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Assessing management factors limiting yield and starch content of cassava in the western Brazilian Cerrado

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Abstract

Cassava (*Manihot esculenta Crantz*) was declared the "crop of the 21st century" by the Food and Agriculture Organization of the United Nations due to its high starch content and low input requirements. The management factors that govern yields and starch content in cassava in Brazil are still unclear. The aim of this study was to identify the main factors that limit the yield and starch content of cassava fields in Brazilian Cerrado. The data were collected as part of a survey covering 300 cassava fields in two growing seasons (2020–2021 and 2021–2022). Throughout the development cycle, management practices, yield, and percentage starch content in the roots were described. The database was divided into high and low yield tertiles. Mean comparison tests, regression tree analyses, and boundary functions were applied. The importance of genetics, environment, and associated crop constraints on cassava production (yields and starch content) was assessed. The yield gap in cassava was 44.6 Mg ha^{-1}. The most important factors leading to yield and starch losses were variety, planting date, and potassium fertilization. By adapting optimal practices, it is possible to produce an additional 1.5 million tons of cassava on the current cultivation area in the western Brazilian Cerrado, which corresponds to 8.3% of total production in Brazil and could increase the production of cassava starch by more than 400,000 Mg.

1 | INTRODUCTION

The world population is expected to grow by 2 billion people over the next 30 years, and the total global food demand is expected to increase by 35%–56% between 2010 and 2050 (van Dijk et al., 2021). Cassava (*Manihot esculenta Crantz*) has been described as the "crop of the 21st century" due to its importance as a source of energy for human nutrition in developing countries in South America, Africa, and Asia (FAOSTAT, 2021). Cassava is the fourth most important staple food around the world after rice (*Oryza sativa*), wheat (*Triticum aestivum*), and maize (*Zea mays*), and it is an important part of the diet of over 1 billion people in the world (FAOSTAT, 2021). In their natural form, cassava roots contain about 30% carbohydrates (25.5% of which is starch), 1.6% fiber, 0.6% protein, and 0.3% fat. It also contains vitamin C (11.1 mg g^{-1}) and the minerals calcium (19 mg g^{-1}), magnesium (27 mg g^{-1}), and phosphorus (22.1 mg g^{-1}), and the leaves contain significant amounts of protein (17.9%–20.0%) (Tagliapietra, Zanon, Tironi et al., 2021).

At the global level, few studies have been conducted to determine the management factors that lead to yield losses in cassava (Fermont et al., 2009), compared to standard crops such as soybean (Grassini et al., 2015; Tagliapietra, Zanon, Streck et al., 2021; Winck et al., 2023), maize (Andrea et al., 2018; Farmaha et al., 2016; Liu et al., 2021), and rice (Ribas et al., 2021; Silva et al., 2021). In Brazil, a study using mathematical modeling was conducted to estimate the cassava yield potential (63.2 Mg ha^{-1}) (Visses et al., 2018). However, research into the management factors that limit cassava roots on-farm yield in Brazil is still at an early stage (Cardoso et al., 2022). As far as we know, the management factors associated with high yields and high starch content of roots in industrial cassava, flour, and starch have not yet been identified.

With an estimated production of around 12 million tons in 2020, cassava starch is the second most produced starch in the world, trailing behind only corn starch. Brazil is the major producer outside of Asia (Vilpoux, 2024). In the last 5 years, an average of 636,000 tons of cassava starch were produced in Brazil (CEPEA, 2022). In the western region of the Brazilian Cerrado, Mato Grosso do Sul (MS) has the highest production and export of Brazilian cassava starch. Despite the socioeconomic importance of cassava in MS, the average yield is 22.0 Mg ha^{-1} (IBGE, 2022), and thus far below the yield potential of 63.2 Mg ha^{-1} (Visses et al., 2018). The yield potential was estimated using the Food and Agriculture Organization Agroecological Zone crop simulation model as proposed by Doorenbos and Kassam (1979) and adapted for cassava. The model takes into account the interactions between solar radiation, temperature, photoperiod duration, and genotype.

Therefore, studies are needed to find out which factors limit the yield and starch content of cassava fields. To address the lack of information on the factors that enable high yield and starch content, 300 site-year observations were evaluated in two growing seasons (2020–2021 and 2021–2022), representing a wide range of management practices in the western Brazilian Cerrado. The objective of this study was to identify the main management factors governing variation in yields and starch content of cassava fields in the western Brazilian Cerrado.

Core Ideas

- The yield gap in cassava fields is 44.6 Mg ha^{-1}.
- Variety, planting date, and potassium fertilization were factors that optimized yield and starch content.
- The highest yields were obtained in fields that were planted by July 18. After that, the yield loss amounted to 0.132 Mg ha^{-1} day^{-1}.
- Advancing the planting date before May 25 led to a decrease in starch content of 8.14 g 5 kg^{-1} of cassava.
- Planting date after August 18 led to a decrease in starch content of 3.0 g 5 kg^{-1} of cassava.

