INTERNATIONAL JOURNAL OF AGRICULTURE & BIOLOGY
ISSN Print: 1560–8530; ISSN Online: 1814–9596
24–0008/2024/31–6–437–446
DOI: 10.17957/IJAB/15.2162
http://www.fspublishers.org

Full Length Article

Age-Related Changes in Magnesium Status within Oil Palm Cultivation in Eastern Amazon

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Received 06 January 2024; Accepted 07 March 2024; Published 16 April 2024

Abstract

The purpose of this study was to describe magnesium (Mg) concentration, accumulation, and export, as well as Mg use efficiency and nutrient requirements in oil palm (*Elaeis guineensis* Jacq.) plants of different ages. For this, an experimental field comprised a completely randomized design (CRD) with seven treatments of plant ages (from 2nd to 8th year) was conducted. We technically assessed numerous vegetative and reproductive components at both plants age. Plant tissue sample were collected and sent to laboratory for extraction of Mg content. The data were submitted to the variance analysis ($P < 0.05$) and to regression model adjustments. Our results showed that plant age influenced the dynamics of Mg, mainly its concentrations in the reproductive organs. Mg showed greater accumulation and export with increasing plant age. The capacity of reuse in senescent tissues provided greater Mg use efficiency and requirement. Mg should be supplied according to plant age and the total quantity extracted and recycled as well as the Mg content in the soil should be considered, besides the quantities exported. Our insights are essential for the management of Mg fertilization in oil palm plantations.

Keywords: *Elaeis guineensis*; Mg immobilization; Mg export; Mg recycling; Mg use efficiency

Introduction

Oil palm (*Elaeis guineensis* Jacq.) stands as a pivotal oilseed crop cultivated predominantly in tropical regions across Africa, Asia and Latin America, with the latter contributing significantly to global oil palm cultivation due to its ample land availability (Tupaz-Vera *et al.* 2021; Viégas *et al.* 2023c). The oil derived from palm trees holds a global trade presence and is acknowledged for its indispensability in human nutrition, offering substantial health benefits (Plyduang *et al.* 2022). However, meeting the escalating global demand for oil necessitates high-yielding plants, thereby emphasizing the pivotal role of fertilization in augmenting crop yield (Budiman *et al.* 2021; Viégas *et al.* 2023a).

Among an array of nutrients essential for oil palm growth, magnesium (Mg) assumes a crucial role, contributing to chlorophyll structure, as cofactor in enzymatic activities, and catalyst in protein synthesis (Prado 2021). Optimal Mg application demonstrates a direct correlation with increased crop yield and enhanced fruit quality in oil palm (Tarmizi and Mohd Tayeb 2006). Nevertheless, excessive Mg application presents a conundrum, potentially resulting in fertilizer wastage and instigating antagonism with other nutrients, leading to plant toxicity due to excessive Mg and metabolic disturbances. Conversely, Mg deficiency disrupts photosynthetic processes (Tiemann *et al.* 2018), culminating in yield losses. Therefore, precise monitoring becomes imperative for effective Mg management, ensuring the plant's nutritional state throughout its growth and development phases. Furthermore, comprehending Mg's dynamics concerning recycling, immobilization, and export within distinct agroecosystems becomes quintessential for adequate fertilization in oil palm plantations.

Recent investigations into magnesium dynamics within the oil palm ecosystem have notably contributed to refining Mg fertilization techniques (Oliveira *et al.* 2018; Matos *et al.* 2018; Viégas *et al.* 2019; Behera *et al.* 2021, 2022; Viégas *et al.* 2022, 2024). These studies have not only elucidated Mg requirements in plants but also recommended optimal Mg supply strategies to bolster crop yield. Assessing nutrient concentrations and incorporation of dry matter into plant

To cite this paper: Viégas IJM, AES Souza, MG Costa, EVO Ferreira, LG Nascimento, DAS Silva, CFO Neto (2024). Age-related changes in magnesium status within oil palm cultivation in eastern amazon. *Intl J Agric Biol* 31:437–446

tissues has been instrumental in determining the necessary nutrient quantities for rectifying deficiencies (Foster and Chang 1977; Siang *et al.* 2022). However, while these studies offer significant insights, the complete comprehension of Mg dynamics within the oil palm agroecosystem remains limited. Consequently, further investigations aiming to elucidate Mg recycling rates, immobilization mechanisms, export dynamics, as well as the potential for Mg reuse in the agroecosystem are imperative.

Variability of Mg dynamics contingent upon oil palm tree age is crucial in refining nutrient management practices (Formaglio *et al.* 2021). Hence, in-depth investigations into Mg dynamics within oil palm agroecosystems, encompassing developmental aspects and nutrient export kinetics, are warranted. This study endeavors to test hypotheses concerning Mg accumulation in accordance with its requirements and how recycling, immobilization, and export dynamics impact Mg use efficiency (MgUE) in oil palm trees of varying ages. Anticipated results aim to furnish comprehensive insights into magnesium dynamics within oil palm agroecosystems, thereby facilitating enhanced Mg fertilization management and augmenting the crop yield potential. In this regard, the objective of the study was to investigate the dynamics of accumulation, distribution, and usage efficiency of Mg in the different components of oil palm plants, as well as the modifications induced in the rates of immobilization, recycling, and exportation within oil palm agroecosystems.

