., A. Karimi, and Z. Gerami. 2025. Extensive field research on the moisture retention curve and the pore size distribution in a sandy loam soil enriched by biochar. Journal of Soil Science and Plant Nutrition 1-13. https://doi.org/10.1007/s42729-025-02328-9

Ozlu, E., and S. Kumar. 2018. Response of soil organic carbon, pH, electrical conductivity, and water stable aggregates to long-term annual manure and inorganic fertilizer. Soil Science Society of America Journal 82(5):1243-1251. https://doi.org/10.2136/sssaj2018.02.0082

Öztürk, H.S., and I. Özkan. 2004. Effects of evaporation and different flow regimes on solute distribution in soil. Transport in Porous Media 56:245–255. https://doi.org/10.1023/B:TIPM.0000026088.13958.43

Pandey, P., Y. Fu, J. Gardner-Garcia, J. Pan, J. Huo, X. Li, R. Zhang, and P. Pandey. 2024. The application of aeration and ozonation for E. coli inactivation in dairy manure slurry. Cleaner and Circular Bioeconomy 8:100086. https://doi.org/10.1016/j.clcb.2024.100086

Pessoa, T.N., R.C. Bovi, M.R. Nunes, M. Cooper, D. Uteau, S. Peth, and P.L. Libardi. 2024. Clay mineral composition drives soil structure behavior and the associated physical properties in Brazilian Oxisols. Geoderma Regional 38:e00837. https://doi.org/10.1016/j.geodrs.2024.e00837

Pilatti, M.A., e S. Imhoff. 2008. Relación general entre densidad de partículas y materia orgánica: su aplicación a Molisoles de Santa Fe (Argentina) y Oxisoles de Brasil. Actas XXI Congreso Argentino de la Ciencia del Suelo, San Luis, Argentina.

Pilatti, M.A., S. Imhoff, P.J. Ghiberto, and R.P. Marano. 2006. Changes in some physical properties of Mollisols induced by supplemental irrigation. Geoderma 133(3-4):431-443. https://doi.org/10.1016/j.geoderma.2005.08.007

Pilatti, M.A., C. Alesso, O. Felli, and M. Miretti. 2022. Toma de muestras en suelos. p. 147-180. In M.A. Pilatti, P.J. Ghiberto, and J.A. de Orellana (eds.). Diagnóstico edafológico: Mirando al suelo con ojos de planta. Ediciones UNL, Santa Fe, Argentina. Ediciones UNL. Available at Accessed on Aug. 11, 2026.

Pragg, B., M.M.T. Lakshani, T.C. Deepagoda, K. Cameron, H. Di, T.J. Clough, and K. Smits. 2024. Identification of plant soil water and soil aeration corequisites: A management tool. Soil Science Society of America Journal 88(6):2078-2089. https://doi.org/10.1002/saj2.20772

R Core Team. 2023. R: a language and environment for statistical computing. Version 4.3.1 [software]. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

Rayne, N., and L. Aula. 2020. Livestock manure and the impacts on soil health: a review. Soil Systems 4(4):64. https://doi.org/10.3390/soilsystems4040064

Reichert, J.M., L.E.A.S. Suzuki, D.J. Reinert, R. Horn, and I. Håkansson. 2009. Reference bulk density and critical degree-of-compactness for no-till crop production in subtropical highly weathered soils. Soil and Tillage Research 102(2):242-254. https://doi.org/10.1016/j.still.2008.07.002

Reynolds, W.D., B.T. Bowman, C.F. Drury, C.S. Tan, and X. Lu. 2002. Indicators of good soil physical quality: density and storage parameters. Geoderma 110(1-2):131-146. https://doi.org/10.1016/S0016-7061(02)00228-8

Reynolds, W.D., C.F. Drury, C.S. Tan, C.A. Fox, and X.M. Yang. 2009. Use of indicators and pore volume-function characteristics to quantify soil physical quality. Geoderma 152(3-4):252-263. https://doi.org/10.1016/j.geoderma.2009.06.009

Richter, T.K.S., M. Kauffman, M.K. Mammel, D.W. Lacher, G. Rajashekara, and S.R. Leonard. 2025. Long-term impacts of untreated dairy manure on the microbiome and Shiga toxin-producing Escherichia coli persistence in agricultural soil. Applied and Environmental Microbiology 91(9):e00447-25. https://doi.org/10.1128/aem.00447-25

Rodríguez, M.P., A. Domínguez, and J.C. Bedano. 2025. Large-scale organic farming enhances soil properties and earthworm communities in relation to conventional farming in the Pampas region of Argentina. Applied Soil Ecology 206:105815. https://doi.org/10.1016/j.apsoil.2024.105815

Safadoust, A., P. Feizee, A.A. Mahboubi, B. Gharabaghi, M.R. Mosaddeghi, and B. Ahrens. 2014. Least limiting water range as affected by soil texture and cropping system. Agricultural Water Management 136:34-41. https://doi.org/10.1016/j.agwat.2014.01.007