2 | MATERIALS AND METHODS

2.1 | Site selection and data collection

The study area corresponds to the two most important cassava-growing areas in the western Brazilian Cerrado (Figure 1A,B). This region is home to 71.5% of cassava-producing communities and the most technologically advanced farmers, accounting for 25.7% of starch production in Brazil (CEPEA, 2022). The climate region is classified as humid subtropical (Cfa) according to the Koppen classification (Alvares et al., 2013).

The daily meteorological data of the last 5 years (2017–2021) were collected at the meteorological stations of the Brazilian Institute of Meteorology (Figure 2). The quality control and completion/correction of the meteorological data were performed based on the dispersion technique developed by van Wart et al. (2013).

The monitoring of 300 site-years cassava fields of the first cycle (12 months) was conducted during the 2020–2021 and 2021–2022 growing seasons. Management data were collected such as variety, planting date, fertilizer rate, weed control, pests, diseases, and yield (Table 1).

2.2 | Evaluation of starch content of roots

To determine the starch content in cassava, the hydrostatic balance technique was used, which consists of measuring the specific density of the material (Grosmann & Freitas, 1950). The roots were washed to remove excess soil and weighed exactly 5 kg. A container was then filled with water and the root sample was suspended in the water using a support, making sure that the roots did not touch the walls or the bottom of the container. The new mass when the roots were fully submerged was recorded and quantified as starch. We have followed the same method used in the industry, which determines the amounts paid to farmers depending on the starch content. In Brazil, as in many other countries, including India, Thailand, Ghana, and Colombia, processing industries determine the total starch content of cassava root using this method (Bantadjan et al., 2020; Cereda & Branco, 2024).

There are analytical methods to determine the starch content in roots. However, these methods require laboratory

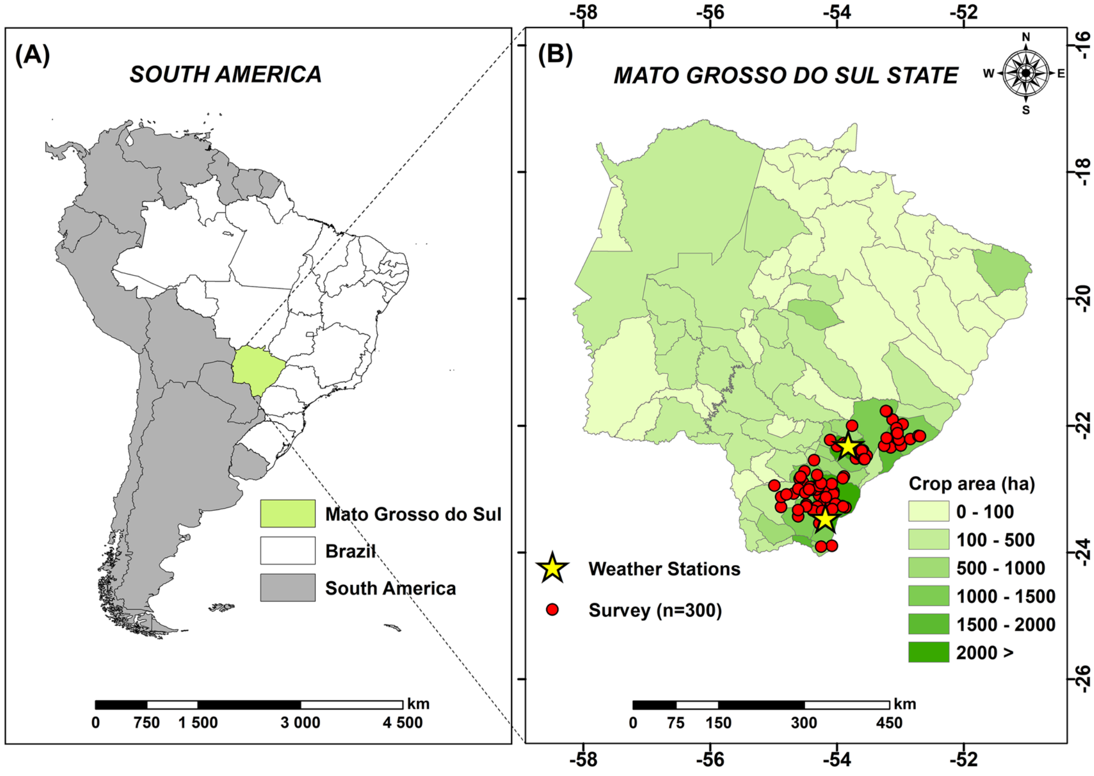

FIGURE 1 Geographical location of Brazil in South America (A), with a focus on the western Brazilian Cerrado (Mato Grosso do Sul) (B). The meteorological reference stations (yellow stars) selected to represent the 2020–2022 cassava harvesting areas (in green) and the locations of cassava fields monitored by surveys (red circles).

facilities as well as drying the samples in an oven for at least 24 h, followed by crushing, preparation, and chemical analysis of the samples by enzymatic hydrolysis (Maraphum et al., 2022). This is a costly and time-consuming process that is not feasible when analyzing large quantities of samples.

