UNIVERSIDADE FEDERAL DO PARANÁ

AGRICULTURAL GYPSUM APPLICATION TO MINIMIZE LOSSES IN MANGO FRUIT YIELD AND QUALITY

Federal University of Paraná – UFPR X National Mango Board

(Final Report)

Volnei Pauletti[1]

Danilo Eduardo Rozane[2]

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[1] Professor Engº Agrº Dr. Department of Soils and Agricultural Engineering, Federal University of Paraná, Curitiba – PR

[2] Professor Engº Agrº Dr. São Paulo State University "Júlio de Mesquita Filho", Registro – SP

PROJECT IDENTIFICATION

Title of Research Project: Agricultural gypsum application to minimize losses in mango fruit yield and quality

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Principal Investigator & Collaborators:

- Prof. Dr. Volnei Pauletti (UFPR) - Coordenador
- Prof. Dr. Danilo Eduardo Rozane (Unesp)
- Doctoral Student Pedro Henrique Malucelli Mariotto (UFPR)

1 Introdution

Mangoes (*Mangifera indica* L.) are grown in tropical and subtropical environments, with Brazil recognized as one of the main producers (KIST et al., 2023; TRIDGE, 2022). These regions generally have irregular water conditions, which can lead to losses in productivity and/or fruit quality.

In a cultivation system (with or without irrigation), increased root growth at greater depths increases the amount of water and nutrients available to the plant. However, for roots to grow at a greater depth, there can be no physical (such as compaction) or chemical restrictions. Among the chemical factors, the presence of aluminum (Al) at toxic levels and low calcium (Ca) content are the two main limiting factors in acidic tropical environments. Al is neutralized with the application of acidity correctors, usually carbonates (limestone), but their action is restricted to the layers in which it was applied/incorporated, with slow mobility in depth (60 to 80cm). Ca is normally supplied through the application of acidity correctors and has low mobility in the soil profile. Furthermore, for mango trees specifically, there are numerous doubts in Brazil regarding the appropriate base saturation for its cultivation, given the variations in recommendations presented in the national literature – from 80% (Van Raij et al., 1997; NEPAR; 2019) to 51% (Correia et al., 2018).

Gypsum ($CaSO_4.2H_2O$) facilitates the rapid movement of Ca in the soil profile (Pauletti et al., 2014; Sumner et al., 1986). This effect may be important because Ca plays a role in cell division and pectate sedimentation in cell walls. It is absorbed almost exclusively in the root cap region and is not mobile within the plant (Hawkesford et al., 2012). Therefore, its deficiency at deeper soil layers, in addition to restricting its absorption, decreases or limits root growth in these layers, making the plant more prone to water and nutrient supply deficiencies due to limited soil exploration. In addition to supplying and moving Ca to greater depths, gypsum reduces the toxic action of Al^{+3} on plants and provides the supply of S, a fact of extreme interest for crops in water-restricted regions. Historically, Ritchey et al. (1980) reported that gypsum contributed to significant reductions in aluminum saturation down to a depth of 1.2 m, where aluminum originally occupied 74% of the soil exchange sites.

Positive effects of gypsum application on productivity are observed mainly in years of water deficit. This increase can be null or range from 6 to 36% in annual species (Tiecher et al., 2018; Pauletti et al., 2014; Caires, Joris, Churkca, 2011; Black, Cameron, 1984) and up to 20% in perennial species (Moreira et al., 2001; Serrano et al., 2018).

Furthermore, the effects of Ca imbalance on the quality of mango fruits are reported by Assis et al. (2004), who indicated that low Ca and Mg concentrations and high K/Ca and N/Ca ratios, both in the pulp and peel, are indicative of physiological disorders. The occurrence of certain physiological disorders in mango fruits have been related to low Ca levels in the pulp (Gunjate et al., 1979; Lima et al., 1997).

However, Sampaio et al. (1999) reported that the causes of pulp collapse are quite complex and are not fully understood. Some attempts to increase calcium availability to the fruits and reduce the problems of physiological disorders have been made. Bissoli Junior (1992) applied calcium chloride (40.000 $mg \cdot L^{-1}$) to 'Tommy Atkins' mangoes during the 60 days after anthesis and found that this treatment increased the calcium content in both the pulp and the peel of the fruit, benefiting post-harvest preservation. However, the author did not mention this effect on pulp collapse. Similarly, Rabelo et al. (1996), calcium chloride (0.6%) three times before harvest in ‘Tommy Atkins’ mangoes but did not observe a reduction in postharvest physiological disorders. The authors attributed the lack of response to the adequate calcium level in the soil.

Sampaio et al. (1999), conducted seven biweekly applications of with $CaCl_2$ (0.6 or 1.2%) on 'Tommy Atkins' mangoes, covering practically the entire fruiting phase of the mango trees. The authors concluded that, besides the pre-harvest sprays not increasing the Ca content in the pulp, the occurrence of physiological disorders was similar in fruits with different Ca levels in the pulp. Similar results were observed when there was variation in the Ca/N ratio. Nevertheless, the authors indicate that it was confirmed that late harvests increase the occurrence of physiological disorders in mangoes.

The importance of the N/Ca, K/Ca, and K/Mg ratios in the occurrence of physiological disorders in mangoes can also be evidenced by the physiological role of these elements and the speed of their absorption and translocation within the plants. According to Hawkesford et al. (2012), nitrogen and potassium are absorbed and distributed rapidly and easily in plant tissues and organs by both the phloem and xylem. In contrast, the absorption of Ca and Mg by plants is much less efficient than that of K and N. Furthermore, phloem vessels, the main provider of nutrients for the fruits, always have very low Ca concentrations. This highlights the importance and need to increase the supply of Ca, especially at greater soil depths. Furthermore, as already discussed, Ca does not compete with the high levels of K required for mango fertilization, which are applied to the surface- and without incorporation.

For both industry and fresh consumption, significant challenges from nutritional disorders that compromise fruit quality. Internal degradation or fruit collapse, characterized by poor cell development, flesh browning, and softening, Asignificantly impairs fruit marketability (MA et al., 2022; ULLAH et al., 2024). The occurrence of this disorder has been particularly associated with calcium deficiency in the fruit, although this relationship remains complex and not yet fully understood (SHIVASHANKAR, 2014).

2 Objectives

To determine the influence of gypsum on soil fertility and on the efficiency of calcium and sulfur correction in soil depth in areas of mango cultivation, as well as its consequences on fruit yield and quality.

3 Material and Methods

Three field experiments were carried out in mango-growing areas in the states of São Paulo (São João and Garbin farms) and Pernambuco (FrutiVita farm) (Table 1). The climate in these regions varies, with Nenê and Garbin having tropical characteristics, and Petrolina being semi-arid. (ALVARES et al., 2013). Both the Garbin and Petrolina areas are irrigated. The studies involved 'Tommy Atkins' in São Paulo areas and 'Kent' in Pernambuco, with harvests typically occurring in mid-December.

Table 1. General data on the location and cultivation method of the mango orchards where the experiments were conducted

Farm	City /State	Irrigation	Latitude	Longitude	Altitude	Experiment implantation
São João	Taquaritinga / SP	No	21°21'03.7"S	48°28'12.6"W	579m	28/10/2021
Garbin	Monte Alto / SP	Yes	21°14'56.6"S	48°33'17.4"W	735m	29/10/2021
FrutiVita	Petrolina / PE	Yes	09°19'05.4"S	40°38'44.0"W	376m	08/12/2021

The Tommy Atkins cultivar orchards were established at Fazenda São Sebastião in Taquaritinga, São Paulo, in 2006, with a spacing of 7.5 x 4.5 m, under dryland conditions; at Fazenda Garbin in Monte Alto, São Paulo, in 1996, with a spacing of 8.0 x 6.0 m, under irrigated conditions; and the Kent cultivar at Fazenda FrutVita in Petrolina, Pernambuco, in 1998, with a spacing of 7.0 x 5.0 m, under irrigated conditions.

Figure 1 – Image indicating the municipalities where the experiments were conducted in the state of São Paulo, Brazil.