Materials and Methods

Study site

This investigation was conducted within the experimental grounds of Agropalma S/A, situated in the municipality of Tailândia, northeastern Pará State, Brazil (2° 56' 50" S and 48° 57' 12" W). This site maintains an average annual temperature of 26.5°C. Climatically, it falls under Ami (tropical rainy) classification, exhibiting an average annual precipitation of 2400 mm and a relative humidity of 84% (Koppen 1918). The soil of this region is typified as dystrophic yellow Latosol, demonstrating an acidic nature, low inherent chemical fertility, and a medium-textured composition (Rodrigues *et al.* 2005). To undertake the chemical and physical profiling of the soil within the experimental site (0–0.3 m depth), composite samples were procured by amalgamating four individual samples retrieved from locations interspersed among the rows of oil palm plantations, corresponding to different plant ages at the time of collection. The specifics of this soil are presented in Table 1.

The experimental site was cultivated using the Tenera hybrid within an equilateral triangle planting system, maintaining a spacing of 9 m between each plant, resulting in a total of 143 plants per hectare. Throughout the study duration, fertilizers detailed in Table 2 were applied, comprising urea (45% N), natural phosphate phosphine (33% P_2O_5 and 42% CaO), potassium chloride (60% K_2O and 45% Cl), and magnesium sulfate (11% S and 9% MgO).

Experimental design

The assessment covered oil palm plantations at seven distinct ages, ranging from the 2nd to the 8th year of growth. This involved the implementation of Completely Randomized Design (CRD), with four replications, with each replication represented by a one-hectare commercial planting area, selecting one plant located at the center of the plot.

Sampling of plant components

To ensure a homogeneous selection, we established specific criteria for plant sampling: i) robust growth, ii) adequate nourishment, iii) absence of pests and diseases, and iv) satisfactory yield. Once these initial criteria were applied, all selected plants underwent measurement of collar circumference and height, from the base of the stipe to the base of leaf 33, to define the population's average. These variables guided the selection of individuals representing the average of the stand population, aimed at minimizing heterogeneity.

Subsequent to individual selection, one plant per stand was harvested and dissected into various components, including petioles, rachis, leaflets, cabbage, stipe, peduncles, arrows, male inflorescence, spikelets, and fruits. Fresh samples from these components were collected, weighed, and subsequently dried in an oven to a constant weight. Dried plant material was then processed using a knife mill (Willey type). Subsequently, the plant tissue underwent digestion using the wet method, employing nitric-perchloric acid digestion, and the Mg concentration was determined via atomic absorption spectrophotometry (Malavolta *et al.* 1997).

Tissue Mg analysis

The impact of treatments on each oil palm plant component was assessed based on Mg concentration, accumulation and export. The accumulated amount was estimated by considering the Mg concentration in the tissue and the dry matter of the respective organ. Additionally, immobilized Mg amounts were calculated as the cumulative amount in the cabbage, stipe, and arrows, while recycled amounts were estimated based on Mg accumulation in petioles, rachis, leaflets, and inflorescences.

The range of Mg concentration variation in each organ across different plant ages was calculated using the arithmetic mean and standard deviation. The lower limit was determined by subtracting the standard deviation from the arithmetic means, while the upper limit was established by adding the standard deviation to the arithmetic means. The amplitude variation was derived from the ratio of standard deviation to the arithmetic means, multiplied by 100.

Total Mg requirement was estimated considering a fertilizer efficiency of 50% (Franzini *et al.* 2020) and the effective Mg requirement (Driessen 1986). Additionally, the Mg use efficiency (MgUE) of each component and the entire plant was computed using the sturdiness quotient (SD) of dry mass and Mg accumulation (Siddiqi and Glass 1981).

Finally, for each growth stage of the plants, Mg supply via fertilization was estimated based on soil content, categorized as $\leq$ 0.5 $cmol_c$ dm^{-3} (low) or above this value also considering total amounts extracted, recycled, and exported by the palm plants (Brasil and Cravo 2020), while also considering the total amounts extracted, recycled, and exported by oil palm plants.

Statistical analysis

The data underwent Shapiro-Wilk's normality test ($P > 0.05$) (Royston 1995) and Levene's homogeneity test ($P > 0.05$) (Gastwirth *et al.* 2009). The data were submitted to the variance analysis (F test; $P < 0.05$) and, when significant, regression models were adjusted according to the age of the oil palm plantation.

Results

Tissue Mg concentration

The Mg concentrations displayed a quadratic increase until the 8th year for arrows and male inflorescence (Fig. 1a-b), extending until the 5th year for peduncle and fruits (Fig. 1c-d). Conversely, spikelets exhibited a positive linear response with the advancing age of plants (Fig. 1d). However, leaflets, petioles, rachis, cabbage, and stipe did not exhibit a significant response (Fig. 1b). Notably, Mg concentrations in vegetative structures remained relatively stable, specifically in rachis (1.0 g kg^{-1}), petioles (1.5 g kg^{-1}), and leaflets (2.4 g kg^{-1}). Among the vegetative organs, cabbage displayed the highest Mg concentrations (7.81 g kg^{-1}), while in the 7th year of plant age, male inflorescence exhibited the highest concentration (6.5 g kg^{-1}) among reproductive organs. Consequently, Mg concentrations varied across plant organs, with plant age significantly influencing these concentrations across most components in oil palm. The widest variation (79%) in Mg concentrations among all oil palm components occurred in the stipe (ranging from 0.65 to 5.64 g kg^{-1}), while the narrowest one (8%) was observed in leaflets ranging from 2.22 to 2.58 g kg^{-1} (Table 3).