2.3 | Identification of agronomic causes of yield gap and reduction of starch content

The surveys categorized cassava fields into high yield (HY) (20% above average) and low yield (LY) (20% below average) groups based on their yield. Similarly, for starch content, fields were classified as high starch content (HS) if their roots had values equal to or greater than 500 g 5 kg^{-1}, and low starch (LS) content if they were below this threshold. Statistical analysis was performed with InfoStat Analysis software (Di Rienzo et al., 2012), using the *t*-test or Wilcoxon test (for nonparametric data) to compare the means of numeric variables, including cassava high and low yields and high and low starch content (Grassini et al., 2015; Ribas et al., 2021; Winck et al., 2023). The categorical variables were analyzed using the chi-square test. The significance level was calculated for 1%, 5%, 10%, or not significant.

Regression tree analysis was used to determine in a hierarchical manner which management practices cause the variation in yield and starch content of cassava roots. The package "rpart" in R was used for this purpose. Regression tree analysis is a nonparametric method that recursively splits data into successively smaller groups with binary subdivisions based on a single continuous predictor variable (Breiman et al., 1984). In response, the regression tree generates a tree diagram with branches determined by the subdivision rules and a set of three terminal nodes containing the average yield (or starch content) and the number of observations contained in each terminal node. Maximum trees are created first, and then the technique of cross-validation is used to prune the tree to an ideal size (Therneau & Atkinson, 1997). The package "caret" in R was used to split the dataset into calibration (80%) and validation (20%) data. The calibration dataset was used to perform the regression tree analysis, while the validation dataset was used to estimate the root mean square error between root yields and starch content. The regression tree analysis dealt with missing values in the explanatory factors (function na.rpart) and excluded data only if the response variable (i.e., root yield and starch content) or all explanatory factors were missing. If missing values were found when looking at a division, these were ignored and predictions were calculated using the non-missing values of that factor (Venables & Ripley, 2002).

Boundary function (French & Schltz, 1984) was performed to separately quantify the influence of the most key factors on

TABLE 1 Surveys were conducted through interviews with industrial cassava farms through 2021–2022 growing season, covering 104 parameters and management variables in Mato Grosso do Sul, Brazil.

Parameters	Requested variables	Information provided
Crop data	Coordinates	Latitude; Longitude
	Variety	Name
	Purpose	Subsistence—agroindustry—market
	Planting date	Date
	Planting density	Row space
	Stems	Origin
	Seedlings	No. of buds
	Crop rotation	Yes/no
	Crop/plot history	Previous crops
	Farm management	Monoculture or consortium
	Soil tillage system	Animal or mechanized
	Weed management	Control frequency
	Development stage	Date
	Landscape relief	Flat—wavy—steep
	Soil analysis	Yes/no
	Soil characteristic	Soil type
	Harvest	Date
	Yield	Mg ha^{-1}
	Starch content	g 5 kg^{-1} of cassava
Crop inputs	Fertilizer	Yes/no
	NPK	Rate and formulation
	K—Top-dressed	Rate and days after panting
	Lime	Yes/no
Phytosanitary management	Herbicide	Yes/no (how many sprays; rate)
	Fungicide	Yes/no (how many sprays; rate)
	Insecticide	Yes/no (how many sprays; rate)
Another	Water excess or deficit	Yes/no

the yield and starch content of the roots. This method allows the optimal value of the analyzed factor to be determined, which is considered when the increase in yield and starch content is less than 0.05% (Zanon et al., 2016). To quantify yield losses as a function of sowing date, the bilinear plateau model was used, which was adapted for the area of highest root yield (Winck et al., 2023; Zanon et al., 2016). The same was done for the starch content in the roots.

3 | RESULTS AND DISCUSSION

3.1 | Agronomic causes of yield variation across farmer fields

The average yield (Ya) of the 300 site-years fields was 18.6 Mg ha^{-1}. Considering the yield potential (Yp) for Mato Grosso do Sul of 63.2 Mg ha^{-1} (Visses et al., 2018), it can be estimated that the yield gap is 44.6 Mg ha^{-1}. Given the large yield gap, cassava yields can be significantly increased by adjusting management practices. According to the quartile analysis, the fields with high yields are planted earlier, with higher phosphorus and potassium fertilization, intensive weed control, and crop rotation (Table 2).

The growth, development, and yield of the cassava are strongly influenced by the planting date (Schons et al., 2007). As cassava is a perennial crop, the development cycle is shortened if planting is delayed and consequently yields are reduced. The low yield of cassava roots is related to insufficient fertilization, which is exacerbated by the fact that the crop is predominantly grown on naturally nutrient-poor soils (Alves et al., 2017). Cardoso et al. (2022) show that fertilizer use is the main limiting factor for cassava yield and that there is a real opportunity to increase yield on current smallholder farmland with some tweaks and improvements in agronomic management practices.