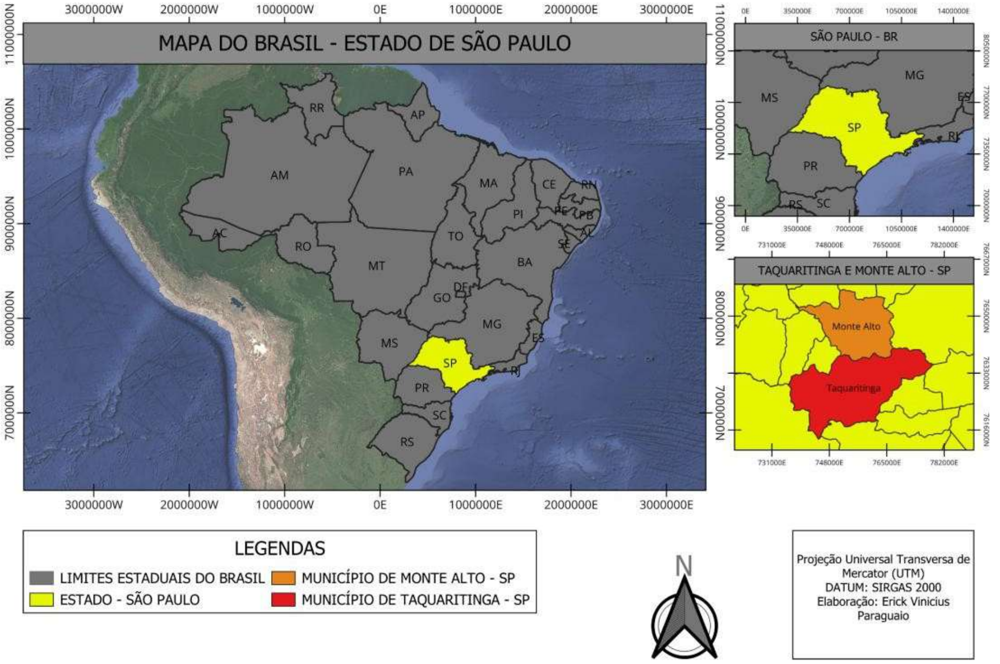
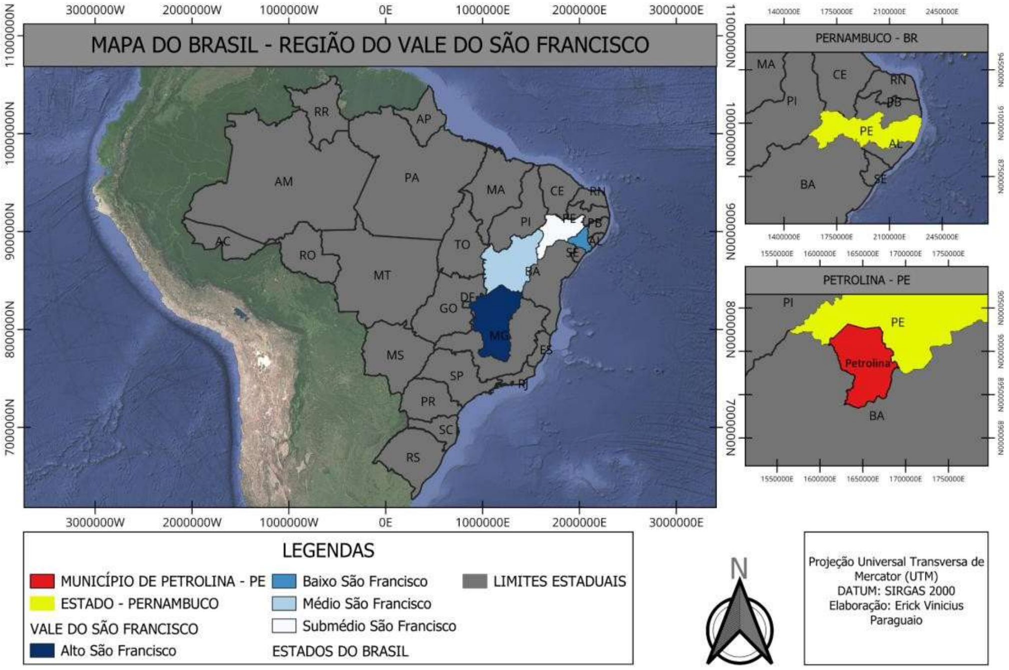


Figure 2 - Image indicating the municipality where the experiments were conducted in the state of Pernambuco - Brazil.



In all areas, mechanical pruning of the plants is performed each harvest to increase light and air intake into the canopy, improve fruit quality, and facilitate harvesting. The method consists of cutting dry, diseased, or inward-growing branches and pruning excessively long branches just below a node or bud, leaving 3 to 4 leaves to encourage new, distributed growth.

The experimental design for the field trials was a factorial setup, combining two doses of limestone and five doses of gypsum applied to the soil surface (2x5). The plots were arranged in four randomized blocks at all study locations. Each replicate consisted of five adjacent trees, with the three central trees selected for assessment. Treatments involved the application of varying rates of lime and gypsum to the soil, aimed at increasing Ca availability:

- Limestone: two rates to raise base saturation (V %) in the 0 - 20 cm soil layer to 51% (CORREIA et al., 2018) or 100%;
- Gypsum: five rates (0 kg ha^{-1} plus four additional rates) calculated to achieve four evenly spaced Ca saturation levels in the 0.2 - 0.4 m soil, from the baseline up to 80 % (0%, 20%, 40%, 60% and 80%). Because baseline Ca % in cation exchange capacity (CEC) varied among sites, gypsum rates were site-specific. To identify soil chemical variability in the experimental area, composite samples were also collected and analyzed in each experimental block (Table 3).

Below is a summary of the treatments applied in each area (expressed in kg of dry mass ha^{-1}):

- Petrolina (FrutiVita farm): lime 0, 735 kg ha^{-1}; gypsum 0, 733, 1466, 2199, 2932 kg ha^{-1};
- Taquaritinga (São Sebastião farm): lime 0, 1200 kg ha^{-1}; gypsum 0, 699, 1398, 2096, 2795 kg ha^{-1};
- Monte Alto (Garbin farm): lime 0, 2881 kg ha^{-1}; gypsum 0, 956, 1911, 2867, 3823 kg ha^{-1}.

The characteristics of the limestone and gypsum used in each area were approximately: limestone - CaO 28%, MgO 12%, PRNT 62%; and gypsum - CaO 30%, Ca 21%, S 17%.

Table 2 – Pre-treatment soil chemical profile across depths in mango orchards from Petrolina, Taquaritinga, and Monte Alto areas.

Variable →	**Depth**	**pH**	**O.M.**	**K**	**Ca**	**Mg**	**Al**	**H+Al**	**S.B.**	**C.E.C.**	**P**	**S-SO_4**	**B**	**Cu**	**Fe**	**Mn**	**Zn**	**V**	**m**	**Ca**	**Mg**
Area↓ Unit →	**cm**	**$CaCl_2$**	**g dm^{-3}**	**mmolc dm^{-3}**							**mg dm^{-3}**							**%**			
Petrolina	0-10	7.5	22.5	10.4	79.2	13.7	0.0	6.0	103.3	109.3	52.2	39.2	2.2	19.1	27.2	37.0	18.2	94.4	0.0	72.3	12.4
	10-20	7.6	12.5	9.2	38.3	5.2	0.0	9.4	52.6	62.0	32.6	19.5	1.1	14.2	23.4	23.3	14.0	84.5	0.0	61.0	8.2
	20-40	7.3	8.5	8.7	23.0	2.7	0.0	7.4	34.3	41.8	22.9	26.7	1.0	8.4	19.4	10.5	15.5	82.1	0.0	54.8	6.5
	40-60	7.4	8.1	6.5	21.6	3.2	0.0	11.4	31.2	42.7	23.4	26.1	1.0	5.3	26.3	15.3	14.9	73.1	0.0	50.5	7.4
	60-80	7.1	7.9	6.1	22.1	3.6	0.0	8.5	31.8	40.3	28.2	26.6	0.8	5.5	24.5	11.8	17.0	78.6	0.0	54.4	9.1
	80-100	7.3	8.1	5.7	22.7	3.6	0.0	11.6	32.0	43.6	27.0	7.2	0.9	6.0	28.4	13.3	18.7	73.1	0.0	51.8	8.3
Taquaritinga	0-10	6.4	15.2	3.9	35.1	6.2	0.0	10.8	45.2	56.0	52.6	5.4	0.6	31.1	14.8	27.3	5.2	80.2	0.0	62.2	10.8
	10-20	5.9	11.4	2.1	25.2	4.3	0.0	13.1	31.5	44.7	30.3	5.6	0.5	16.2	20.0	19.8	4.0	70.7	0.0	56.5	9.6
	20-40	5.9	9.9	1.1	28.4	5.0	0.0	14.0	34.5	48.4	20.3	17.9	0.5	9.2	28.0	17.8	6.7	70.9	0.0	58.4	10.2
	40-60	5.9	9.7	1.5	36.2	6.7	0.0	14.0	44.4	58.4	18.5	21.5	0.5	8.3	32.5	17.5	7.6	75.7	0.0	61.9	11.2
Monte Alto	0-10	6.1	21.4	3.7	62.8	17.1	0.0	9.5	83.6	93.1	57.9	3.5	0.4	5.7	27.5	14.8	3.5	89.8	0.0	67.5	18.3
	10-20	6.2	13.0	2.8	47.0	15.9	0.0	11.2	65.8	77.0	50.2	3.6	0.3	4.0	32.8	13.8	2.3	85.5	0.0	61.1	20.7
	20-40	5.4	8.9	3.1	54.7	16.9	0.0	16.3	74.6	90.9	30.1	2.7	0.3	1.2	35.8	11.5	1.5	82.0	0.0	60.1	18.5
	40-60	5.3	8.3	3.8	65.7	21.4	0.0	17.5	90.9	108.4	21.0	3.2	0.3	0.9	28.8	11.5	2.1	83.8	0.0	60.6	19.7

NOTE: O.M. = organic matter content; S.B. = total sum of bases; C.E.C. = cation exchange capacity; V = base saturation percentage; m = acid saturation percentage (H+Al).

Table 3. Chemical analysis of soil samples collected per block before application of treatments in the three experimental areas.

