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SOIL MANAGEMENT AND APPLICATION OF MICROORGANISMS IN THE PRODUCTIVITY OF SOYBEAN, COMMON BEAN, RICE, WHEAT, SORGHUM, AND CORN CROPS IN THE CERRADO REGION

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Abstract: The use of microorganisms in agricultural production systems has shown potential for increasing productivity and optimizing cultivation costs in various crops. In this context, the present study aimed to evaluate the effect of different soil management practices, associated with the application of plant growth-promoting microorganisms (PGPM), on the productivity of soybeans, beans, rice, wheat, sorghum, and corn. The experiment was conducted in the experimental area of UNESP – Ilha Solteira, located in the municipality of Selvíria (MS), in a randomized block design with seven replicates. The treatments consisted of three types of management: conventional management, with seed treatment and inoculation, mineral fertilization, and chemical control of pests, diseases, and weeds according to the requirements of each crop; semi-organic management 1, with the application of half the recommended mineral fertilization, soil remineralizer (Brutal Rocks®),organic compost, MPCP (Brutal Plus®), and nutrients (Brutal Calcium® andUltrasal®);semi-organic management 2, similar to the previous one, but without the use of mineral fertilization. In semi-organic management, there was no chemical control of pests and diseases, with only herbicides being used for weed management. The evaluations performed were the grain yield of each crop and an economic analysis of each management system. The yield data were submitted to Tukey's test at a 5% probability, using SISVAR(®) software.The results indicated that, in semi-organic management systems, the plants presented similar health and agronomic performance to conventional management in terms of grain yield. In addition, a reduction in mineral fertilizer costs was observed. These data highlight the potential of using microorganisms associated with

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nutritional supplementation as a viable strategy for promoting more sustainable, economically efficient, and highly productive cropping systems.

Keywords: Soil Remineralizer. Nutrients. Microorganisms. Plant Growth Promoters. Sustainability.

Introduction

Intensive agricultural production systems are generally characterized by monoculture or crop succession and the large-scale use of chemical inputs, such as fertilizers. Given the current scenario of climate change and environmental degradation, it is essential to adopt sustainable practices in production systems. In this context, conservationist management systems, such as the No-Till Farming System (NTFS), stand out for promoting benefits to agricultural production and, simultaneously, to the conservation of natural resources.

The No-Till Farming System (NTFS) is based on three principles: crop rotation, minimum tillage, and permanent soil cover. These characteristics allow for improvements in the physical, chemical, and biological conditions of the soil, resulting in greater stability and productivity of agricultural systems (Denardin et al., 2012; Madari, 2018). Crop rotation with legumes, for example, contributes to the availability of nitrogen (N) in the soil, due to their ability to form symbiosis with diazotrophic bacteria, thus reducing the need for nitrogen fertilization (Hungria, 2011).

Grasses, in turn, produce a significant amount of dry matter per area, characterized by a high carbon/nitrogen (C/N) ratio and lignin content, which allows for slow degradation and longer soil coverage, protecting it against erosion, moisture loss, and large temperature fluctuations (Fernandes et al., 2024). According to Hungria et al. (2007), maintaining plant residues from different crops increases the population and diversity of microorganisms, which decompose this material, contributing to the increase of organic matter in the soil.

The increase in organic matter in the soil is directly associated with microbial activity. Microorganisms perform essential functions in agricultural systems, such as the cycling of carbon (C), nitrogen (N), phosphorus (P), and sulfur (S), the immobilization of heavy metals, and the degradation of xenobiotic compounds. Additionally, they synthesize phytohormones, induce the production of defense compounds in plants, and act as biological control agents of phytopathogens (Hungria, 2011; Cardoso and Andreote, 2016). Furthermore, the inoculation of microorganisms is low cost, making it an economically viable technique. Thus, its use contributes to the sustainability of production systems.

Given the above, this study aimed to evaluate the effects of different soil management practices associated with the application of plant growth-promoting microorganisms (PGPM) on the chemical characteristics of the soil and the productivity of soybeans, beans, rice, wheat, sorghum, and corn.

Materials and Methods

The experiments were conducted during the 2019/20 to 2023/24 agricultural years in an experimental area irrigated by a center pivot belonging to the Faculty of Engineering – UNESP, Ilha Solteira Campus, located at approximately 51º 22' west longitude and 20º 22' south latitude, at an altitude of 335 meters. The soil at the site is classified as dark red LATOSSOLO, epi-eutrophic alic, with a clayey texture (EMBRAPA, 2018).