Tissue Mg accumulation

There existed a discernible relationship between Mg accumulation in both vegetative and reproductive components of oil palm, exhibiting a linear response correlated with the plants' cultivation age (Fig. 2a). Notably, the stipe (278.1 g $plant^{-1}$) and crown (293.49 g $plant^{-1}$) demonstrated the highest Mg accumulation during the 7th and 8th years of plant age, respectively. Among the reproductive components, a substantial Mg accumulation (126.19 g $plant^{-1}$) was observed in bunches during the 8th year of cultivation. The distribution of Mg accumulation in the crown, bunches, and male inflorescence exhibited a quadratic response to plant age (Fig. 2b). Mg distribution exhibited exponential growth until the 6th year of plant age for bunches and male inflorescence, while a decline in Mg distribution was noted in the crown concerning plant age. Furthermore, Mg distribution in the stipe did not show significant variations relative to plant age.

Regarding Mg accumulation within oil palm components, a linear relationship was evident for plant age (Fig. 3). The order of Mg accumulation by components decreased as follows: leaflets > petioles > fruits > rachis > spikelets > arrows > peduncles > cabbage (Fig. 3a–b). Overall Mg accumulation increased both on a per-plant basis (Fig. 4a) and per hectare (Fig. 4b), showcasing a percentage increase corresponding to plant age (Fig. 4c). The highest Mg accumulation was observed during the 8th year of plant age.

Mg exportation

The age of the plants emerged as a crucial determinant in defining Mg export values, distinctly explained by positive linear models (Fig. 5a–b). Notably, older plants exhibited higher Mg export, while younger plants demonstrated Mg export values close to zero. Among the evaluated components, bunches displayed the highest Mg export rates (50%), trailed by fruits, spikelets, and peduncles throughout the entire assessment period (Fig. 5c). Although peduncles exhibited a behavior akin to bunches, their Mg export remained notably lower (2.26%). The export of Mg in fruits and spikelets was elucidated by second-order polynomial models. Fruits exhibited the highest Mg export during the 4th year of plant age, in contrast to spikelets, which peaked Mg export solely during the 8th year of cultivation.

Mg content

The Mg contents exhibited a gradual increase throughout the seven years of plant development (Fig. 6). The highest values for total (103.06 kg ha^{-1}), immobilized (41.37 kg ha^{-1}), recycled (45.03 kg ha^{-1}), and exported (18.04 kg ha^{-1}) Mg contents were recorded during the 8th year of oil palm cultivation. Overall, plant age showcased a more pronounced response concerning Mg recycling and immobilization compared to the amount of Mg exported by the oil palm.

Mg requirement

The responses towards Mg requirement were characterized by linear and positive trends in both total and effective Mg requirements concerning oil palm age (Fig. 7). The pinnacle of the total Mg requirement (1098 g $plant^{-1}$) was

Table 1: Soil chemical and physical characteristics (0–0.3 m) in oil palm plantations at different ages

Feature	Plant age						
	2	3	4	5	6	7	8
pH ($CaCl_2$)	4.3	4.4	4.1	4	4	4.3	4
K* ($cmol_c$ dm^{-3})	0.007	0.006	0.005	0.007	0.005	0.005	0.006
Ca* ($cmol_c$ dm^{-3})	0.07	0.07	0.09	0.08	0.07	0.07	0.06
Mg* ($cmol_c$ dm^{-3})	0.04	0.02	0.02	0.03	0.03	0.03	0.03
Al ($cmol_c$ dm^{-3})	0.04	0.03	0.03	0.05	0.08	0.04	0.06
H+Al** ($cmol_c$ dm^{-3})	0.34	0.28	0.31	0.38	0.34	0.26	0.34
SB ($cmol_c$ dm^{-3})	0.117	0.096	0.115	0.117	0.105	0.105	0.096
P* (mg dm^{-3})	4.0	6.0	5.0	6.0	6.0	6.0	8.0
V (%)	24	24	24	22	22	27	20
O.M.*** (g dm^{-3})	1.6	2.3	1.5	1.9	2	2.1	1.8
Coarse sand (g kg^{-1})	450	320	500	370	380	340	510
Fine sand (g kg^{-1})	280	300	190	310	210	320	230
Silt (g kg^{-1})	40	160	80	100	80	100	60
Clay (g kg^{-1})	230	220	230	220	330	240	200