Farm	Municipality	Block	Depth	pH	C	P	$S\text{-}SO_4$	K	Ca	Mg	H+Al	Al	V
			cm		g dm^{-3}	mg dm^{-3}		mmol$_c$ dm^{-3}					%
Fz. Garbin	Monte Alto - SP	1	0-10	5,2	14	77	6	4,1	65	19	10	0	90
Fz. Garbin	Monte Alto - SP	1	0-20	6,1	9	58	3	3,8	55	17	11	0	88
Fz. Garbin	Monte Alto - SP	1	10-20	6,2	7	71	3	3,4	50	17	11	0	86
Fz. Garbin	Monte Alto - SP	1	20-40	5,2	5	28	3	3,8	58	19	14	0	85
Fz. Garbin	Monte Alto - SP	1	40-60	5,3	5	17	3	3,8	65	23	18	0	84
Fz. Garbin	Monte Alto - SP	2	0-10	6,3	12	71	3	3,4	61	17	9	0	90
Fz. Garbin	Monte Alto - SP	2	0-20	5,9	10	47	3	2,7	55	16	14	0	84
Fz. Garbin	Monte Alto - SP	2	10-20	6,2	8	49	2	2,2	45	17	11	0	85
Fz. Garbin	Monte Alto - SP	2	20-40	5,3	6	34	2	2,9	54	17	18	0	80
Fz. Garbin	Monte Alto - SP	2	40-60	5,3	5	19	2	2,9	60	20	18	0	82
Fz. Garbin	Monte Alto - SP	3	0-10	6,4	12	39	2	4,3	68	18	10	0	90
Fz. Garbin	Monte Alto - SP	3	0-20	6,1	8	34	3	3,1	58	16	11	0	88
Fz. Garbin	Monte Alto - SP	3	10-20	6,1	8	33	3	3,2	51	16	13	0	85
Fz. Garbin	Monte Alto - SP	3	20-40	5,3	5	41	3	2,7	58	17	16	0	83
Fz. Garbin	Monte Alto - SP	3	40-60	5,3	5	18	4	4,0	75	23	20	0	84
Fz. Garbin	Monte Alto - SP	4	0-10	6,5	13	44	3	3,1	57	14	8	0	90
Fz. Garbin	Monte Alto - SP	4	0-20	6,1	7	43	12	2,9	51	15	12	0	85
Fz. Garbin	Monte Alto - SP	4	10-20	6,3	7	47	6	2,5	42	13	9	0	86
Fz. Garbin	Monte Alto - SP	4	20-40	5,6	5	18	3	3,1	50	14	16	0	81
Fz. Garbin	Monte Alto - SP	4	40-60	5,4	5	30	3	4,7	63	20	15	0	86
Fz. São Sebastião	Taquaritinga - SP	1	0-10	6,4	9	59	5	3,8	42	9	11	0	83
Fz. São Sebastião	Taquaritinga - SP	1	0-20	6,1	7	37	56	2,2	35	6	13	0	77
Fz. São Sebastião	Taquaritinga - SP	1	10-20	6,1	7	35	7	1,8	28	5	13	0	72
Fz. São Sebastião	Taquaritinga - SP	1	20-40	6,1	6	30	33	2,0	32	5	13	0	75
Fz. São Sebastião	Taquaritinga - SP	1	40-60	6,0	6	23	25	1,4	32	5	13	0	74
Fz. São Sebastião	Taquaritinga - SP	2	0-10	6,3	8	54	8	3,8	43	8	10	0	85
Fz. São Sebastião	Taquaritinga - SP	2	0-20	6,1	6	50	7	1,6	27	6	12	0	73
Fz. São Sebastião	Taquaritinga - SP	2	10-20	5,8	6	33	6	2,0	23	4	12	0	71
Fz. São Sebastião	Taquaritinga - SP	2	20-40	5,7	5	20	7	1,3	23	4	15	0	66
Fz. São Sebastião	Taquaritinga - SP	2	40-60	5,8	5	16	10	2,2	44	9	13	0	80
Fz. São Sebastião	Taquaritinga - SP	3	0-10	6,3	9	52	4	4,1	27	5	12	0	74
Fz. São Sebastião	Taquaritinga - SP	3	0-20	6,0	6	29	6	1,1	27	4	11	0	75
Fz. São Sebastião	Taquaritinga - SP	3	10-20	5,9	7	22	4	2,0	26	5	16	0	68
Fz. São Sebastião	Taquaritinga - SP	3	20-40	5,8	6	13	7	0,4	30	8	13	0	74
Fz. São Sebastião	Taquaritinga - SP	3	40-60	5,7	6	15	9	1,4	37	8	16	0	74
Fz. São Sebastião	Taquaritinga - SP	4	0-10	6,4	9	45	4	4,0	28	4	10	0	79
Fz. São Sebastião	Taquaritinga - SP	4	0-20	5,9	6	22	46	1,3	25	4	14	0	69
Fz. São Sebastião	Taquaritinga - SP	4	10-20	5,9	7	31	6	2,5	24	4	12	0	72
Fz. São Sebastião	Taquaritinga - SP	4	20-40	5,9	5	18	25	0,9	28	4	15	0	69
Fz. São Sebastião	Taquaritinga - SP	4	40-60	6,0	5	21	42	1,1	32	6	14	0	74
Fz. Fruti Vita	Petrolina-PE	1	0-10	7,2	14	58	53	11,2	79	14	6	0	95
Fz. Fruti Vita	Petrolina-PE	1	10-20	6,9	6	27	41	9,8	32	5	11	0	80
Fz. Fruti Vita	Petrolina-PE	1	20-40	7,2	5	18	75	9,8	23	3	8	0	82
Fz. Fruti Vita	Petrolina-PE	1	40-60	7,1	5	21	87	7,7	22	4	11	0	74
Fz. Fruti Vita	Petrolina-PE	1	60-80	7,0	5	24	84	6,1	20	5	8	0	79
Fz. Fruti Vita	Petrolina-PE	1	80-100	7,3	5	19	7	5,3	22	5	12	0	72
Fz. Fruti Vita	Petrolina-PE	2	0-10	7,5	12	77	23	10,5	63	11	6	0	93
Fz. Fruti Vita	Petrolina-PE	2	10-20	7,6	7	51	7	9,8	30	4	9	0	82
Fz. Fruti Vita	Petrolina-PE	2	20-40	7,1	5	38	3	8,4	19	3	7	0	80
Fz. Fruti Vita	Petrolina-PE	2	40-60	7,3	5	34	4	5,2	18	3	13	0	67
Fz. Fruti Vita	Petrolina-PE	2	60-80	7,0	4	46	5	4,8	18	4	9	0	76
Fz. Fruti Vita	Petrolina-PE	2	80-100	7,3	5	40	4	6,4	19	3	12	0	70
Fz. Fruti Vita	Petrolina-PE	3	0-10	7,7	10	31	30	10,9	80	11	6	0	95
Fz. Fruti Vita	Petrolina-PE	3	10-20	7,9	7	22	9	9,3	41	5	9	0	86
Fz. Fruti Vita	Petrolina-PE	3	20-40	7,5	5	14	14	8,9	24	3	7	0	84
Fz. Fruti Vita	Petrolina-PE	3	40-60	7,7	4	14	6	7,7	22	3	10	0	76
Fz. Fruti Vita	Petrolina-PE	3	60-80	7,3	4	16	6	6,4	24	4	9	0	80
Fz. Fruti Vita	Petrolina-PE	3	80-100	7,5	5	18	12	5,7	29	4	11	0	78
Fz. Fruti Vita	Petrolina-PE	4	0-10	7,7	15	42	51	8,9	95	19	6	0	95
Fz. Fruti Vita	Petrolina-PE	4	10-20	7,9	9	31	21	8,0	51	8	9	0	89
Fz. Fruti Vita	Petrolina-PE	4	20-40	7,5	5	22	14	7,7	26	3	8	0	82
Fz. Fruti Vita	Petrolina-PE	4	40-60	7,6	5	25	7	5,5	25	4	11	0	75
Fz. Fruti Vita	Petrolina-PE	4	60-80	7,3	5	27	12	7,3	26	3	9	0	81
Fz. Fruti Vita	Petrolina-PE	4	80-100	7,2	5	32	5	5,2	22	4	12	0	72

3.1 Assessments

- Soil analysis before implementation, and after the 1st and 3rd harvest: 0.0-0.10, 0.10-0.20, 0.20-0.40, 0.40-0.60, 0.60-0.80, 0.80-1.00 m. Eight sub-samples were collected per plot, mixed, approximately 300 g separated, and sent to the laboratory for drying, grinding, and analysis.

- Productivity: harvest and weighing of all fruits from the 3 central plants in the plot.

- Number of fruits: counting the number of fruits harvested per plot.

- Fruit quality: In the 2023 and 2024 harvests, the qualitative aspects of the fruits were evaluated. For this purpose, in the second week after the beginning of the harvest, two fruits per plant (eight fruits per plot) were randomly separated for analysis of dry matter, total soluble solids (TSS) (ºBrix), pulp firmness (Newtons), according to the methodology described by the Adolfo Lutz Institute (2008), as well as internal damage and shelf life (Rodrigues, et al., 2008). First, the flesh firmness of the fruits was determined using a Brookfield CT3 Texturometer with a 2 mm tip, 5 mm penetration, and a penetration speed of 5 $mm.s^{-1}$. Subsequently, the fruits were crushed for analysis of the total soluble solids content, measured using a model N-1E refractometer. Dry matter was determined in four fruits from each plot, one per useful plant, which were weighed at harvest and subsequently crushed for drying to a constant weight in a study at 65°C. Shelf life was determined by storing the fruits at 10 to 12°C until fully ripened, when the incidence of internal damage such as collapse, stalk rot, and physiological disturbance was determined.

- Leaf analysis: In all harvests, four leaves with petioles were collected from each useful plant in the plot at flowering, one at each cardinal point, in the middle of the last vegetation flush, in the middle third of the plant. The samples were placed in a forced-air oven at 45°C to dry for 72 hours until constant mass was achieved and then ground. To digest the plant tissue, a 1g sample was placed in porcelain crucibles and calcined at 500°C for 3 hours. The resulting ash was dissolved in hydrochloric acid with a concentration of 3 mol L^{-1} and heated for 20 minutes on a hot plate at 70°C. After dissolution, the extracts were filtered using blue-banded filter paper with dimensions between 5-8 micrometers and subsequently diluted to a final volume of 100 mL using reverse osmosis water. The quantification of the elements P, K, Ca, Mg, B, Cu, Fe, Mn and Zn was performed using the Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES, Varian 720-ES) technique, following the methodologies adapted from Martins and Reissmann (2007) for chemical determinations. N was determined by sulfuric digestion and subsequent vapor stripping in a semi-micro Kjeldahl apparatus (Tedesco et al., 1995).

- Ca distribution within fruit tissues: Fruit samples were collected at harvest and subjected to controlled ripening and storage conditions. Post-harvest evaluations included the assessment of internal collapse incidence, as present or absent. The Ca fractions were determined in the peel, pulp near the pell and pulp near the seed, determining the Ca soluble in ethanol, water, acetic acid, hydrochloric acid and residuals.