The climate, according to the Köppen classification, is Aw, characterized as humid tropical with a rainy season in summer and dry in winter. The average annual rainfall is 1,370 mm, the average annual temperature is 23.5ºC, and the relative humidity is between 70 and 80% (annual average).

Before the project was implemented, soil samples were collected from the 0-0.20 m layer for chemical characterization of the experimental area, according to the method proposed by Raij et al. (2001). The soil fertility analysis presented the values described in Table 1.

OM: Organic matter; S-SO_4^{2-}: Extractable sulfur; P: Phosphorus; K: Potassium; Ca: Calcium; Mg: Magnesium; H+Al: Hydrogen + Aluminum (exchangeable acidity); CTC: Cation exchange capacity; V%: Base saturation; B: Boron; Cu: Copper; Fe: Iron; Mn: Manganese; Zn: Zinc. Extraction methods: P – Resin; B – Hot water; Cu, Fe, Mn, and Zn – DTPA.

On October 24, 2019, liming was carried out over the entire area using 1.3 t ha^{-1} of dolomitic limestone. Prior to sowing the first crop (soybeans), there were corn crop residues, so chemical weed management was performed with the application of glyphosate herbicide (1560 g ha^{-1} a.i.) was applied for chemical weed management, and subsequently, the crop residues were managed using a mechanical disintegrator to uniform the straw approximately seven days before soybean sowing.

The experimental design was randomized blocks with seven replicates. The plots consisted of an area 6.30 m wide by 7 m long, with rows spaced according to the crop, considering the side rows of the plot and 0.5 m at both ends of each row as borders.

The treatments consisted of a combination of three management practices, namely:

Conventional management: seed treatment according to the specificity of each crop; mineral fertilization recommended for crops, taking into account the chemical characteristics of the soil ; application of insecticides, fungicides, and herbicides according to the needs of each crop.

MOMFS 1 Management (Sustainable Organic Minho Fertile Management)*:* application of 1.5 t ha^{-1} of Brutal Rocks® soil remineralizer , broadcast, before soybean sowing; application of 2.0 t ha^{-1} of Minho Fertile® organic compost broadcast on March 29, 2021; *on* September 15, 2022, a new application of 1.7 t ha^{-1} of Brutal Rocks(®) was made; inoculation of seeds with growth-promoting microorganisms contained in Brutal Plus(®)(200 mL per 40 kg of seeds) + 1/2 of the mineral fertilizer used in the conventional system + foliar applications of Brutal Plus® (250 mL per hectare), 150 g per hectare of Brutal Calcio® (fertilizer containing 32% calcium and 2% magnesium) and 200 g ha^{-1} of Ultrasal(®)(fertilizer containing 3.5% zinc, magnesium, and sulfur); foliar applications of Brutal Plus(®) every 10-12 days (totaling, on average, five to seven applications per crop).

P	M.O	pH	K	Ca	Mg	H+Al	Al	CTC	V	S-SO_4^{2-}	B	Cu	Fe	Mn	Zn
mg dm^{-3}	mg dm^{-3}	$CaCl_2$	----------- mmol$_c$ dm^{-3} ------------						%	------------- mg dm^{-3} --------------					
25	18	5.0	0.7	19	16	31	1	66.7	54	3	0.27	1.6	25	11.1	0.6

Table 1. Values of the chemical characteristics of the soil in the experimental area from the 0-0.20 m layer. Selvíria (MS), 2019.

MOMFS 2 management: application of 2.5 t $^{ha^{-1}}$of Brutal Rocks®by broadcasting before soybean sowing; application of 2.0 t $^{ha^{-1}}$of Minho Fértil®organic compost by broadcasting on March 29, 2021; on September 15, 2022, a new application of Brutal Rocks(®)using 2.5 t $^{ha^{-1}}$;seed inoculation with Brutal $^{Plus®}$ (200 mL ^{per} 40 $^{kg^{-1}}$ ^{of}seeds) + zero kg $^{ha^{-1}}$ ^{of}mineral fertilizer + foliar applications of Brutal $^{Plus®}$ (250 mL per $^{ha^{-1}}$),Brutal $^{Calcio®}$ (150 g ha^{-1}) andUltrasal® (200 g $^{ha^{-1}}$)every 10-12 days (totaling, on average, five to seven applications in each crop).