TABLE 2 Comparative statistical analysis for cassava fields with high and low yields.

Variables		Units	*n*	HY	LY	HY-LY
Yield		Mg ha^{-1}	128	23.8	14.4	9.4***
Planting date		DOY	128	174.0	186.0	−12.0***
P_2O_5		kg ha^{-1}	128	74.8	65.2	9.3*
K_2O		kg ha^{-1}	128	69.1	56.9	12.2*
Weed control number		WCS	128	4.9	3.1	1.8***
Crop rotation	No	%Field	13	7.7	91.7	−84.0ns
	Yes	%Field	115	52.2	48.2	4.3***

Abbreviations: DOY, day of the year; HY, high yield; K_2O, total potassium fertilization; LY, low yield; ns, not significant; P_2O_5, phosphate fertilization; WCS, weed control spray.
***$p < 0.01$; **$p < 0.05$; *$p < 0.1$.

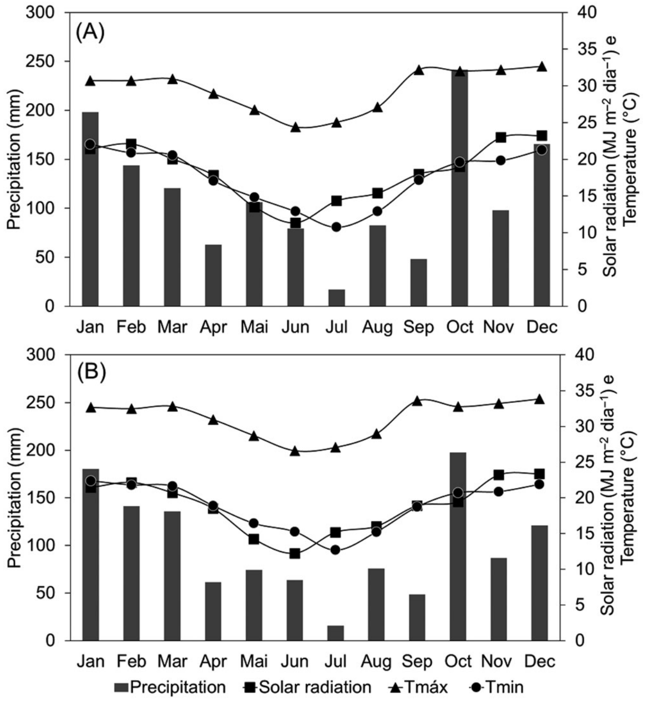

FIGURE 2 Five-year average (2017–2021) of monthly solar radiation, maximum (T_{max}) and minimum (T_{min}) temperature, and total precipitation (bars) for the cassava-growing regions in western Mato Grosso do Sul (MS), (A) Itaquiraí and (B) Ivinhema.

The more weed control measures, whether chemical or mechanical, are carried out, the higher the yield of the cassava fields (Cardoso et al., 2022). The adoption of crop rotation in cassava fields helps maintain soil health and reduce the incidence of weeds, diseases and pests, in addition to increasing yield and diversifying the producer's income (Maraphum et al., 2022). The varieties with high yields are B36 (IPR B 36), B420 (BRS 420), BCS (BRS CS 01), I14 (IAC-14), IU (IPR UNIÃO), and P (IPR Paraguainha) (Figure 3). The varieties with low yields are B (Baianinha), FB (Fécula Branca), FM (Fécula Modificada), I15 (IAC-15), I90 (IAC-90), IP (Iapar Porã), NM (Nega Maluca), O (Olho Junto), and SG (São Geraldo). The red boxes are division nodes; the lower gray boxes represent the end nodes. The values within each end node indicate the average cassava yield (kg ha^{-1}) and the percentage of observations in each end node.

For fields classified as high yielding, four variables (variety, base fertilizer, planting date, and potassium fertilization) accounted for 54.7% of the variation in root yield. For low yielding, two variables (variety and planting date) accounted for 45.3% of the variation in yield (Figure 3). Variety was the most important management factor associated with high root yields. These high-yielding fields use varieties introduced by research institutions less than 5 years ago, such as IPR B36, BRS 420, BRS CS 01, IAC-14, IPR União, and IPR Paraguainha (Rangel et al., 2022). The higher root yields of the varieties recommended by researchers can be explained by the gains achieved through genetic improvement, as well as greater resistance to soil diseases and early maturity, which allows harvesting in a 12-month cycle (Alves & Bressan et al., 2017). Among the low-yielding fields, traditional varieties such as Baininha, Fécula Branca, Fécula Melhorada, Nega Maluca, Olho Junto, and São Geraldo predominate. These varieties, which were commercialized more than a decade ago and some of which have no defined origin, show a loss of vigor due to contamination by diseases, bacteria, and the accumulation of genetic mutations during vegetative propagation cycles (Maraphum et al., 2022).