3.2 Statistical Analyses

The results obtained were tabulated and tested for normality using the Shapiro-Wilk test and homoscedasticity using the Oneillmathews test. When necessary, the Kruskal-Wales method was used to verify nonparametric data. Subsequently, the variance test (ANOVA) was performed in the R software, RStudio interface, version 4.3.0; 9.2.191.153, standard packages of the version (R CORE TEAM, 2023; RSTUDIO TEAM, 2023).

4 Results

4.1 Effects on the plant

Fruit yield varied between harvests in experiments conducted in São Paulo state (Taquaritinga and Monte Alto) but not in Petrolina - Pernambuco. However, leaf nutrient levels varied between evaluation years at all sites. Limestone application had an effect only on foliar Zn levels in Petrolina, N levels in Taquaritinga, and Ca and B levels in Monte Alto. Gypsum alone had an effect only on foliar S levels in Monte Alto. Interaction effects between the two products (limestone and gypsum) were observed for Mg levels in Petrolina and Taquaritinga, and for Mn levels in Petrolina (Table 4).

Table 4. Summary of ANOVA analysis (p-value) for the variables Yield (Prod) and leaf nutrient content, as a function of time (years), application of limestone ($CaCO_3$) and gypsum ($CaSO_4$) in the experiments in Petrolina, Taquaritinga and Monte Alto.

Factor	G.L.	Petrolina																							
		Prod	*p*	N	*p*	P	*p*	K	*p*	Ca	*P*	Mg	*p*	S	*p*	B	*p*	Cu	*p*	Fe	*p*	Mn	*p*	Zn	*p*
T (Time)	2	0,16	0,85	9,41	0,00	42,95	0,00	94,75	0,00	192,77	0,00	33,71	0,00	78,10	0,00	471,52	0,00	169,65	0,00	15,47	0,00	85,39	0,00	141,30	0,00
$CaCO_3$	1	0,49	0,49	0,00	0,99	1,03	0,31	0,28	0,60	0,57	0,45	2,03	0,16	0,21	0,65	1,29	0,26	3,48	0,07	0,02	0,90	0,00	0,96	9,76	0,00
$CaSO_4$	4	3,02	0,02	0,59	0,67	1,21	0,31	0,39	0,81	1,12	0,35	0,98	0,42	0,85	0,50	0,11	0,98	1,29	0,28	1,88	0,12	0,06	0,99	1,46	0,22
T*$CaCO_3$	2	2,47	0,09	0,71	0,49	0,14	0,87	0,27	0,76	0,84	0,43	0,08	0,92	0,35	0,70	1,36	0,26	0,42	0,66	1,46	0,24	0,14	0,87	0,56	0,57
T*$CaSO_4$	8	0,21	0,99	0,44	0,89	0,27	0,98	0,80	0,60	0,57	0,80	0,76	0,64	1,45	0,19	0,20	0,99	0,71	0,68	0,78	0,62	0,27	0,98	0,57	0,80
$CaCO_3$*$CaSO_4$	4	0,71	0,59	0,62	0,65	0,20	0,94	0,58	0,68	1,49	0,21	4,04	0,00	0,22	0,93	0,89	0,47	0,98	0,42	1,76	0,14	2,65	0,04	1,05	0,39
T*$CaCO_3$*$CaSO_4$	8	1,09	0,38	0,38	0,93	0,24	0,98	0,93	0,50	1,13	0,35	0,30	0,96	1,30	0,25	0,85	0,56	0,47	0,88	0,16	1,00	0,19	0,99	0,54	0,83
		Taquaritinga																							
T (Time)	2	1587,90	0,00	8,81	0,00	8,63	0,00	4,77	0,01	1,29	0,28	7,40	0,00	20,64	0,00	10,19	0,00	45,12	0,00	8,25	0,00	7,72	0,00	75,02	0,00
$CaCO_3$	1	0,03	0,86	5,12	0,03	0,01	0,91	0,15	0,70	1,76	0,19	0,26	0,61	0,16	0,69	0,91	0,34	0,02	0,89	0,00	0,94	0,07	0,79	0,12	0,73
$CaSO_4$	4	0,59	0,67	1,61	0,18	0,66	0,62	1,08	0,37	1,36	0,26	0,35	0,84	0,53	0,71	1,03	0,40	0,68	0,61	0,64	0,63	1,25	0,29	1,06	0,38
T*$CaCO_3$	2	0,11	0,90	0,91	0,41	1,39	0,26	0,41	0,66	0,77	0,47	0,03	0,97	0,03	0,98	0,10	0,90	0,06	0,94	0,04	0,96	1,61	0,21	0,03	0,97
T*$CaSO_4$	8	0,31	0,96	0,35	0,94	0,65	0,74	1,15	0,34	0,93	0,50	1,11	0,36	0,51	0,85	1,73	0,10	0,83	0,58	0,78	0,62	0,79	0,61	1,04	0,41
$CaCO_3$*$CaSO_4$	4	2,22	0,07	2,21	0,07	2,13	0,08	1,20	0,32	0,68	0,61	3,49	0,01	1,14	0,34	0,11	0,98	0,38	0,82	1,41	0,24	0,69	0,60	1,31	0,27
T*$CaCO_3$*$CaSO_4$	8	0,49	0,86	1,08	0,39	0,53	0,83	1,00	0,44	1,82	0,08	1,77	0,09	1,32	0,24	0,98	0,46	1,30	0,25	0,93	0,50	1,26	0,27	0,93	0,49
		Monte Alto																							
T (Time)	2	47,97	0,00	6,25	0,00	28,36	0,00	3,40	0,04	31,32	0,00	21,01	0,00	96,42	0,00	108,68	0,00	31,66	0,00	89,35	0,00	5,84	0,00	26,53	0,00
$CaCO_3$	1	0,01	0,93	0,67	0,42	0,04	0,84	0,32	0,58	7,84	0,01	0,42	0,52	0,18	0,67	6,34	0,01	1,69	0,20	1,06	0,31	2,00	0,16	2,70	0,10
$CaSO_4$	4	1,11	0,36	0,31	0,87	2,10	0,09	0,52	0,72	0,76	0,55	0,83	0,51	3,00	0,02	0,74	0,57	0,34	0,85	0,50	0,73	1,30	0,28	1,04	0,39
T*$CaCO_3$	2	0,43	0,65	0,78	0,46	0,60	0,55	0,32	0,72	0,94	0,39	0,15	0,86	1,84	0,16	1,81	0,17	0,87	0,42	1,64	0,20	0,42	0,66	0,93	0,40
T*$CaSO_4$	8	1,75	0,10	0,82	0,59	1,39	0,21	0,95	0,48	0,99	0,45	0,66	0,72	0,76	0,63	0,20	0,99	0,36	0,94	1,29	0,26	0,21	0,99	0,68	0,71
$CaCO_3$*$CaSO_4$	4	1,70	0,16	0,61	0,66	1,42	0,23	1,86	0,12	0,84	0,50	1,07	0,38	1,03	0,40	0,30	0,87	0,96	0,43	0,38	0,82	2,31	0,06	0,86	0,49
T*$CaCO_3$*$CaSO_4$	8	0,78	0,62	0,71	0,68	0,45	0,89	1,31	0,25	1,77	0,09	1,46	0,18	0,60	0,78	0,36	0,94	1,25	0,28	0,42	0,91	0,29	0,97	1,17	0,33

G.L. = degrees of freedom; Time = harvest years 2022, 2023 and 2024. Variables highlighted in red indicate significant difference (p>0.05).

The significant effects of the application of limestone and/or gypsum or the interaction between these factors are shown in Figures 4, 5 and 6, with the midpoint and confidence interval indicated, for each of the locations evaluated.

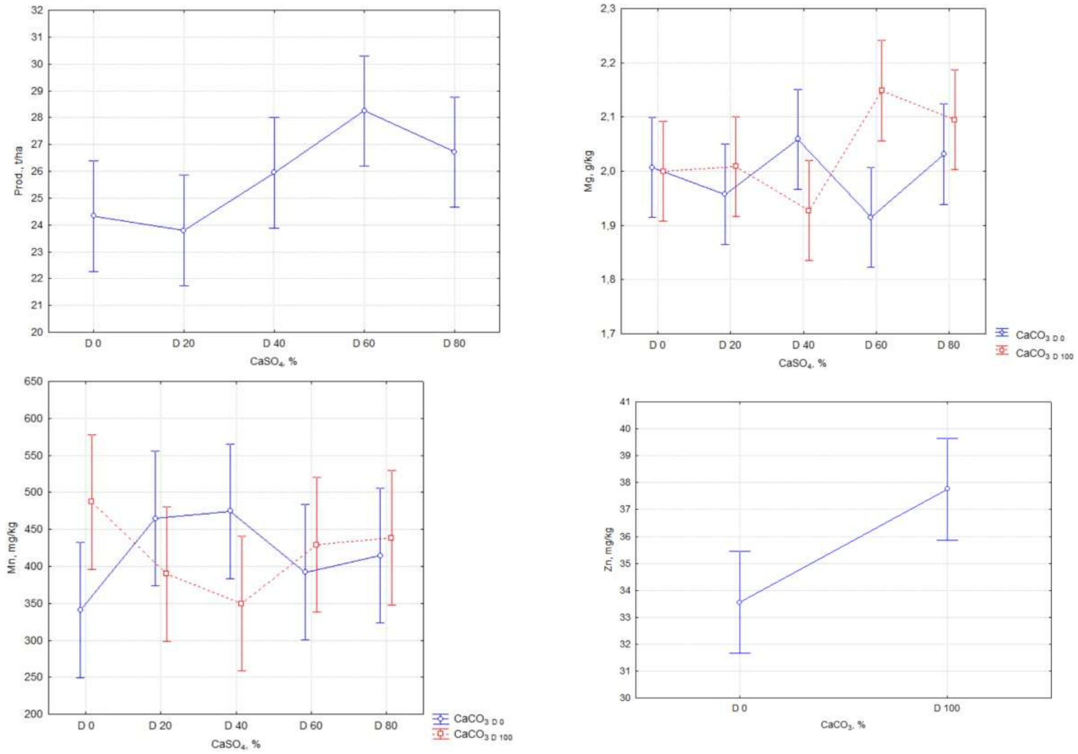


Figure 4. Variation in Yield (Prod) of mango fruits as a function of gypsum doses, foliar Mg and Mn content as a function of gypsum doses with or without limestone application and foliar Zn content as a function of limestone application in the experiment conducted in a mango orchard in Petrolina – PE.

