











Whey as an additive in maize silage

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Abstract

The aim of this study was to evaluate the effect of including whey at different inclusion rates on the chemical composition and mineral profile of maize silage. Five whey inclusion rates (0, 2.5, 5, 7.5, and 10% w/w of fresh forage) were tested in a completely randomized design with five replicates. After 80 days of ensiling, samples were analyzed for moisture, dry matter, crude protein, neutral detergent fiber, acid detergent fiber, ash, and the concentrations of calcium, phosphorus, magnesium, potassium, and sodium. Whey inclusion rates significantly increased ash content, reflecting the mineral contribution of this by-product, particularly sodium and potassium. Sodium (Na) concentration followed a quadratic response ($p < .05$) to whey inclusion rates, reaching a minimum at 3.16% whey. Magnesium (Mg) concentration decreased linearly, possibly due to dilution, leaching, or chemical interactions during ensiling. In contrast, moisture, dry matter, crude protein, and fibrous fractions did not significantly differ among treatments, indicating that whey at the tested inclusion rates does not affect cell-wall constituents or crude protein content of the silage. The results indicate that whey can be used as a mineral source in maize silage, increasing mineral content and potentially improving ensiling characteristics. However, high whey inclusion rates should be avoided to prevent excessive sodium concentrations and possible mineral imbalances. Whey represents a viable option for maize silage production when applied at controlled inclusion rates and when its impact on the overall diet of ruminants is considered.

Keywords: agro-industrial by-products; lactic fermentation; ensiling; nutritional quality.

Practical Application: This study evaluates whey as a sustainable additive for maize silage and its effects on mineral composition and nutritional quality. The findings provide producers and researchers with evidence to support the reuse of this agro-industrial by-product, thereby improving resource efficiency and reducing waste.

1 INTRODUCTION

In Brazil, dairy herd nutrition relies predominantly on pasture-based systems due to economic advantages, diverse soil and climate conditions, and the wide availability of tropical forage species. However, during the dry season, forage production declines markedly, failing to meet the nutritional requirements of lactating cows. Consequently, conserved forages become essential to provide supplementary feed during periods of shortage (Johnson et al., 2020).

Among conserved forages, maize silage is one of the most widely used for high-producing dairy cows. This preference is attributed to its established production system, suitability for mechanized harvesting, high dry matter yield, favorable fermentation characteristics, high energy concentration, and good palatability (Guan et al., 2020).

Although maize ensiles readily, producers often apply additives, frequently synthetic, to improve fermentation and

nutritive value (Oliveira et al., 2019). However, agro-industrial by-products generated on-farm or locally, which are often underutilized, can also serve as effective alternative additives. Examples include vinasse (Oliveira et al., 2014), citrus pulp (Souza et al., 2022), rock powder (Taveira et al., 2024), and whey (Muck et al., 2018).

Whey, the liquid by-product obtained during cheese manufacturing and other dairy processing operations, has traditionally been discarded by dairy plants or used with limited efficiency in animal feed. Its appropriate reuse is advantageous because it adds economic value to the dairy chain and mitigates environmental risks associated with improper disposal (Campos et al., 2023).

Whey has emerged as a promising additive for maize silage because of its high concentrations of lactose, soluble proteins, and minerals. These constituents provide fermentable substrates for lactic acid bacteria present in the forage, thereby accelerating

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lactic acid production and pH reduction during ensiling (Souza et al., 2020).

Rapid pH reduction is essential for suppressing undesirable microorganisms, particularly clostridia and enterobacteria, that impair silage quality. Moreover, the nutrients supplied by whey may increase the nutritional value of the silage by raising the concentrations of soluble protein, essential amino acids, and minerals available in the diet (Oliveira et al., 2012).

The principal minerals in whey are calcium, phosphorus, potassium, sodium, and magnesium, with trace amounts of zinc and copper (Lupo et al., 2019). These elements are essential for ruminant metabolism and microbial activity during ensiling. Calcium and phosphorus are required for bone mineralization, enzyme activation, and energy transfer (Silva et al., 2015), whereas potassium and sodium contribute to osmotic and acid–base balance and support nerve and muscle function. Magnesium functions as a cofactor in numerous enzymatic reactions, including those involved in protein synthesis and carbohydrate metabolism (Martinsen et al., 2019).