*Extracted with ion exchange resin; ** SMP method; ***Colorimetric method

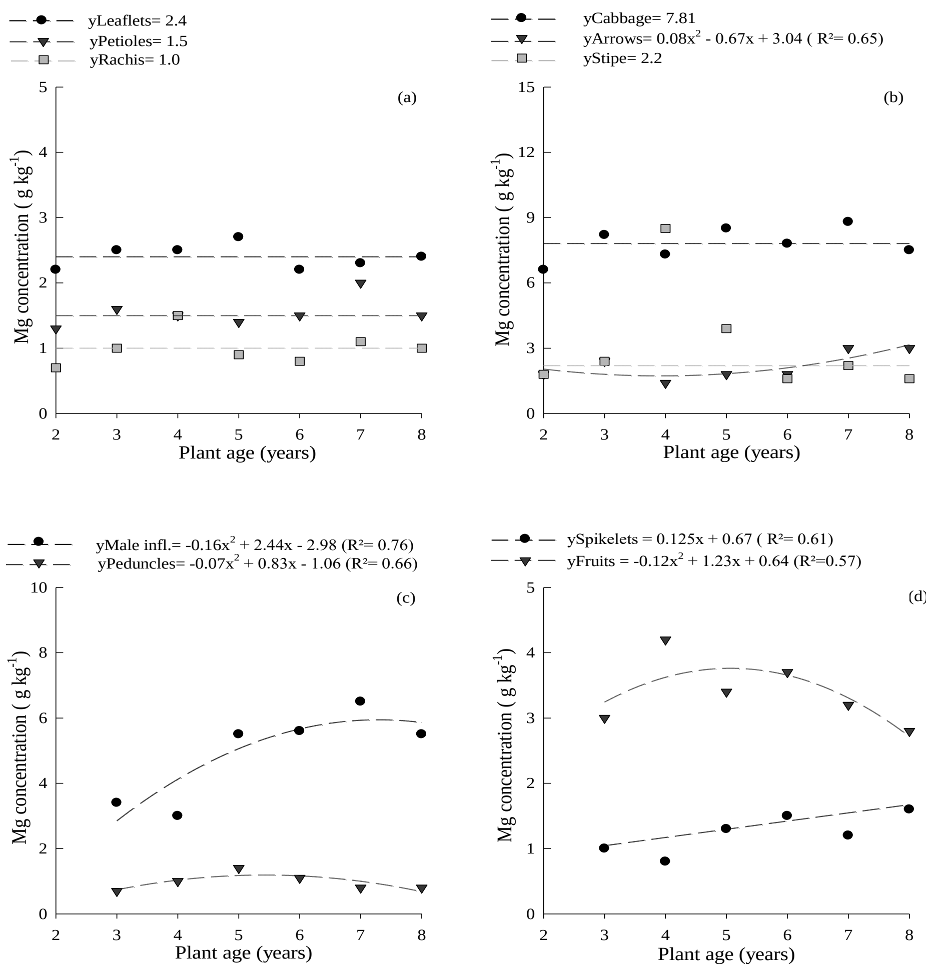

Fig. 1: Mg concentration in leaflets, petioles, and rachis (a); cabbage, arrows, and stipe (b); male inflorescence and peduncles (c); and spikelets and fruits (d) according to the age of oil palm plantation

reached during the 8th year of cultivation (Fig. 7a). Conversely, the apex of the effective Mg requirement (534 g $plant^{-1}$) was noted during the 7th year of cultivation (Fig. 7b).

MgUE

The MgUE displayed quadratic responses in the reproductive components of peduncles and spikelets

Table 2: Nutrient levels (g plant^{-1}) used in oil palm plantations according to plant age and crop yield

Plant age	Yield (t ha^{-1})	Mineral fertilization					
		N	P_2O_5	K_2O	Mg	S	H_3BO_3
2	-	35	60	60	-	24	-
3	1.5	18	77**	154	-	-	-
4	7	56	115	300	60	45	-
5	9	97	336	240	60	45	-
6	15	135	470	335	77	58	-
7	19	135	470	335	102	58	50
8	20	160	384	324	68	52	62

**Application of 500 kg ha^{-1} of phosphine (rock phosphate)

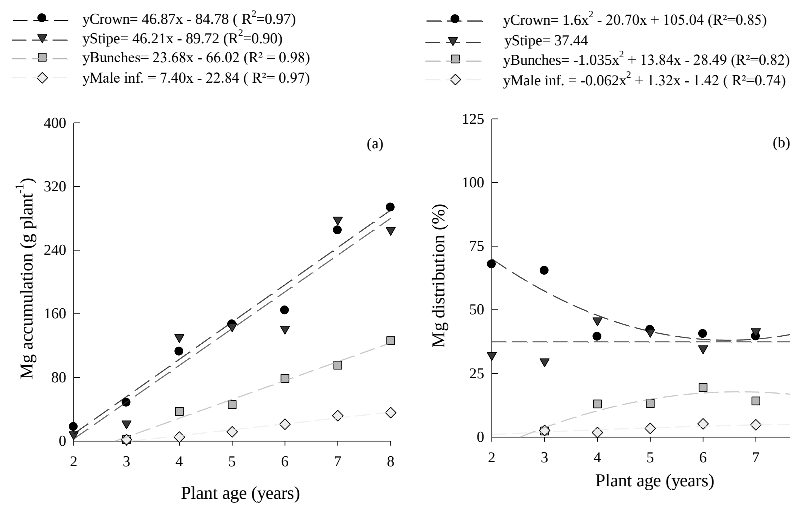

Fig. 2: Mg accumulation in crown, stipe, bunches, and male inflorescence (a) and percent distribution of Mg in crown, stipe, bunches, and male inflorescence (b) as a function of age of oil palm cultivation