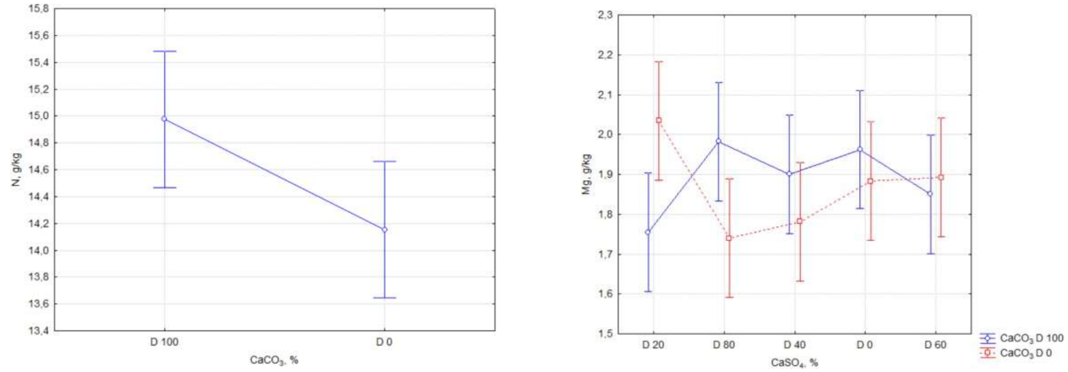


Figure 5. Variation of foliar N content as a function of the limestone dose applied and of Mg content as a function of gypsum doses with or without limestone application in an experiment conducted in a mango orchard in Taquaritinga – SP.

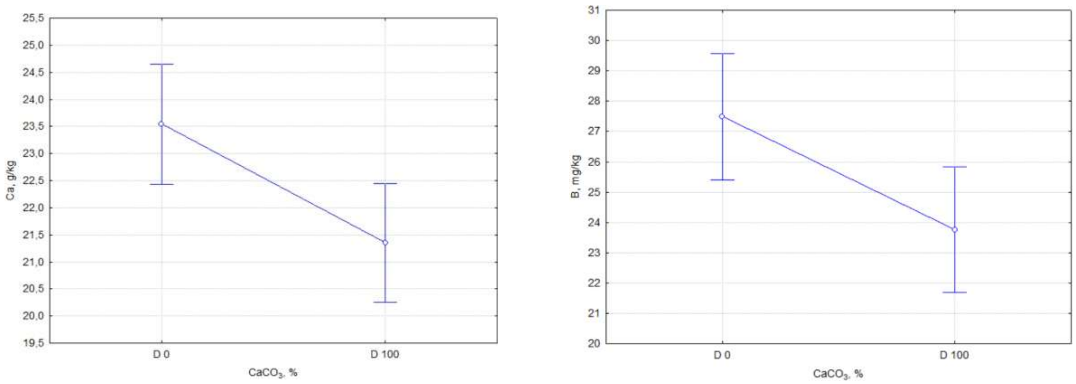


Figure 6. Variation in the foliar content of Ca and B in mango plants, as a function of the limestone dose applied in the experiment conducted in a mango orchard in Monte Alto – SP.

In Petrolina, the application of higher gypsum doses (Figure 4) resulted in higher mango fruit yields, an effect not observed with the application of limestone. Yield increased from 24 to 28 tons per hectare, representing an increase of approximately 16%. This effect of the treatments, with both limestone and gypsum application, was not observed in Taquaritinga and Monte Alto (Table 4).

Limestone application in Petrolina was important for maintaining and increasing foliar Mg levels at higher gypsum rates (Figure 4). Typically, raising soil pH due to limestone application would be expected to decrease Mn and Zn uptake, but the opposite was observed in this experiment. This increase in foliar Zn levels due to limestone application is contrary to that observed by Natale et al. (2007), who tested lime rates on guava trees. It is possible that the fertigation used in the area may be providing sufficient quantities of these nutrients, compensating for the high soil pH. As the local soil already had an alkaline pH at the beginning of the experiment (Table 2), competition for adsorption sites or changes in oxidation/reduction conditions in the soil may also be interfering with the greater absorption of Mn and Zn with the application of limestone.

As in Petrolina, lime application was important in increasing Mg levels in mango leaves when gypsum was applied in the Taquaritinga experiment (Figure 5). This effect observed in both locations is expected, considering that Ca and Mg compete for uptake sites in root cells (Pauletti and Monte Serrat, 2025). The only source of Mg applied in the experiments was lime, which, by adding this nutrient to the soil, mitigated the effects of the increased amount of Ca applied with gypsum. Liming also increased leaf N levels in Taquaritinga (Figure 5).

The various benefits of liming the soil, increasing biological activity and mineralization of organic matter may have been the cause of this increase.

In Monte Alto, Ca and B levels (Figure 6) decreased with liming. This result was unexpected, considering that limestone is a source of Ca and that increasing pH can increase B availability for plant uptake.

4.2 Effects on the soil

Chemical analyses revealed that the greatest effects of lime and gypsum application were observed in the Petrolina experiment, with an interaction between lime and gypsum on pH and levels of exchangeable Ca and Mg in the soil. In Taquaritinga, only an isolated effect of lime and gypsum on Mg content was proven, while in Monte Alto, there was a significant effect of liming on pH and of gypsum on Mg content in the soil (Table 5).

Table 5. Summary of ANOVA analysis (*p*-value) for soil chemical attributes in the 0-20 cm layer, as a function of time (years), application of limestone ($CaCO_3$) and gypsum ($CaSO_4$) in the experiments of Petrolina, Taquaritinga and Monte Alto.

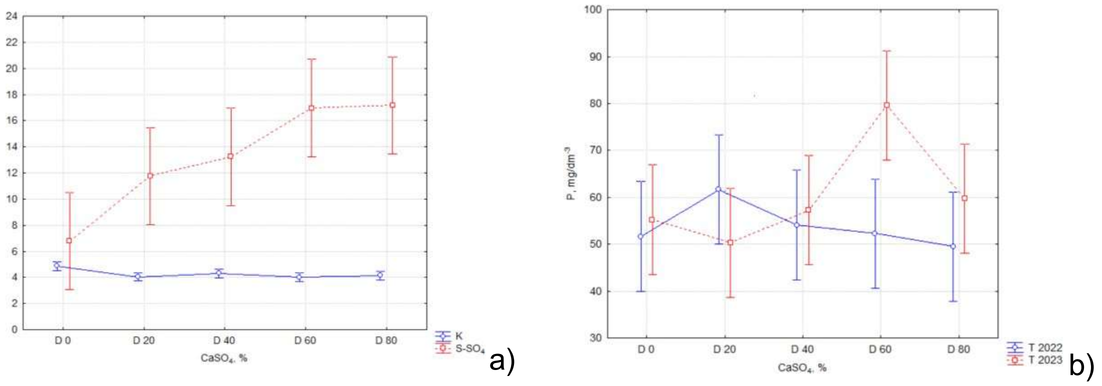
	G.L.	Petrolina																	
Factor		pH	*p*	M.O.	*p*	P	*p*	K	*p*	Ca	*p*	Mg	*p*	H+Al	*p*	V	*p*	S-SO_4	*p*
T (Time)	2	60,19	0,00	42,32	0,00	3,20	0,08	148,15	0,00	1043,72	0,00	91,41	0,00	37,48	0,00	790,70	0,00	12,97	0,00
$CaCO_3$	1	2,45	0,12	3,93	0,05	1,18	0,28	0,00	0,96	0,60	0,44	0,03	0,87	3,15	0,08	3,15	0,08	0,01	0,91
$CaSO_4$	4	0,30	0,88	2,09	0,09	1,48	0,22	4,64	0,00	0,73	0,57	3,47	0,01	0,66	0,62	1,27	0,29	5,30	0,00
T*$CaCO_3$	2	0,00	0,95	0,17	0,69	0,45	0,50	0,01	0,91	0,26	0,61	0,01	0,92	0,17	0,68	0,76	0,39	2,83	0,10
T*$CaSO_4$	8	0,31	0,87	1,73	0,16	2,89	0,03	0,35	0,85	1,60	0,19	0,49	0,74	1,26	0,30	2,09	0,09	1,71	0,16
$CaCO_3$*$CaSO_4$	4	4,03	0,01	1,64	0,18	2,01	0,10	0,89	0,47	3,67	0,01	3,68	0,01	2,22	0,08	1,63	0,18	0,73	0,57
T*$CaCO_3$*$CaSO_4$	8	2,65	0,04	1,94	0,12	2,07	0,10	0,27	0,89	4,73	0,00	3,79	0,01	2,75	0,04	2,92	0,03	1,33	0,27
		Taquaritinga																	
T (Time)	2	5,96	0,02	11,03	0,00	0,50	0,48	18,80	0,00	2,22	0,14	3,00	0,09	57,18	0,00	7,12	0,01	187,43	0,00
$CaCO_3$	1	12,33	0,00	0,02	0,88	0,76	0,39	1,36	0,25	1,06	0,31	4,82	0,03	8,92	0,00	4,81	0,03	0,13	0,72
$CaSO_4$	4	0,23	0,92	0,25	0,91	0,25	0,91	0,88	0,48	0,82	0,52	6,59	0,00	0,54	0,71	1,28	0,29	2,31	0,07
T*$CaCO_3$	2	1,88	0,18	1,57	0,22	0,18	0,68	0,73	0,40	1,10	0,30	1,35	0,25	0,01	0,93	0,04	0,84	0,58	0,45
T*$CaSO_4$	8	0,86	0,49	0,86	0,49	0,19	0,94	0,93	0,45	0,99	0,42	0,89	0,48	0,13	0,97	0,67	0,62	1,87	0,13
$CaCO_3$*$CaSO_4$	4	2,64	0,04	1,86	0,13	0,99	0,42	0,64	0,64	0,85	0,50	0,13	0,97	2,31	0,07	0,94	0,45	0,56	0,69
T*$CaCO_3$*$CaSO_4$	8	1,29	0,29	0,40	0,81	0,50	0,73	1,11	0,36	1,05	0,39	0,49	0,74	0,47	0,76	0,34	0,85	0,15	0,96
		Monte Alto																	
T (Time)	2	1868,94	0,00	578,65	0,00	9,68	0,00	9,28	0,00	631,94	0,00	228,07	0,00	1,61	0,21	3908,55	0,00	2,86	0,10
$CaCO_3$	1	5,26	0,03	0,22	0,64	1,19	0,28	1,08	0,30	0,18	0,67	0,35	0,56	12,42	0,00	2,40	0,13	0,69	0,41
$CaSO_4$	4	0,33	0,86	1,78	0,14	0,86	0,49	0,53	0,72	0,44	0,78	4,06	0,01	0,95	0,44	0,02	1,00	2,18	0,08
T*$CaCO_3$	2	0,89	0,35	0,07	0,79	1,05	0,31	0,30	0,59	0,17	0,68	3,93	0,05	0,98	0,33	1,04	0,31	0,54	0,47
T*$CaSO_4$	8	1,69	0,16	0,36	0,84	0,46	0,77	0,61	0,66	0,53	0,71	1,64	0,18	2,06	0,10	0,59	0,67	0,78	0,54
$CaCO_3$*$CaSO_4$	4	0,78	0,54	2,98	0,03	0,73	0,58	0,87	0,49	0,95	0,44	0,52	0,72	0,78	0,54	1,20	0,32	0,85	0,50
T*$CaCO_3$*$CaSO_4$	8	0,64	0,63	1,26	0,29	1,31	0,28	0,65	0,63	1,37	0,25	1,91	0,12	1,18	0,33	2,75	0,04	1,81	0,14