Thus, incorporating whey into maize silage can increase the mineral concentration of the forage and contribute to fermentative stability, potentially improving the productive and reproductive performance of ruminants. In this context, the objective of this study was to evaluate the effects of including different amounts of whey on the chemical composition and mineral profile of maize silage.

1.1 Relevance of the work

This study evaluates whey as a sustainable additive for maize silage and its effects on mineral composition and nutritional quality. The findings provide producers and researchers with evidence to support the reuse of this agro-industrial by-product, thereby improving resource efficiency and reducing waste.

2 MATERIALS AND METHODS

The experiment was conducted in Quirinópolis, Goiás, Brazil, from December 2023 to June 2024. A completely randomized design with five treatments and five replications (25 experimental units) was used. Treatments consisted of five whey inclusion rates (0, 2.5, 5, 7.5, and 10% w/w of fresh forage). Each experimental unit was a PVC mini-silo (100 mm internal diameter, 750 mm height, 5.89 L volume) filled with approximately 4 kg of fresh material. The whey inclusion rates were defined based on previous research demonstrating the potential of whey as an ensiling additive (Souza et al., 2020).

Soil chemical analysis (Table 1) prior to maize planting indicated the need for liming; therefore, dolomitic limestone was applied at 1.3 Mg ha⁻¹ to increase base saturation.

The maize hybrid AG 8701 PRO4 was selected for silage production because of its high yield potential and adaptation to regional climate. Seeds were sown at 0.50 m row spacing to achieve a population of 60,000 plants ha⁻¹, under a no-tillage system in a medium clay-textured Oxisol in December 2023. Basal fertilization was applied, using 358 kg ha⁻¹ of an N–P₂O₅–K₂O fertilizer (8-28-16), according to local recommendations (EMGOPA, 1988). Nitrogen topdressing was applied 15 days after emergence, using 100 kg ha⁻¹ of urea.

Maize was harvested at the full dent stage (R6), approximately 90 days after sowing, when dry matter and soluble carbohydrate concentrations are adequate for ensiling. The harvested material was chopped and thoroughly mixed with the corresponding whey inclusion rates in sterilized plastic containers. Whey was supplied by a local cheese-processing plant and had the following chemical composition: 360 mg L⁻¹ P; 1600 mg L⁻¹ K; 7 mg L⁻¹ Ca; 2 mg L⁻¹ Mg; 8 mg L⁻¹ S; 600 mg L⁻¹ Na; and pH 3.6. Mini-silos were filled with 300 g of dry sand separated from the forage by a cotton cloth and nylon screen to allow effluent drainage. Forage–whey mixtures were compacted by hand, sealed, and stored upright in a controlled environment for 80 days.

Following the 80-day ensiling period, mini-silos were opened, and the contents were thoroughly homogenized. Samples were analyzed for moisture, dry matter, ash, crude protein (CP), neutral detergent fiber (NDF), and acid detergent fiber (ADF), according to standard procedures (Silva & Queiroz, 2002). For mineral analysis, samples were dried and ground, and aliquots of 15 g were evaluated for P, Ca, Mg, and Na concentrations, following the methods of Malavolta et al. (1997).

Data were subjected to analysis of variance using SISVAR 5.6 (Ferreira, 2019). When treatment effects were significant ($p < .05$), regression analysis (linear or quadratic) was performed.

3 RESULTS AND DISCUSSION

Analysis of variance revealed significant treatment effects only for ash content (Table 2). No significant differences were observed for moisture, dry matter, CP, and NDF.

Silage ash content increased linearly with whey inclusion rates (Figure 1A). The highest whey inclusion rate (10%) increased ash concentration by 13% compared to the control (0% whey). This increase is attributed to the high mineral content of the whey, particularly K (1600 mg L⁻¹) and Na (600 mg L⁻¹).