Fields planted before June 8 with high root yields (23.5 Mg ha^{-1}) had an average yield that was 17% higher than fields planted after this date (20.1 Mg ha^{-1}) (Figure 3). The highest yields were obtained in fields planted until July 18, after which the yield loss was 0.132 Mg ha^{-1} day^{-1} (Figure 4A). In the Brazilian Cerrado, the main planting window is between June and August, a period of low rainfall but with sporadic showers that allow the farmer to plant and carry out an initial treatment with pre-emergent herbicides. The soil moisture allows the initial sprouting of the cassava plants in the soil with low disease pressure (Visses et al., 2018). Like the results found in this study for a tropical environment, a delay in sowing date reduces the yield potential of cassava up to 0.364 Mg ha^{-1} for

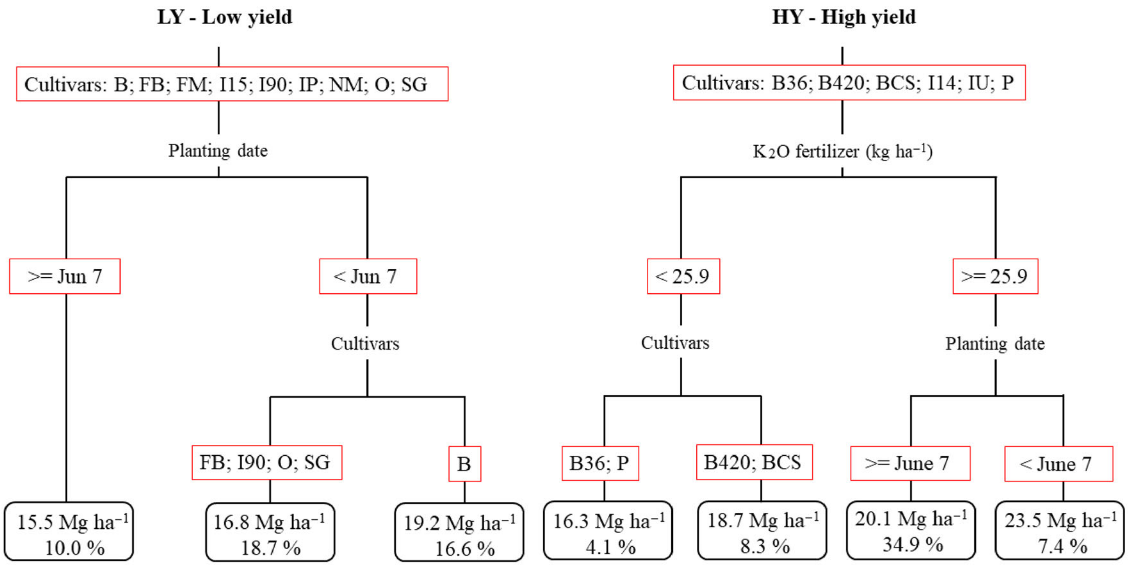

FIGURE 3 Regression tree analysis of management factors influencing yield variation in cassava. Values within each terminal node indicate the average grain yield (Mg ha^{-1}) and the percentage of observations in each terminal node. The cultivars B, FB, FM, I15, I90, IP, NM, O, SG, B36, B420, BCS, I14, IU, and P correspond to Baianinha, Fécula Branca, Fécula Modificada, IAC-15, IAC-90, Iapar Porã, Nega Maluca, Olho Junto, São Geraldo, IPR B 36, BRS 420, BRS C 01, IAC-14, IPR União, and IPR Paraguainha, respectively.

TABLE 3 Comparative statistical analysis for cassava fields with high and low starch content.

Variables	Units	*n*	HS	LS	HS-LS
Starch content	G	133	637.6	457.9	179.7***
Planting date	DOY	133	187.0	177.0	10.0***
Meristematic buds	No.	133	6.6	6.1	0.5***
Yield	Mg ha^{-1}	133	19.8	17.6	2.2***
Variety					
Baianinha	%Field	26	23.0	76.0	−53.0***
BRS 420		18	44.0	55.0	−11.0***
BRS CS 01		29	96.5	3.5	93.0***
Fécula Branca		11	–	100.0	ns
IAC-14		3	–	100.0	ns
IAC-90		4	25.0	75.0	−50.0ns
Iapar Porã		12	33.0	66.0	−33.0*
IPR B36		6	–	100.0	ns
Paraguaiainha		14	78.5	21.5	57.0*
Olho Junto		6	88.0	16.0	72.0ns

Abbreviations: DOY, day of the year; HS, high starch content; LS, low starch content; ns, not significant.
***$p < 0.01$; *$p < 0.1$.

a delay of one day in sowing from September 11 to November 30 in a subtropical environment (Borges et al., 2020). Of the farmers who participated in this study, 95% are land tenants. In several cases, the availability of land by landowners does not coincide with the ideal sowing window identified in the analyses. This occurs for reasons such as an increase in livestock farming and in areas where crop rotation is practiced. In such scenarios, the crop that precedes the cassava has often not yet reached the appropriate harvest stage. For example, a second maize crop that coincides with the cassava planting may not yet be ready for harvest, which in turn delays the cassava planting date.