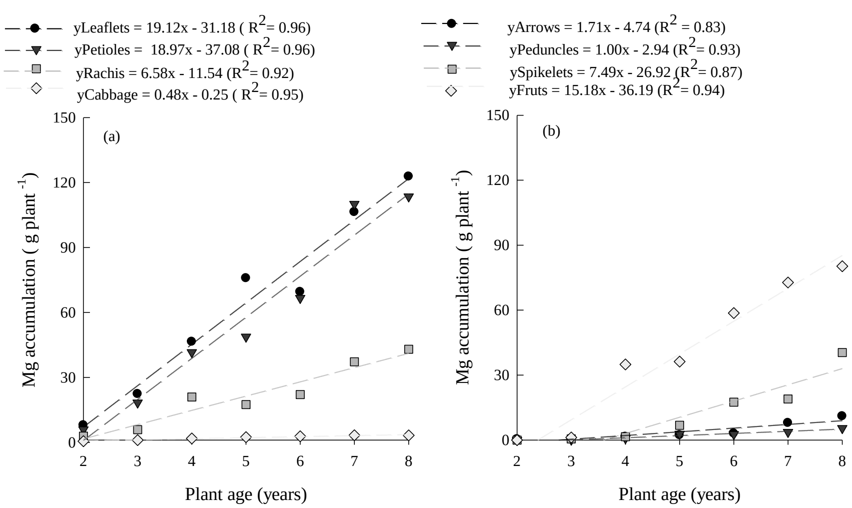

Fig. 3: Mg accumulation in leaflets, petioles, rachis, and cabbage (a) and in fruits, spikelets, arrows, and peduncles (b) according to the age of oil palm cultivation

concerning crop age (Fig. 8a–b). Conversely, other components exhibited positive linear models relative to the age of the oil palm (Fig. 8a). Notably, the stipe demonstrated the highest MgUE (98.36 kg² g^{-1}), whereas cabbage displayed the least efficiency in Mg utilization (0.01 kg² g^{-1}). Overall MgUE responded quadratically to the years of oil palm cultivation (Fig. 8c), attaining its peak value (240.85 kg² g^{-1}) during the 8th year of cultivation.

Table 3: Variation of Mg concentrations in oil palm components

Palm oil organs	Mg concentration (g kg^{-1})	Variation (%)
Leaflets	2.22–2.58	8
Petioles	1.32–1.77	14
Rachis	0.74–1.26	26
Cabbage	7.06–8.57	10
Arrows	1.53–2.81	29
Stipe	0.65–5.64	79
Male Inflorescence	3.53–6.30	28
Peduncles	0.71–1.22	27
Spikelets	0.93–1.53	24
Fruits	2.88–3.89	15

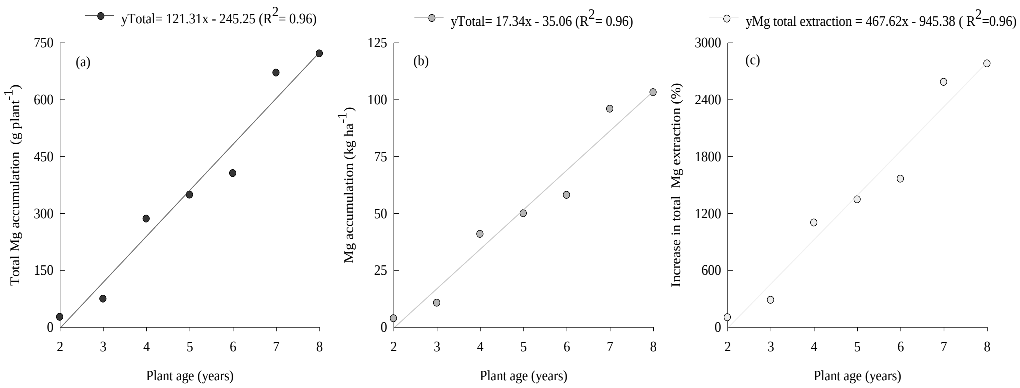

Fig. 4: Total Mg accumulation by plant (a), by hectare (b), and percentage increase (c) as a function of the age of oil palm cultivation

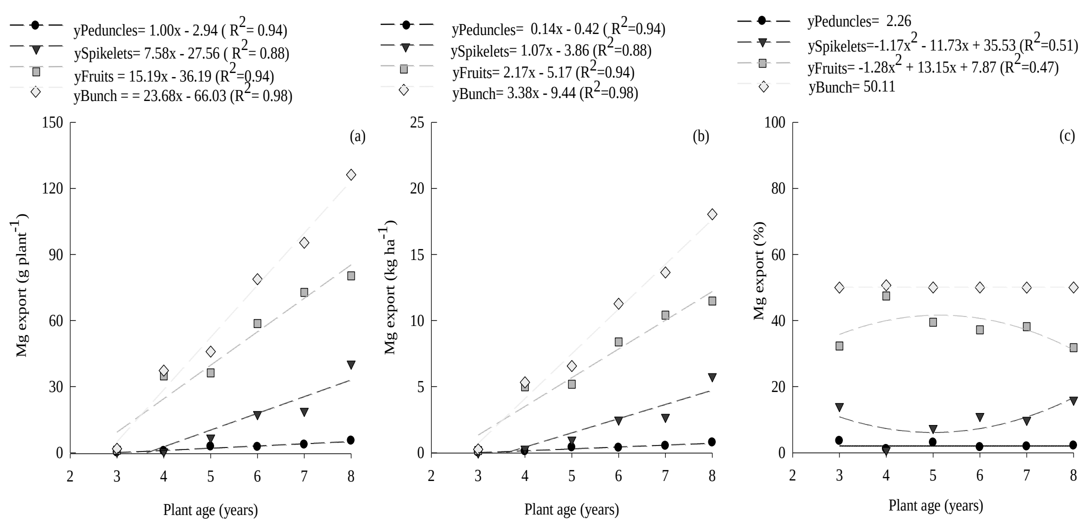

Fig. 5: Mg export in peduncles, spikelets, fruits and bunches by plant (a), by hectare (b), and percentage distribution (c) as a function of age of oil palm cultivation