Safar, F., and J.K. Whalen. 2023. Mechanical stability of newly-formed soil macroaggregates influenced by calcium concentration and the calcium counter-anion. Geoderma 430:116333. https://doi.org/10.1016/j.geoderma.2023.116333

SAMLA. 2004. Sistema de Apoyo Metodológico a los Laboratorios de Análisis de suelos, agua, vegetales y enmiendas orgánicas (SAMLA): Recopilación de técnicas de laboratorio. Secretaría de Agricultura, Ganadería y Pesca [SAGyP], Asociación Argentina de la Ciencia del Suelo [AACS]. Buenos Aires, Argentina. Formato CD-ROM. ISBN 987-9184-40-8.

Sangotayo, A.O., P. Chakraborty, S. Xu, S. Kumar, and P. Kovacs. 2023. Cattle manure application for 12 and 17 years enhanced depth distribution of soil organic carbon and X-ray computed tomography-derived pore characteristics. Scientific Reports 13(1):23042. https://doi.org/10.1038/s41598-023-50110-7

Scanlon, B.R., B.J. Andraski, and J. Bilskie. 2002. Miscellaneous methods for measuring matric or water potential. p. 643-670. In J.H. Dane and G.C. Topp (eds.). Methods of soil analysis. Part 4. Physical methods. Soil Science Society of America Book Series, Madison, Wisconsin, USA.

Schwenk, A.E., N. Jarvis, M. Larsbo, and J. Koestel. 2023. Three-dimensional X-ray imaging of macropore flow. Geoderma 440:116721. https://doi.org/10.1016/j.geoderma.2023.116721

Servicio Nacional de Sanidad y Calidad Agroalimentaria (SENASA). 2021. Caracterización de tambos bovinos. Informe. https://www.argentina.gob.ar/sites/default/files/87caracterizacion_tambos_bovinos_diciembre_2021.pdf

Silva, A.P., and B.D. Kay. 1997. Estimating the least limiting water range of soils from properties and management. Soil Science Society of America Journal 61(3):877-883. https://doi.org/10.2136/sssaj1997.03615995006100030023x

Silva, A.P., B.D. Kay, and E. Perfect. 1994. Characterization of the least limiting water range of soils. Soil Science Society of America Journal 58(6):1775-1781. https://doi.org/10.2136/sssaj1994.03615995005800060028x

Silva, F.G.D., R.N. Assis Junior, R.S. Toma, L.S. Oliveira, E.S. Marques, and J.C.A. Mota. 2022. Physical-hydraulic attributes as indicators of functionality of soil pores under different compaction levels. Revista Caatinga 35(4):884-893. https://doi.org/10.1590/1983-21252022v35n416rc

Sumner, M.E., and W.P. Miller. 2009. Cation exchange capacity and exchange coefficients. p. 1201-1229. In D.L. Sparks, A.L. Page, P.A. Helmke, and R.H. Loeppert (eds.). Methods of soil analysis. Part 3. Chemical methods. John Wiley and Sons, Hoboken, New Jersey, USA.

Tian, Z., W. Gao, D. Kool, T. Ren, R. Horton, and J.L. Heitman. 2018. Approaches for estimating soil water retention curves at various bulk densities with the extended van Genuchten model. Water Resources Research 54(8):5584-5601. https://doi.org/10.1029/2018WR022871

Usowicz, B., J. Lipiec, and A. Siczek. 2024. Fitting the van Genuchten model to the measured hydraulic parameters in soils of different genesis and texture at the regional scale. International Agrophysics 38:373-382. https://doi.org/10.31545/intagr/191380

van Genuchten, M.T. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Science Society of America Journal 44(5):892-898. https://doi.org/10.2136/sssaj1980.03615995004400050002x

van Genuchten, M.T., J. Šimůnek, F.J. Leij, and M. Sejna. 1998. Code for quantifying the hydraulic functions of unsaturated soils – RETC Version 6.0. U.S. Salinity Laboratory, Riverside, California, USA.
Vepraskas, M.J. 1984. Cone index of loamy sands as influenced by pore size distribution and effective stress. Soil Science Society of America Journal 48(6):1220-1225. https://doi.org/10.2136/sssaj1984.03615995004800060003x
Whalen, J.K., B.W. Thomas, and M. Sharifi. 2019. Novel practices and smart technologies to maximize the nitrogen fertilizer value of manure for crop production in cold humid temperate regions. Advances in Agronomy 153:1-85. https://doi.org/10.1016/bs.agron.2018.09.002
Yan, F., Fu, Y., Paradelo, M., Zhang, F., and Arthur, E. 2023. Long-term manure and cropping systems effect on soil water vapour sorption characteristics is controlled by soil texture. Geoderma, 436:116533. https://doi.org/10.1016/j.geoderma.2023.116533