A greater number of weed controls (chemical or manual) were observed in fields with higher root yields (Figure 4B).

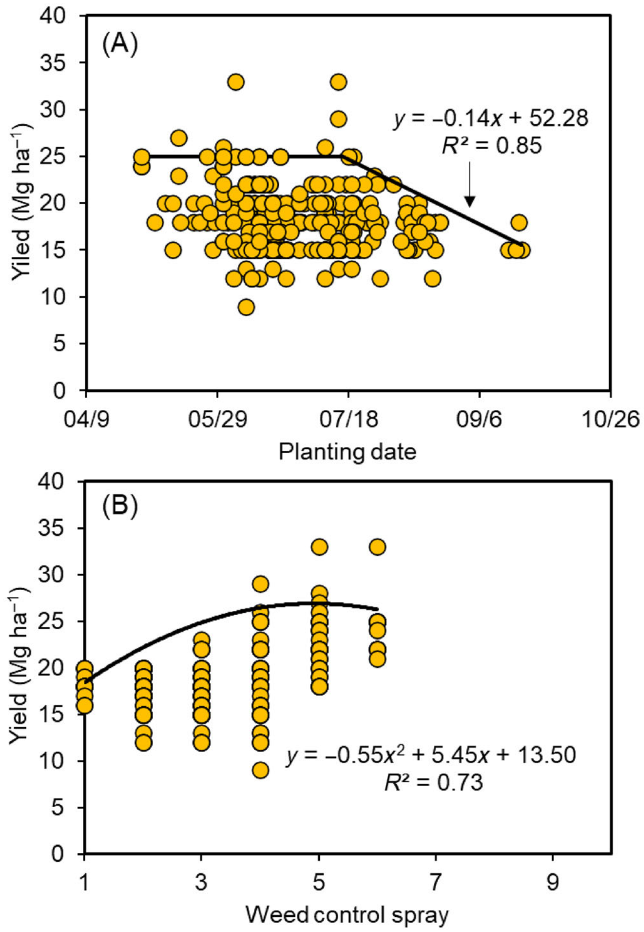

FIGURE 4 Yield of cassava roots (Mg ha^{-1}) as a function of planting date (A) and yield of cassava roots (Mg ha^{-1}) as a function of the weed control spray (B). The yellow circles represent the 300 site-years evaluated. The arrow points to the segment of the boundary function described by the equation. The black solid line represents the boundary function.

A considerable proportion of small-scale cassava producers often hold the misconception that, because cassava is a traditional (rustic) crop, the management of invasive plant species is not an imperative measure (Cardoso et al., 2022). However, in the opposite direction, science has demonstrated that the interference caused by invasive plants, in general, induces anomalous growth and development of cassava, resulting in a decrease in the plant's dimensions, weight, and root count (Fermont et al., 2009).

3.2 | Agronomic causes of variation in starch content

The limiting factors for starch accumulation in cassava roots were variety, planting date, and potassium fertilization. In the fields with low starch content in the roots (52.9%), variety and planting date were found to limit greater starch accumulation. Studies carried out in Nigeria and Thailand show that the starch content in cassava roots varies between 10% and 40% depending on the variety and climate (Enesi et al., 2022; Maraphum et al., 2022). Some varieties can have a starch content of more than 30%, while others contain less than 20% starch (Moorthy et al., 2018); therefore, selecting varieties is one of the easiest ways to increase the starch content in cassava roots (Rangel et al., 2022). In Figure 5, the boxes are split nodes, with the bottom boxes representing the terminal nodes. The values within each end node indicate the average starch content in cassava roots and the percentage of observations at each end node.

For cassava fields classified as high starch, three variables (variety, planting date, and K_2O fertilization) accounted for 47.1% of the variation in total starch yield. For low starch content, two variables (variety and planting date) accounted for 52.9% of the variation in starch yield (Figure 5). Application of K_2O fertilizer increased biomass production and starch content in high-yielding fields. Potassium fertilizer, by providing an essential macronutrient for growth, plays a fundamental role in a variety of physiological processes in the cassava plant, such as root growth, absorption of other nutrients, regulation of stomatal opening and metabolism, and enzymatic activities, improving root quality and increasing amylose content, a component of starch that gives more stability to the final product (Tagliapietra, Zanon, Tironi et al., 2021). The highest starch contents were determined for planting dates between May 25 and August 18. According to the angular coefficients of the equations (Figure 6), for each day before May 25, there was a reduction in starch content of 8.14 g 5 kg^{-1} of cassava, while for each planting date after August 18, there was a reduction of 3.0 g per 5 kg of cassava. The starch content of cassava is influenced by climate, crop management, and most importantly, the planting date (Srirotha et al., 1999). Early planting (before May 25) may cause cassava to grow excessively during the rainy season, resulting in more vegetative growth at the expense of root development, which lowers carbohydrate allocation to the roots, and consequently, starch content (El-Sharkawy, 2004). Additionally, cassava relies on an appropriate photoperiod for efficient nutrient translocation to the roots (Gabriel et al., 2014). If planted too early, the plant may miss these optimal conditions at crucial points in its growth cycle, reducing starch accumulation (Amelework & Bairu, 2022).