Estimates of Mg supply

Total quantities of extracted, recycled, and exported Mg for each year of plant growth served as a basis for estimating their provision to the oil palm plantations. Two distinct scenarios were taken into account: i) low soil Mg content (≤ 0.5 cmol$_c$ dm^{-3}) and ii) soil Mg content above 0.5 cmol$_c$ dm^{-3}. In the former scenario, owing to the lower Mg content in the soil, Mg supply was determined based on the total amount extracted and recycled by the plants. Conversely, in soils with higher Mg content (> 0.5 cmol$_c$ dm^{-3}), Mg supply was estimated solely based on the exported amount, contingent upon crop yield. In both scenarios, considering lower or higher soil Mg content, an average Mg fertilization efficiency of 50% was assumed (Table 4).

The Mg applied via fertilizer increased with plant age and proved more substantial in soils with low Mg content compared to soils with adequate Mg content. For instance,

Table 4: Estimated plant Mg supply by fertilizer (kg ha^{-1}) as a function of soil Mg contents and total amounts extracted, recycled, and exported at each age of oil palm

Plant age	Yield	Mg applied	Soil Mg content (≤ 0.5 cmol$_c$ dm^{-3})			Soil Mg content (> 0.5 cmolc dm-^{3})	
(year)	(t ha^{-1})	(kg ha^{-1})	Total extraction	Recycled	Supply*	Exported	Supply**
2	0	0.00	3.71	2.39	2.65	0.00	0.00
3	1.5	0.00	10.56	6.92	7.28	0.26	0.52
4	7.0	8.58	40.78	16.30	48.96	5.33	10.67
5	9.0	8.58	49.87	21.97	55.80	6.56	13.13
6	15	11.01	57.92	25.64	64.55	11.27	22.53
7	19	14.59	95.83	40.82	110.01	13.64	27.28
8	20	9.72	103.06	45.03	116.05	18.04	36.09

*Supply = (Total extraction - Recycling) * 2 (average Mg fertilization efficiency of 50 %). **Supply = Export * 2 (average Mg fertilization efficiency of 50 %)

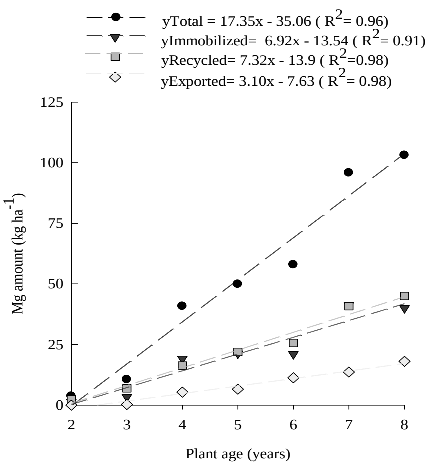

Fig. 6: Amounts of immobilized, recycled, exported, and total Mg as a function of age of oil palm cultivation

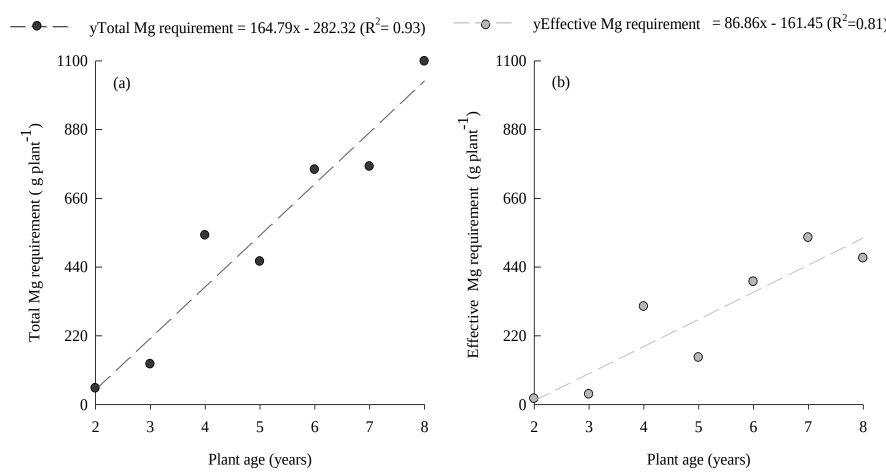

Fig. 7: Total Mg requirement (a) and effective Mg requirement (b) as a function of age of oil palm cultivation

during the 8th year of plant age with an average yield of 20 t ha^{-1}, estimates suggested an application of 116 kg ha^{-1} Mg in a Mg-poor soil and 36 kg ha^{-1} Mg in soil with sufficient Mg levels. Additionally, in Mg-poor soil, the recycled Mg quantities significantly contributed to fulfilling plant demands, consequently reducing the required supply. Notably, during the 2nd and 8th years of age, the quantities of Mg recycled by oil palm trees represented 64 and 44% of the total plant demands, respectively.