Supplementary material

Equations

van Genuchten (1980) equation with the Mualem (1976) restriction:

$$\theta = \theta_r + \frac{(\theta_{vs} - \theta_{vr})}{[1 + (\alpha\,|\Psi_m|)^n]^m} \quad (1)$$

where θ is the volumetric water content ($cm^3\ cm^{-3}$); Ψ_m is the matric potential ($|kPa|$); θ_{vs} is the volumetric water content at saturation ($cm^3\ cm^{-3}$); θ_{vr} is the residual volumetric water content ($cm^3\ cm^{-3}$), corresponding to Ψ_m of -1500 kPa; α (cm^{-1}), m and n are empirical parameters of the model, where m y n are dimensionless.

First derivative of the van Genuchten equation (1980):

$$S_v(h) = -mn(\theta_{vs} - \theta_{vr})\alpha^n h^n[1 + (\alpha|\Psi_m|)^n]^{-(m+1)} \quad (2)$$

where $S_v(h)$ is the slope of the tangent to the water retention curve in the soil as a function of the Ψ_m.

Capillarity equation:

$$d_e = \frac{4\gamma}{\rho_a g h} \approx \frac{2980}{h}; \text{h} > 0; \text{d}_e;\ 20^{\circ}C \quad (3)$$

where d_e is the effective pore diameter; γ is the surface water tension (72.8 $g\ m\ s^{-2}$), ρ_a is the water density (0.998 $g\ cm^{-3}$) and g is the gravity acceleration (980 $cm\ s^{-2}$).

Tangent inclination at the soil water retention curve (*SWRC*) inflection point:

$$S_{\text{vi}}(h) = \left|-n(\theta_{vs} - \theta_{vr})[1 + (\alpha h)^n]^{-(m+1)}\right| \quad (4)$$

Normalized pore distribution:

$$S^*(h) = \frac{S_v(h)}{S_{vi}} = \frac{m(\alpha h)^n[1 + m^{-1}]^{(m+1)}}{[1 + (\alpha h)^n]^{(m+1)}}; 0 \le S^*(h) \le 1 \quad (5)$$

Structural stability index (Reynolds et al., 2009):

$$SI = \frac{OM}{(clay + loam)} \times 100 \quad (6)$$

where *OM* is the organic matter content.

Equation proposed by Silva and Kay (1997) for fittin the *SWRC*:

$$\theta = d\,\Psi_m{}^{-e} \quad (7)$$

where *d* and *e* are the adjustment parameters.

Soil water content when aeration porosity is 15%:

$$\theta_{PA} = \left(1 - \frac{D_s}{D_p}\right) - 0{,}15 \quad (8)$$

where D_s is the soil density (*g cm*$^{-3}$) and D_p is the particle density (*g cm*$^{-3}$), for which a value of 2.58 *g cm*$^{-3}$ was considered, which is representative of the study area (Pilatti and Imhoff, 2008).

Mullins and Panayiotopoulos (1984) model (effective stress for unsaturated soils):

$$\sigma = \theta_{sr} |\Psi_m| \quad (9)$$

where σ is the effective stress (*kPa*); and θ_{sr} is the relative saturation, i.e., ratio between the volumetric water content at the applied potential and the volumetric water content at saturation (θ/θ_{vs}).

Relationship between σ and *PR*:

$$PR = a + b\,\sigma \quad (10)$$

where *PR* is the soil penetration resistance (*kPa*); *a* and *b* are the model parameters, where *a* represents the cohesion effect due to aggregating substances and *b* the soil compaction effect.

Tables

Table S1. Parameters of the soil water retention curve ($\theta = d\,y_m^{--e}$) for a Typic Argiudoll, Rincon de Ávila soil series, with application of liquid dairy manure (*LDM*), evaluated at 0-15 *cm* depth.

Parameters	D0	D1	D2	D3
d	0,167	0,192	0,187	0,198
e	-0,171	-0,149	-0,143	-0,139

D0: control dose (0 m^3 ha^{-1}); D1: low dose (60 m^3 ha^{-1}); D2: medium dose (120 m^3 ha^{-1}); D3: high dose (180 m^3 ha^{-1}).

Table S2. Adjusts parameters of the soil resistance curve ($RP = a\,\theta^{-b}\,D_s^{c}$) for a Typic Argiudoll, Rincon de Ávila soil series, with application of liquid dairy manure (*LDM*), evaluated at 0-15 *cm* depth.

Parameters	D0	D1	D2	D3
a	0,09	0,03	0,17	0,13
b	-1,18	-1,33	-1,27	-1,48
c	5,51	7,78	3,05	3,23

D0: control dose (0 m^3 ha^{-1}); D1: low dose (60 m^3 ha^{-1}); D2: medium dose (120 m^3 ha^{-1}); D3: high dose (180 m^3 ha^{-1}).