Estimating the starch content in the raw material is desirable for effective control of the extraction process. If the productive yield (Mg h^{-1}) is low and the percentage of dry matter (DM) accumulated in the roots is less than 30%, the performance becomes unsatisfactory for the processing industry, resulting in lower yields. This requires higher agricultural productivity in terms of acreage to compensate for this deficiency. Maximizing the starch content in the roots is desirable

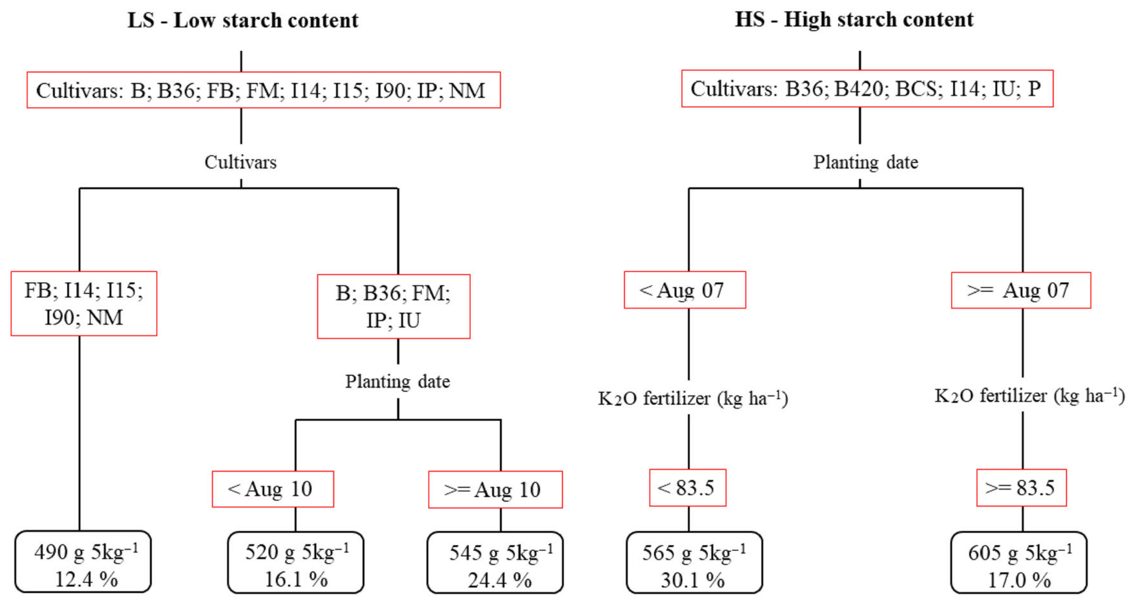

FIGURE 5 Regression tree analysis of management factors influencing starch content variation in cassava. Values within each terminal node indicate the average starch content in cassava roots (g 5 kg^{-1} of cassava) and the percentage of observations in each terminal node. The cultivars B, B36, FB, FM, I14, I15, I90, IP, NM, B420, BCS, O, and SG correspond to Baianinha, IPR B 36, Fécula Branca, Fécula Modificada, IAC-14, IAC-15, IAC-90, Iapar Porã, Nega Maluca, BRS 420, BRS C 01, Olho Junto, and São Geraldo, respectively. Fields planted by July 6 (day of the year [DOY] 187) had high starch content, while low starch content fields were planted by June 26 (DOY 177) (Table 3). This difference may be related to the fact that starch accumulates more in the cassava roots when the plant starts the physiological ripening phase. The best time is when the plants are in a dormant phase, that is, when the number and size of leaves and leaf lobes have decreased, a state in which they reach maximum root production and starch content, resulting in a better quality of the final product (Enesi et al., 2022).