G.L. = degrees of freedom; Time = Years of soil collection. Variables highlighted in red indicate significant difference ($p>0.05$).

The variables with significant effects from the treatments applied in Petrolina are shown in Figure 7. There was a decrease in exchangeable K content and an increase in S-SO_4^- content in the 0-20 cm surface layer as a function of the increasing gypsum dose (Figure 7a). This effect was expected, especially in relation to sulfur, since gypsum is a source of this nutrient. The small decrease in exchangeable K in the surface layer with the application of gypsum may reflect the leaching of this nutrient by its displacement from the exchange sites of the colloids to the soil solution as a function of the increase in Ca, or even, but less likely, by the formation of an ion pair between K and SO4-, facilitating its movement in the profile.

An increase in soil P was also observed (Figure 7b) with increasing gypsum dose, especially in the second year (2023) evaluated. Since the applied gypsum is derived from phosphoric acid production, it can contain between 0.8 and 1.2% P, justifying the result observed in this study.

In the variables related to the basic soil elements Ca (Figure 7d) and Mg (Figure 7e), base saturation (V%) (Figure 7g), and acidity (pH – Figure 7c, H+Al – Figure 7f), there is a more consistent effect of gypsum application in the first year of sampling. Similarly to the K content, a tendency towards a decrease in the content of exchangeable Ca and Mg in the soil is observed, especially the latter, with increasing doses of gypsum. Although gypsum is a source of Ca, since this chemical analysis is restricted to the surface layer, it is possible that this nutrient has leached to deeper layers due to the presence of SO_4^-. This explanation applies well to Mg, since gypsum is not a source of this nutrient, and the presence of the SO_4^- anion favors its leaching. This effect on Ca and Mg levels is reflected in the results obtained for base saturation (V%), which tends to decrease significantly with increasing doses of gypsum.



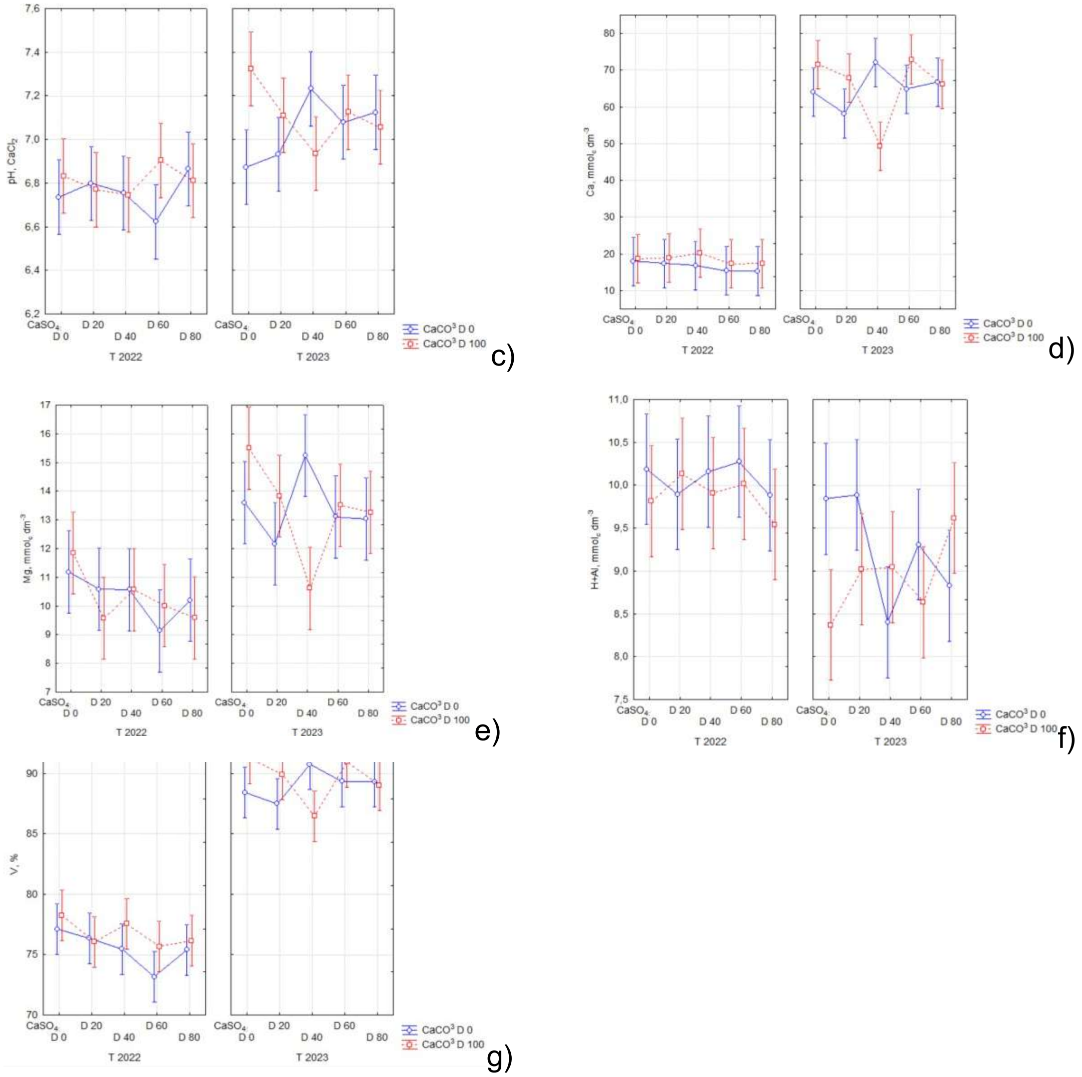


Figure 7. Breakdown of the ANOVA as a function of the significance between variables for the experimental area of Petrolina – PE.

In the Taquaritinga experiment, the effect of liming in raising the pH is evident (Figure 8a), consequently decreasing the potential acidity – H+Al (Figure 8d) and increasing the exchangeable Mg content (Figure 8c) and base saturation – V% (Figure 8e). The effect of gypsum application was basically to decrease the exchangeable Mg content on the soil surface (0-20 cm) (Figure 8b), as a consequence of the leaching of this element with the formation of an ion pair with SO_4^-.