The increase in ash content is consistent with previous studies that attribute this response to the mineral contribution of whey, which is rich in potassium, sodium, calcium, phosphorus, and magnesium (Faustino et al., 2018). Higher whey inclusion

Table 1. Chemical properties of the Oxisol used for maize silage production in the 0–0.25 m layer.

pH	P	K	Ca ²⁺	Mg ²⁺	Al ³⁺	H+Al	SB	CEC	OM	BS
	Mg dm ⁻³				cmol _c dm ⁻³				%	
4.3	7.97	0.12	1.77	0.58	0.21	3.77	2.5	6.24	1.87	39.53

pH measured in CaCl₂ (1:2.5 soil:solution); P extracted by anion-exchange resin; K extracted with Mehlich 1; Ca²⁺, Mg²⁺, and Al³⁺ extracted with 1 mol L⁻¹ KCl; potential acidity (H + Al) determined with 0.5 mol L⁻¹ calcium acetate (pH 7.0); SB: sum of bases; CEC: cation exchange capacity at pH 7.0; OM: organic matter (Walkley–Black method, organic carbon × 1.724); BS: base saturation.

rates resulted in greater incorporation of these elements into the silage mass. The highly soluble nature of whey minerals likely minimized losses via effluent, thereby enhancing their retention in the final silage (Shabi et al., 1999).

Although moisture content was not significantly affected by whey inclusion rates, a dual effect has been reported in the literature. At moderate inclusion rates, whey can improve fermentation efficiency, increase microbial water-binding capacity, and slightly reduce final moisture (Tavares et al., 2020). However, at high inclusion rates, the additional water introduced by whey exceeds the forage's absorption capacity, resulting in higher moisture content (Lupo et al., 2019). Therefore, silage moisture does not show a linear response and depends on the fermentative effect of intermediate inclusion rates or the excess liquid associated with higher inclusion rates.

Dry matter concentration was also unaffected by whey inclusion rates. Despite the high moisture content of whey, it

contains residual sugars and organic compounds that likely stimulate rapid lactic acid production, accelerating pH reduction and stabilizing the silage (Santos et al., 2006). This rapid stabilization reduces losses from effluent and plant respiration, thereby preserving dry matter. In addition, studies indicate that adding liquid by-products to silage can improve final dry matter recovery by limiting the development of enterobacteria and clostridia, which degrade soluble compounds and contribute to dry matter reduction (Pacheco et al., 2014).

Significant treatment effects were observed for magnesium (Mg) and sodium (Na) concentrations (Table 3), which align with the observed increase in total ash content. In contrast, no significant differences were observed for ADF, phosphorus (P), potassium (K), or calcium (Ca).

The absence of significant effects on NDF and ADF (Tables 2 and 3) indicates that whey did not affect the structural carbohydrate fractions of the forage. Whey primarily supplies

Table 2. Analysis of variance for moisture, dry matter (DM), ash, crude protein (CP), and neutral detergent fiber (NDF) of maize silage ensiled with increasing whey inclusion rates.

Source of variation	DF	Mean square				
		Moisture	DM	Ash	CP	NDF
Whey inclusion rates	4	2.15 ^{ns}	2.15 ^{ns}	0.000441*	1.56 ^{ns}	6.81 ^{ns}
Residual	20	4.51	4.51	0.000693	0.74	15.13
CV%	—	3.0	7.31	7.16	11.23	7.91

*Significant at $p < .05$; ^{ns}not significant; DF: degrees of freedom; CV: coefficient of variation.