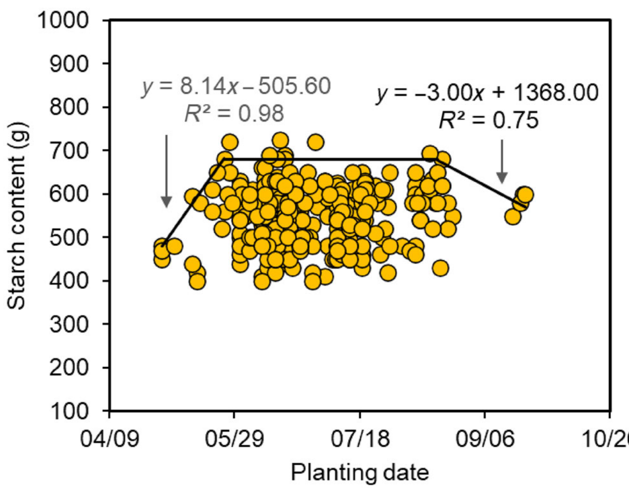

FIGURE 6 Starch content (g in 5 kg of cassava root) as a function of planting date. The yellow circles represent the 300 site-years evaluated. The arrow points to the segment of the boundary function described by the equation. The black line represents the boundary function.

for starch factories as it is associated with high extraction efficiency and higher starch yield (Vilpoux, 2024).

The global starch market scenario demands the production of a low-cost product, manufactured in large quantities, and readily available across a vast geographical area. Given that the cost of raw materials constitutes the primary portion of the total starch cost, exceeding 50% in the case of cassava starch, the efficiency of agricultural yields plays a significant role (Vilpoux, 2023). By focusing solely on DM productivity per hectare, cassava demonstrates higher yields compared to wheat and rice. However, cereals, due to their lower water content, allow for the extraction of larger quantities of starch with less raw material, leading to reduced production costs. The advantage of cassava lies in its ability to be harvested throughout the year, making it a raw material with significant economic potential in tropical countries (Vilpoux, 2023).

To compete in the international market, characteristics beyond cost are crucial. Cassava starch is preferred in many food products due to its neutral taste, being free from lipids and proteins, unlike many cereal starches, which often have a lipidic flavor. The pure white color of cassava starch is also advantageous as it provides transparent starch pastes, expanding its applicability in a wide range of food products (Moorthy et al., 2018).

Considering the yield gap of 44.6 Mg ha^{-1} estimated in this study and a cassava cultivation area of 35,488 ha in the western Brazilian Cerrado, it is possible to increase root production by 100% if good management practices are applied and environmental protection is harmonized. Similarly, the starch content can be increased from an average of 457.9–637.6 g in 5 kg of cassava roots, representing 39.81% of the total dry-based starch. This increase is of considerable importance to the industry, as it increases the value offered to farmers and boosts the profitability of cassava cultivation. Mato Grosso do Sul will currently be able to produce and sell approximately 403,605.1 tons of starch. The study highlights the management, genetics, and environment that affect yield and starch content and updates guidelines for research and extension of cassava cultivation in the Brazilian Cerrado.

4 | CONCLUSIONS

The main management factors that reduce the yield and starch content of cassava fields are the variety, the amount of total K_2O fertilization, the planting date, and the amount of weed control. Through the adoption of good management practices, it is possible to increase the production of industrial cassava by 1.5 million tons and increasing approximately 403,605.1 tons of starch in the west of the Brazilian Cerrado. The instability of the cassava market and the unpredictability of prices represent a significant barrier to investment and result in limited adoption of advanced management practices by producers. This study clearly shows that cassava yields can be significantly increased through the adoption of agricultural management practices. This ongoing cycle of low profitability and disinvestment highlights the need for targeted policies and support mechanisms to stabilize the market, incentivize sustainable practices and improve productivity to ensure the long-term viability of cassava production.

AUTHOR CONTRIBUTIONS

Cleiton Simão Zebalho: Conceptualization; data curation; formal analysis; funding acquisition; investigation; project administration; resources; visualization; writing—original draft. **Isabela Bulegon Pilecco**: Data curation; formal analysis; investigation; methodology; software; visualization; writing—original draft; writing—review and editing. **Nereu Augusto Streck**: Funding acquisition; investigation; resources; visualization; writing—review and editing. **Paula de Souza Cardoso**: Conceptualization; data curation; project administration; supervision. **Charles Patrick de Oliveira de Freitas**: Conceptualization; data curation; project administration. **Eduardo Alano Vieira**: Conceptualization; data curation; project administration; supervision; investigation; methodology; writing—original draft. **Mauricio Fornalski Soares**: Project administration; visualization; writing—review and editing. **Bruna Lago Tagliapietra**: Data curation; formal analysis; investigation; methodology; software; visualization; writing—original draft; writing—review and editing. **Alexandre Alves Ferigolo**: Conceptualization; data curation; methodology; project administration; writing—review and editing. **Alexandre Swarowsky**: Funding acquisition; supervision; visualization. **Diego Nicolau Follmann**: Conceptualization; funding acquisition; project administration. **João Vitor Santos de Souza**: Investigation; methodology; visualization. **Alencar Junior Zanon**: Conceptualization; data curation; formal analysis; funding acquisition; investigation; project administration; resources; supervision; writing—review and editing.

CONFLICT OF INTEREST STATEMENT

The authors report no conflicts of interest.

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