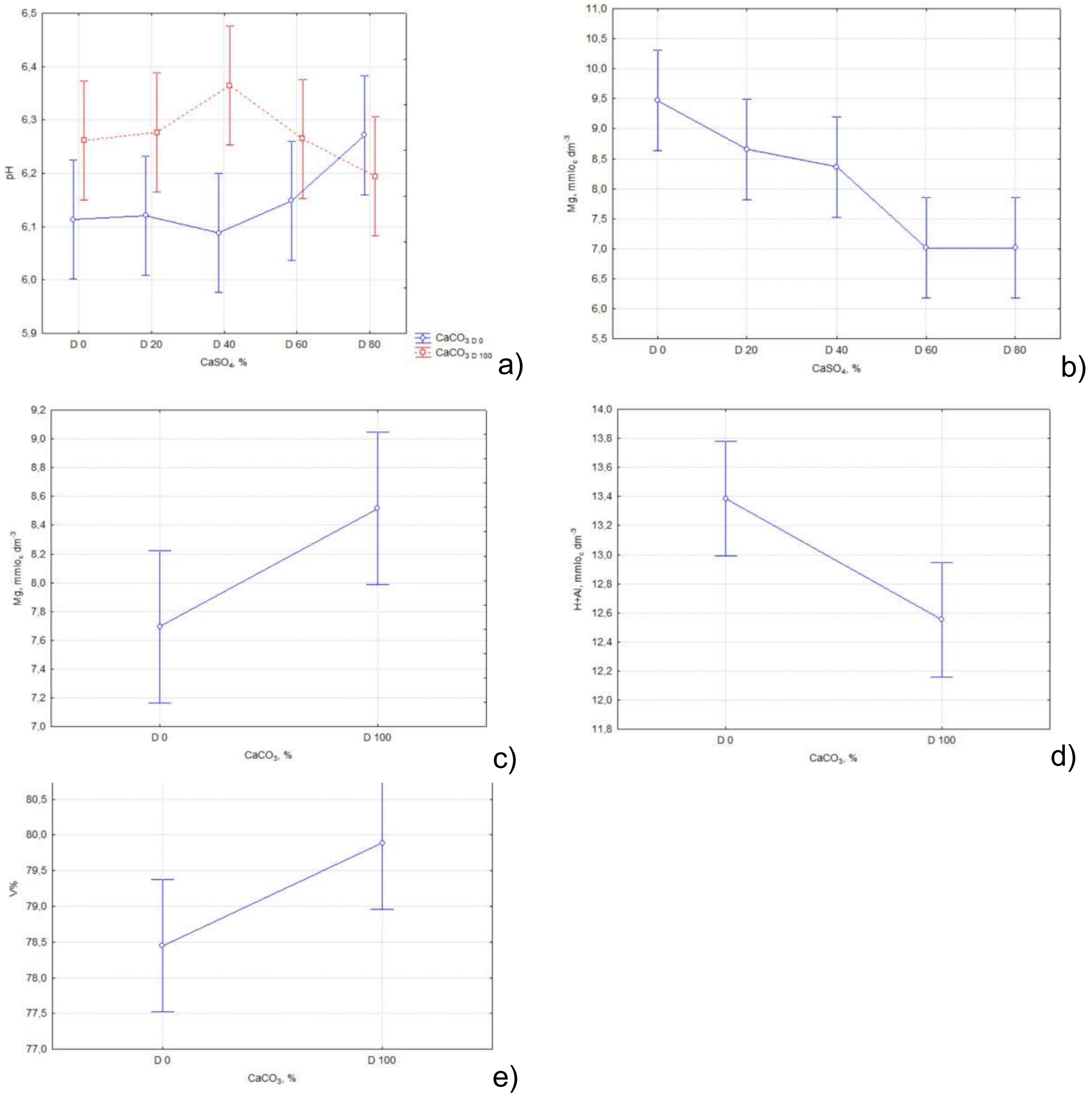


Figure 8. Breakdown of the ANOVA as a function of the significance between variables for the experimental area of Taquaritinga – SP.

In the Monte Alto experiment, smaller effects of the treatments on the chemical parameters of the soil were observed in the 0-20 cm depth layer. Basically, liming increased the pH (Figure 9a) and decreased the potential acidity (H+Al) (Figure 9b), and the application of gypsum decreased the presence of exchangeable Mg (Figure 9c).

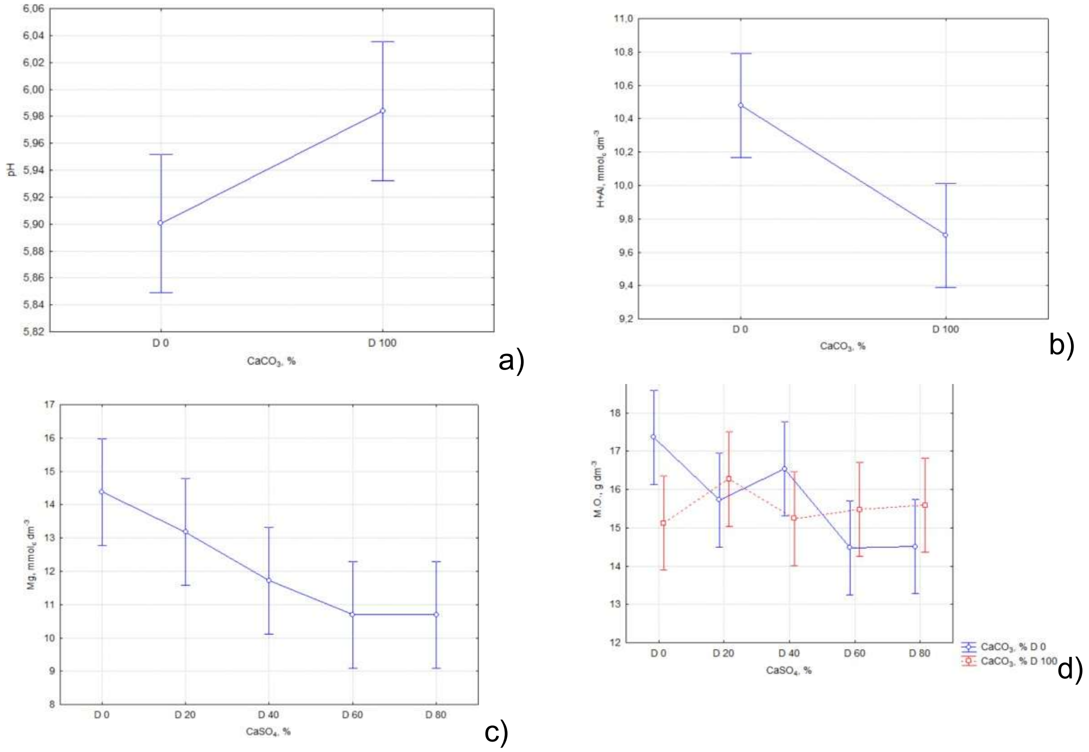


Figure 9. Breakdown of the ANOVA as a function of the significance between variables for the experimental area of Monte Alto - SP.

The changes provided by liming and gypsum application can be verified by comparing the initial analysis of the areas with the increase in the doses of corrective agent. In general, there was a significant increase in pH, Ca^{2+}, Mg^{2+}, and V%, and a significant reduction in H + Al.

It is worth remembering that the application of limestone occurred superficially in established and already mature orchards, and that the changes in the chemical attributes of the soil analyzed in this work, in the correlation and fertilization indication layer (0-20cm), can be explained in many ways, despite the known low solubility and restricted movement of limestone in the soil profile (Gonzales-Érico et al., 1979).

There are other factors that can explain the displacement of limestone particles along the soil profile in these experiments, modifying the chemical parameters in this layer. The contribution of physical factors can be highlighted, such as the channels left by root decomposition (Pearson et al., 1962), due to the activity of macro and microfauna. According to Harter & Naidu (1995) and Aoyama (1996), another explanation would be the formation of pairs between highly soluble bases (Ca^{2+} and Mg^{2+}) and organic acids (RO^- and $RCOO^-$) with low molecular weight, which would allow the transport of these pairs to subsurface layers. This reaction is explained by Miyazawa et al. (1996) by the formation of organic ligands, which complex soil Ca, forming CaL^0 or CaL^- complexes. In addition to these compounds, others may be formed, such as $Ca(HCO_3)_2$ and $Mg(HCO_3)_2$, according to Oliveira & Pavan (1996), and also, when nitrogen fertilization occurs, the formation of soluble salts, such as calcium nitrate, may occur, which percolate through the downward movement of water in the soil profile (Blevins et al., 1997). It is reasonable to assume, however, that the sum of the contributions of all processes is more important than each one individually.

4.3 Cellular morphology and microanalytical mapping of calcium from Taquaritinga area fruits

Preliminary findings provided insights into the cellular structure of mango fruits and the micro-localization of Ca. Microanalytical mapping via SEM-EDS revealed significant differences in Ca distribution between the peel and pulp tissues, as well as between control and treated fruits (Table 66).

Table 6 - SEM-EDS semi-quantitative analysis summary for peel, inner and outer pulp fruit fractions for Taquaritinga area. Results in percentage (%).

	C	O	Na	P	Ca	Si	Mg	S	Al	Br	Fe	Cu	Total
Peel	64.39	30.16	2.39	0.70	0.46	1.28	0.06	0.16	0.04	0.03	0.26	0.08	100.00
Inner Pulp	54.84	38.18	3.52	2.57	0.16	0.50	0.00	0.17	0.05	0.00	0.00	0.00	100.00
Outer Pulp	58.03	39.43	1.33	0.65	0.12	0.20	0.03	0.23	0.00	0.00	0.00	0.00	100.00

Calcium was predominantly found within the cell walls, with higher concentrations observed in the peel compared to the pulp. Treatments involving lime and gypsum applications led to an increase in cell wall-bound Ca in the fruit tissues, suggesting enhanced Ca uptake and incorporation into structural components. These observations underscore the critical role of Ca in maintaining cellular integrity and structure, which is directly relevant to fruit quality and susceptibility to disorders like internal collapse.

4.3.1 Linking limestone and gypsum application to postharvest quality parameters and internal collapse incidence on fruits

In Petrolina, the majority of evaluated fruit quality variables - including fruit dry matter, soluble solids, texture, and the incidence of internal collapse - were not significantly influenced by the treatments (Table 7). Among the measured parameters, only titratable acidity exhibited a statistically significant effect, which was only observed 21 days after storage.