Discussion

Our findings underscored the significance of plant age in influencing Mg dynamics in oil palm cultivation. Additionally, Mg dynamics exhibited varying patterns among different plant components concerning concentration, accumulation, and export (Fig. 1). Evaluations of Mg concentrations in leaf components indicated minimal variations over the assessed period

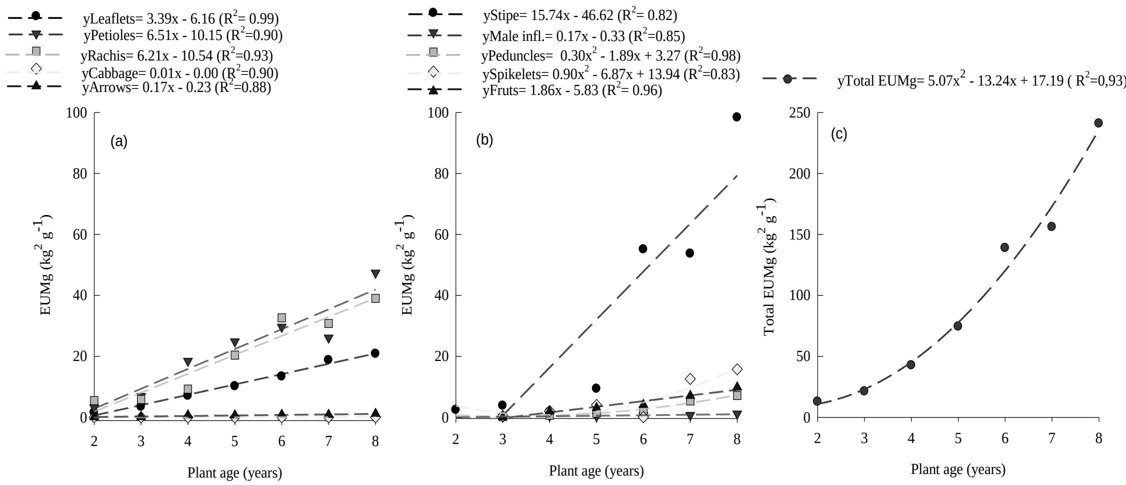

Fig. 8: MgUE of leaflets, petioles, rachis, cabbage, and arrows (a); stipe, male inflorescence, peduncles, spikelets, and fruits (b); and total (c) as a function of the age of oil palm cultivation

(Matos *et al.* 2016). This suggested that plants maintained stable nutrient concentrations in leaves while undergoing development (Behera *et al.* 2022). Moreover, within leaf components, leaflets exhibited the highest Mg concentration. This is an anticipated outcome given their role as the most photosynthetically active tissue within the leaf (Fairhurst 1996; Tiemann *et al.* 2018), where Mg plays a pivotal structural role in chlorophyll formation and acts as an enzyme activator in photosynthesis (Prado 2021; Viégas *et al.* 2023d).

Regarding nutritional status, foliar Mg concentrations indicated plants within the sufficiency range, aligning with findings in the existing literature (Behera *et al.* 2019, 2021). For instance, Matos *et al.* (2016) established Mg sufficiency ranges at 2.2 to 2.9 g kg^{-1} for young plants (< 6 years) and 1.9 to 2.5 g kg^{-1} for adult plants (> 6 years). More recent studies suggested sufficiency ranges of 2.5 to 4.0 g kg^{-1} of Mg in oil palm plants (Veloso *et al.* 2020).

In vegetative components, cabbage exhibited the highest Mg concentrations (Fig. 1). Cabbage represents the primary growth plant organ responsible for producing new tissues such as immature leaves and leaf bases, thus consistently demanding higher nutrient concentrations (Siang *et al.* 2022). Among reproductive components, the male inflorescence displayed the highest Mg concentration (Fig. 1). As Mg is a phloem-mobile nutrient, its redistribution from vegetative to reproductive components and growing organs contributed to variations in Mg concentration within the male inflorescence, reaching its maximum concentration during the 7th year of plant age. This can be attributed to the larger amounts of Mg applied during fertilization (Table 2), as nutrient concentration variations often stem from soil nutrient levels and fertilizer quantities applied (Behera *et al.* 2016). Soil Mg contents were notably low across different plant growth ages in this study (Table 1), enhancing the potential for plant response to nutrient application (Brasil and Cravo 2020).

Accumulation of nutrients is pivotal in determining plant nutrient requirements and is intricately linked to the amount of dry matter (DM) in plant tissues (Siang *et al.* 2022). An inherent characteristic of oil palm cultivation is the continuous increase in DM production, particularly in the initial eight years (Viégas *et al.* 2001; Siang *et al.* 2022), supported by the high yield of palm plants (Table 2). Analyses of Mg accumulation across vegetative and reproductive components indicated linear increments with plant age. Additionally, oil palm necessitates substantial Mg amounts, up to 56 kg ha^{-1} (Tarmizi and Mohd Tayeb 2006; Franzini *et al.* 2020) to attain higher DM production, particularly with plant age.

The crown emerged as a pivotal component contributing to over 70% of Mg distribution in the initial cultivation years (Fig. 2b). This insight is crucial as leaf nutrient concentrations directly correlate with oil palm DM production (Behera *et al.* 2021). Moreover, plant age significantly influenced Mg export, with older plants exporting the highest Mg quantities (Fig. 6), mirroring the increase in plant yield potential with age (Table 2). Notably, bunches (~50%) and fruits (~40%), respectively constituted the primary plant organs exporting Mg. Mg dynamics in oil palm plants indicated that immobilized and recycled Mg amounts surpassed the exported quantity.