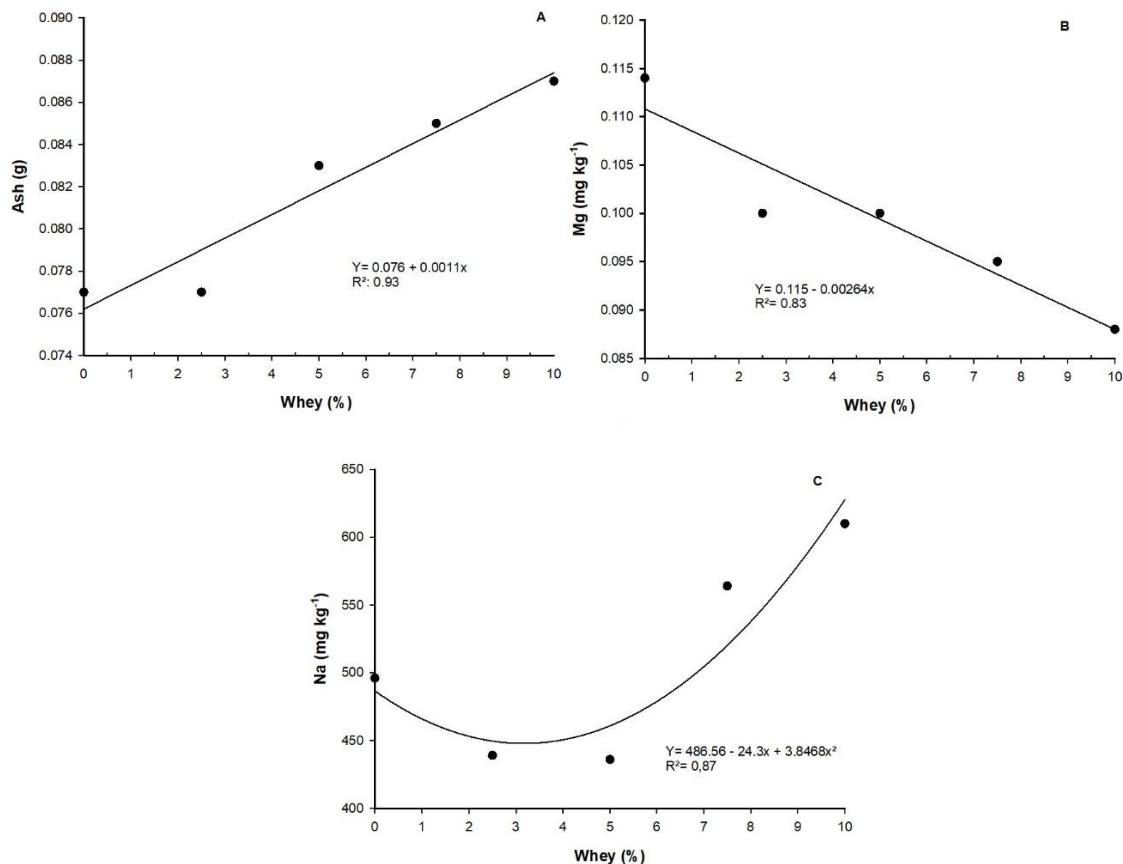


Figure 1. Ash (a), magnesium (Mg) (b), and sodium (Na) (c) concentrations in maize silage ensiled with increasing whey inclusion rates.

Table 3. Analysis of variance for the variables acid detergent fiber (ADF), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na) of maize silage ensiled with increasing whey inclusion rates.

Source of variation	Mean square						
	DF	ADF	P	K	Ca	Mg	Na
Whey inclusion rates	4	1.81 ^{ns}	0.000066 ^{ns}	1.941 ^{ns}	0.00082 ^{ns}	0.000654 ^{**}	29671.56 ^{**}
Residual	20	7.81	0.00009	4.35	0.00062	0.000132	6379.76
CV%	—	11.06	6.27	17.68	13.17	11.22	15.68

*Significant at $p < .05$; ^{ns}not significant; DF: degrees of freedom; CV: coefficient of variation.

soluble carbohydrates and proteins rather than components that modify cell wall constituents such as cellulose, hemicellulose, and lignin (Berchielli et al., 2001). Similar results have been reported by Rocha Neto et al. (2018), who concluded that changes in fiber fractions during ensiling are driven mainly by the extent and type of microbial fermentation rather than by the addition of liquid additives.

Despite the soluble protein and non-protein nitrogen supplied by whey, CP concentration was not significantly affected (Table 2). The whey inclusion rates applied apparently provided insufficient nitrogen to substantially alter silage CP after dilution in the large forage mass (Possenti et al., 2005). Moreover, a considerable portion of whey nitrogen is present as non-protein nitrogen, which is readily metabolized or lost as ammonia during ensiling, thereby limiting its contribution to final CP concentration (Ávila et al., 2019).

Phosphorus (P) and potassium (K) concentrations were not significantly affected by the whey inclusion rates. The absence of significant responses may reflect microbial utilization or precipitation into less soluble forms due to pH changes and interactions with other minerals (Campos et al., 2023). Similarly, calcium (Ca) was not significantly affected by the whey inclusion rates, despite the mineral composition of the whey and the chemical changes occurring during fermentation. The high moisture content of the whey likely favored losses through leaching or precipitation into less soluble forms (Palamidi et al., 2023).

Magnesium (Mg) concentration decreased linearly with whey inclusion rates (Figure 1B). This decrease is associated with the dilution caused by the high moisture content of the additive, which can facilitate losses of soluble minerals such as magnesium, particularly during early stages of fermentation (Carvalho et al., 2017). Additionally, the acidic environment may have promoted leaching or precipitation of Mg into less soluble forms (Garcia et al., 2007).