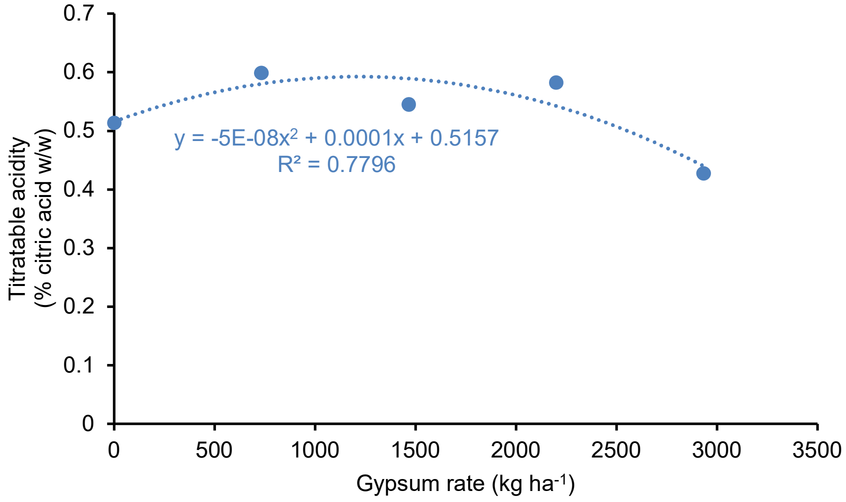
This lack of overall response is attributed to the high baseline calcium content and base saturation levels present in this experimental area prior to implementation (Table 2). For instance, pre-treatment soil analysis showed base saturation (V%) as high as 94.4% in the 0-10 cm layer. Consequently, the marginal increases in calcium provided by the limestone and gypsum treatments were insufficient to induce significant changes in the response variables. It is well established that the nutritional status of the plant, and specifically calcium levels, correlates strongly with the incidence of internal collapse (Ma et al., 2022). Hence, the high initial fertility of the Petrolina site likely satisfied the plant’s requirements regardless of the supplemental applications.

Table 7 – Analysis of variance summary for fruit fresh and dry mass, soluble solids content (ºBrix), titratable acidity, sugar-acid ratio, texture, and internal collapse incidence in mangoes subjected to gypsum and lime application, evaluated at harvest and after 21 days of storage, in the Petrolina. Taquaritinga and Monte Alto areas.

		Response variable												
Area	**Factor**	**Fruit dry mass avg. (%)**	**Fresh fruit mass avg. (g)**	**ºBrix avg. (after harv.)**	**ºBrix avg. (after stor.)**	**Acidity^1 avg. (after harv.)**	**Acidity^1 avg. (after stor.)**	**Ratio (after harv.)**	**Ratio (after stor.)**	**Texture (after harv. - N)**	**Texture (after stor. - N)**	**Collapse (after harv. - %)**	**Collapse (after stor. - %)**	**Collapse (total - %)**
Petro-lina	Limestone	n.s.	n.s.	n.s.	n.s.	n.s.	0.096	n.s.	n.s.	0.060	n.s.	n.s.	n.s.	n.s.
	Gypsum	n.s.	n.s.	n.s.	n.s.	n.s.	*	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
	L x G	n.s.	n.s.	n.s.	n.s.	0.059	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Taquari-tinga	Limestone	*	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
	Gypsum	n.s.	n.s.	n.s.	n.s.	*	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
	L x G	*	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	*
Monte Alto	Limestone	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
	Gypsum	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
	L x G	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

NOTE: ^{1} = Titratable acidity. Results expressed in % citric acid w/w; n.s. = not significant ($p > 0.10$); value is shown ($0.10 \geq p > 0.05$); $p \leq 0.05$ (*), $p \leq 0.01$ (**), $p \leq 0.001$ (***); avg. = average; harv = harvest; stor. = storage.

Figure 10 - Titratable acidity (% citric acid w/w) after 21 days of storage for Petrolina area: regression for gypsum rates.



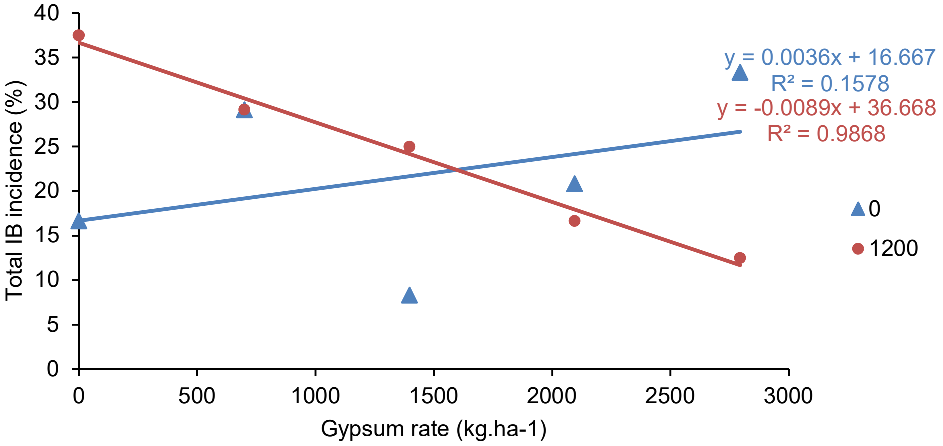
Regarding acidity levels, the observed data were somewhat unexpected and deviated from prevailing literature. The regression analysis indicated a slight yet significant ($p < 0.05$, Table 7) reduction trend in titratable acidity at 21 days of storage as more gypsum were applied (Figure 10). Generally, an inverse relationship is expected between Ca availability and the rate of acidity loss (Bitange et al., 2023; Seibert, Bender, 2024). Increased Ca concentration in fruit tissue typically slows down the natural decline of organic acids during the ripening process. Consequently, mangoes treated with calcium often maintain higher titratable acidity at harvest and throughout the shelf-life period compared to untreated controls (Bitange et al., 2023).

During ripening, organic acids (citric, malic) are metabolized as substrates for cellular respiration. Ca application mitigates this depletion by reducing the activity of ripening enzymes (malic, pyruvate decarboxylase enzymes) (Gao et al., 2019). Furthermore, Ca also binds to the pectin in the middle lamella to form Ca-pectates, which stabilize cell walls and reduce the overall respiration rate, contributing to the preservation of the fruit's acid profile (Seibert, Bender, 2024).

In Taquaritinga, however, the results differed. The application of soil limestone and gypsum significantly affected post-harvest acidity and, more importantly, reduced the total incidence of collapse (Table 7).

In this area, both lime and gypsum, when applied individually or in combination, led to an increase in fruit dry mass and affected acidity at harvest. These Ca amendments significantly reduced the total incidence of internal collapse. The combined application of limestone and gypsum was particularly effective in mitigating the disorder, suggesting a synergistic effect of increased Ca availability from both sources (Figure 11).

Figure 11 - Total internal collapse incidence (in %) for Monte Alto area: regression for interaction lime × gypsum rates.



This reduction in internal collapse highlights the direct link between enhanced Ca nutrition and improved fruit physiological stability and quality.

Conversely, the field trials conducted in the Monte Alto area did not show statistically significant treatment effects on fruit quality parameters or internal collapse incidence. This lack of response, despite similar treatments, can be attributed to several factors inherent to the Monte Alto edaphoclimatic conditions, including irrigation. Furthermore, during lab work it was noted to be significant heterogeneity in fruit size and maturity at harvest, due to a possible occurrence of distinct flowering flushes that can affect fruit development uniformly across the experimental blocks. In this area, such variability likely masked any potential benefits from the Ca amendments, emphasizing the importance of site-specific management strategies and accounting for environmental factors in perennial crop research.

In conclusion, this research reinforces the critical role of Ca in mitigating internal collapse in mango fruits. The results demonstrate an increase in Ca bound to the cell wall with soil amendments, provide a cellular basis for the observed improvements in fruit quality. The results from the Taquaritinga area clearly show that targeted limestone and gypsum applications can significantly reduce internal collapse incidence and enhance fruit dry mass as well as affect acidity levels. While variability in the Monte Alto area highlights the complexity of field conditions, the overall evidence points towards effective Ca management as a vital strategy for improving mango fruit quality and reducing postharvest losses due to internal collapse.

5 Key findings

- Improved soil fertility and plant nutrition: the application of limestone and gypsum successfully increased the availability of Ca, Mg, and S. Gypsum was particularly effective at providing Ca capable of leaching to deeper soil layers.
- Regional productivity pains: soil fertility improved across all sites, and a significant increase in fruit yield was specifically recorded in the Petrolina area experiment. In this region, higher gypsum doses resulted in a 16% increase in yield, raising production from 24 to 28 tons per hectare.
- Mitigation of internal collapse: in Taquaritinga, soil applications of both limestone and gypsum led to a major reduction in the incidence of internal fruit collapse. The combined application of these amendments was found to be an effective strategy for mitigating this disorder in the area. For Petrolina and Monte Alto, on the other hand, no significant effect was reported.

- Fruit cellular integrity: microscopic and EDS analysis confirmed that these soil treatments increased the concentration of calcium bound to the cell walls within the fruit. It is believed that this structural improvement is the main reason for gains in fruit dry mass and postharvest quality.
- Site-specific variations: results varied significantly by location, highlighting the complexity of internal collapse mitigation. In Monte Alto, no significant treatment effects were observed; this lack of response is likely attributable to localized irrigation practices and high natural variability in fruit maturity. Similarly, Petrolina demonstrated minimal response, except for acidity levels at 21 days post-harvest. These findings show the necessity for site-specific management strategies and ongoing research to refine internal collapse across diverse edaphoclimatic conditions.
- Management recommendations: combined limestone and gypsum application showed itself to be an adequate strategy for Ca supplementation. This combined application improves mango quality and reduces economic losses caused by internal collapse, particularly in regions prone to water restrictions.

6 Conclusion

The application of limestone and gypsum resulted in changes in soil fertility, mainly by increasing the availability of Ca, Mg, and S to the plants; however, the effect of these changes was only observed in fruit productivity in the experiment conducted in northeastern Brazil. The occurrence of fruit collapse with the combined application of limestone and gypsum was related to the presence of Ca in the cell wall.

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