The MgUE increased with plant age, suggesting oil palm plants' capacity to reuse Mg from senescent tissues to meet the nutritional demands of new tissues. This increase in MgUE influenced oil palm plants' ability to biosynthesize DM, consequently altering nutrient accumulation dynamics (Fig. 3, 4). Changes in nutrient accumulation directly impact Mg recycling, immobilization, and export in oil palm plants, renowned for high conversion rates of metabolic energy into biomass (Siang *et al.* 2022; Viégas *et al.* 2023b).

Consequently, oil palms demonstrate an amplified Mg requirement rate (Fig. 7), necessitating adjustments in Mg management to ensure an efficient supply and prevent nutritional deficiency.

Our results highlighted an escalating Mg requirement with plant age (Fig. 8), underscoring the reliance of oil palm trees on MgUE to reuse nutrients from senescent tissues for the nutritional needs of new tissues. This study delineates that Mg accumulation intensifies with plant age, reshaping the dynamics of Mg recycling, immobilization, and export due to the heightened adoption of MgUE as a strategy to fulfill Mg requirements.

Understanding the total quantities of Mg extracted, recycled, and exported at each plant age is crucial for effective Mg supply management via fertilization, especially during the productive phase, where dosages are recommended based on expected fresh fruit bunch (FFB) yields. Existing literature suggests an average export of 1 kg ha^{-1} of Mg for a yield of 1 t ha^{-1} of FFB (Franzini *et al.* 2020). Considering the highest oil palm yield in this study (20 t ha^{-1}) and an average fertilizer efficiency of 50%, we recommend 40 kg ha^{-1} of Mg for eight-year-old plants, irrespective of soil nutrient content. However, in Mg-deficient soil ($\leq$ 0.5 $cmol_c$ dm^{-3}), the estimates for Mg supply via fertilization are higher. For instance, during the 8th year of plant age, an application of 116 kg ha^{-1} of Mg, equivalent to 811 g $plant^{-1}$ of Mg at a density of 143 plants ha^{-1}, is suggested. As observed in this study's soil with low Mg content (Table 1), the applied Mg amounts fell short of the estimates for Mg supply across all plant ages (Table 4). This indicated an escalating Mg requirement with increasing plant age, particularly in Mg-deficient soils.

A study by Oliveira *et al.* (2018) assessing a three-year-old oil palm plantation in Mg-poor soil (0.1 $cmol_c$ dm^{-3}) in northeastern Pará State, Brazil, reported the highest yield (7.5 t ha^{-1}) with a Mg dose of 48 kg ha^{-1}, considering 143 plants ha^{-1}. For Mg-poor soils and a yield of 7.0 t ha^{-1}, a supply of 49 kg ha^{-1} of Mg is recommended (Table 4). Thus, in Mg-deficient soil, the proposal of Mg fertilization based on total plant demand seems more suitable, encompassing not only exported quantities but overall plant requirements.

Managing crop residues in oil palm plantations significantly contributes to Mg recycling, partially fulfilling plant demands. At eight years of age, 45 kg ha^{-1} of Mg was recycled, accounting for 44% of the palm tree demand at that age (Table 4). The Mg accumulated in foliar components is notably recycled through cultural practices like pruning and organic fertilizer application, enhancing Mg contributions (Henson *et al.* 2012; Matos *et al.* 2018). Additionally, cultivating *Pueraria phaseoloides* L. between rows in oil palm plantations could further boost Mg recycling. *P. phaseoloides* cultivation as a cover plant in oil palm plantations demonstrated an average cycling of 20.3 kg ha^{-1} of Mg, considering plantations aged two to eight years (Viégas *et al.* 2022). This information holds significance for efficient Mg fertilization management, reducing environmental and economic impacts while enabling more informed decisions for Mg supply in oil palm cultivation.

Conclusion

The dynamic nature of Mg in oil palm plants significantly varied with plant age, offering invaluable insights to guide nutrient management strategies. A consistent increase in Mg accumulation and export with plant age was directly correlated with increased dry matter yield. Older plants exhibit a remarkable capacity to recycle Mg from senescent tissues, leading to enhanced MgUE and heightened Mg requirements. The management of residues contributed in substantially meeting the Mg demand of oil palm, supplementing the nutrient cycle within the plantation. As the plant age advanced, there was an escalating need for increased Mg supply. This demand intensified particularly in Mg-deficient soils, emphasizing the necessity for heightened Mg replacement. The findings are pivotal for refining Mg fertilizer management, thereby offering a timely and informed framework to optimize Mg fertilization strategies and ensuring optimal plant health and productivity in oil palm plantations.

Acknowledgements

The authors acknowledge the Agropalma company for the experimental field support. We also dedicate this work to Professor Ronaldo Ivan Silveira from ESALQ-USP (*in memoriam*).

Author Contributions

IJMV conceptualization and methodology to data collection, formal analysis, writing, review, and editing, as well as overseeing the study. AESS original draft, actively, participated in the review and editing. MGC, EVOF, LGN, DASS, and CFON provided substantial input through detailed manuscript reviews and critical adjustments at different stages of the writing process.

Conflicts of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Data Availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Ethics Approval

The experimental research was carried out in accordance with the relevant institutional, national, and international guidelines and legislation and, still, does not involve an endangered species.

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