Sodium (Na) concentration varied significantly, following a quadratic model with whey inclusion rates, reaching a minimum at 3.16% whey (Figure 1C). At this rate, Na concentration was 24% lower than in the control (0% whey). Above 3.16%, Na concentration increased with whey inclusion rates.

The relatively high sodium concentration observed in the control treatment exceeded values commonly reported for maize silage. The initial decline in Na at low whey inclusion rates may be associated with increased leaching, potentiated by the high initial Na concentration, which may have altered effluent production and ionic interactions during early fermentation (Souza et al., 2020).

During cheese manufacturing, a substantial portion of the salt (primarily NaCl) added to or applied on the curd surface is transferred to the whey, resulting in a by-product with high sodium content and electrical conductivity. This residual NaCl influences whey protein stability and mineral solubility, complicating its direct use as a feed ingredient (Nair et al., 2004) and the wastewater treatment when it is discarded (Diblíková et al., 2013). These factors highlight the importance of reallocating whey for use in animal feed.

The highest whey inclusion rates markedly increased sodium concentration in the maize silage because of the high Na content of the whey (600 mg L⁻¹) and the high solubility of sodium, which limits precipitation or effluent losses during ensiling (Vidal & Saran Netto, 2018). In contrast to magnesium, sodium showed a relatively consistent increase above 3.16% whey, indicating that whey can serve as a supplementary Na source in the animal diet.

The observed variation in Na and Mg concentrations with whey inclusion rates indicates that whey not only modified the silage mineral profile but may also influence its nutritional contribution to the total diet of ruminants. According to Motta et al. (2020), maize silage naturally contains low sodium concentrations, generally below 0.03% of dry matter, which explains the need for mineral supplementation in production systems. However, increasing forage sodium concentrations through supplementation should consider Na requirements. According to Ferreira et al. (2023), complete diets for cattle should contain sodium at 0.08–0.12% of dry matter to meet physiological requirements adequately. Therefore, although whey increases silage mineral content, dietary mineral balance still requires additional supplementation to fully comply with nutritional recommendations.

The progressive increase in sodium concentration with higher whey inclusion rates has relevant physiological implications for osmotic regulation, nerve impulse transmission, and intestinal nutrient absorption (Dias et al., 2018). However, increased sodium concentrations may alter acid-base balance by modifying the dietary cation–anion difference, especially in prepartum dairy cows (Castro et al., 2009; Moraes, 2001). In Brazilian production systems, where mineral supplementation is frequently based on empirical practices or excessive dependence on standardized commercial mixtures, inadequate mineral management can lead to suboptimal animal performance (Malafaia et al., 2014). Thus, the present results indicate a beneficial nutritional contribution of whey but highlight that its use should be combined with proper dietary mineral balancing tailored to the specific production system.

The observed decreases in magnesium concentration with whey inclusion rates contradict the expectation for a mineral-rich additive and suggest dilution or chemical interactions during ensiling. Magnesium is highly susceptible to leaching during ensiling, particularly when the forage moisture is high (Motta et al., 2020). Furthermore, high dietary concentrations of sodium and potassium can antagonize magnesium absorption and retention through competitive interactions at intestinal and ruminal epithelial transport sites (Ferreira et al., 2023; Moraes, 2001). This inverse relationship observed in the present study suggests that, although whey can supplement minerals, high inclusion rates may induce macroelement imbalances, especially in potassium-rich diets, such as those based on maize silage.

According to nutritional requirements established by the NRC (2001) and corroborated by Ferreira et al. (2023) and Silveira (2017), maize silage treated with whey partially meets the cattle sodium requirements (0.08–0.12% of dry matter) but does not supply sufficient magnesium and phosphorus for all physiological stages. These results indicate that whey should be used strategically as a complementary additive rather than as a full replacement for mineral supplements. Furthermore, the findings emphasize the necessity of rigorous mineral management because inadequate practices can impair both the productive performance and metabolic health of cattle (Giacomel et al., 2022; Malafaia et al., 2014).

4 CONCLUSION

Including whey as an additive in maize silage increases sodium concentration and enriches the silage mineral profile, thereby improving the nutritional value of the ensiled forage; however, its use should be accompanied by appropriate dietary mineral balancing to ensure adequacy for specific physiological stages and production categories. Although magnesium concentration decreased with whey inclusion rates, the overall effect remains favorable and supports the use of this dairy by-product as a cost-effective and sustainable additive in silage production.

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