Ten crops were grown in the experimental area involving the first and second harvests over five years, in the following sequence:

1. Soybeans

Mechanized sowing of soybeans took place on December 9, 2019, using the TMG 7063 IPRO cultivar, with a spacing of 0.45 m and a density of 16 seeds m$^{(-1)}$.In the conventional system ( ), the seeds were treated with the fungicide Derosal(®) and inoculated with *Bradyrhizobium japonicum.* In the MOMFS 1 and MOMFS 2 management systems, the seeds were not treated with fungicide, but only inoculated with Brutal Plus(®) (200 mL 40 kg$^{(-1)}$ of seeds).

Mineral fertilization in the seed furrows in the conventional system was 300 kg h$^{a^{-1}}$ of the 02-20-20 (NPK) formulation, calculated according to the chemical characteristics of the soil, considering the expected yield of 3.0 to 3.4 t $^{ha^{-1}}$ ^{and}taking into account the recommendations of Mascarenhas and Tanaka (1996). In MOMFS 1 and MOMFS 2 management, fertilization in the seed furrow was 150 kg $^{ha^{-1}}$ ^{of}the 02-20-20 formulation and no fertilization, respectively. Seedling emergence occurred five days after sowing.

Weed control was performed post-emergence using herbicides registered for the crop. In MOMFS 1 and 2 management, 100 mL $^{ha^{-1}}$of Brutal Plus was added to the herbicide mixture.

In the Conventional System area, three applications of insecticides and fungicides registered for the crop were made to control pests and diseases. In the areas with MOMFS 1 and 2 management, no insecticides or fungicides were applied.

In MOMFS 1 and MOMFS 2 management, foliar applications of Brutal Plus (250 mL ha^{-1}) and Ultrasal (200 g $^{ha^{-1}}$) were performed on 01/20; February 2; February 13; February 24; March 2; and March 11, 2020. In the applications carried out on March 2 and March 11, Brutal Calcio (150 g $^{ha^{-1}}$) was also added.

The harvest was carried out on March 26, 2020, in the conventional system area and on April 2, 2020, in the areas managed with MOMFS 1 and MOMFS 2.

2. Common beans

Mechanized sowing of beans took place on April 23, 2020, using the BRS Estilo cultivar, with a spacing of 0.45 m and a density of 12 seeds $^{m^{-1}}$. In the conventional system, the seeds were treated with the fungicide Standak Top(®)(2 mL $^{kg^{-1}}$of seeds) and inoculated with *Rhizobium tropici (*200 mL $^{ha^{-1})}$. In the MOMFS 1 and MOMFS 2 treatments, the seeds were not treated with insecticide and fungicide, but only inoculated with Brutal Plus(®)(200 mL 40 kg($^{-1)}$of seeds).

Mineral fertilization in the seed furrows in the conventional system was 250 kg $^{ha^{-1}}$of the 08-28-16 (NPK) formulation, calculated according to the chemical characteristics of the soil, considering the expected yield of 2.5 to 3.5 t $^{ha^{-1}\ and}$taking into account the recommendations of Ambrosano et al. (1996). In MOMFS 1 and MOMFS 2 management, fertilization in the seed furrow was 136 kg $^{ha^{-1}\ of}$the 08-28-16 formulation and no fertilization, respectively. Seedling emergence occurred five days after sowing.

Weed control was performed post-emergence using herbicides registered for the crop (Podium EW® - 0.7 L $^{ha^{-1}}$ and Flex® - 0.85 L $^{ha^{-1}}$). In MOMFS 1 and 2 management, 100 mL $^{ha^{-1}}$of Brutal $^{Plus®}$was added to the herbicide mixture.

In the conventional system area, four applications of insecticides and fungicides registered for the crop were made to control pests and diseases. In the MOMFS 1 and 2 management areas, only one application of fungicides (Dithane(®) - 1.3 kg $^{ha^{-1}}$ + FOX XPRO - 0.5 L $^{ha^{-1})}$was used with 100 mL $^{ha^{-1}}$ of Brutal Plus(®) in the application mixture.

In MOMFS 1 and MOMFS 2 management, foliar applications of Brutal Plus®(250 mL ha^{-1}), Ultrasal®(200 g ha^{-1}), and Brutal Calcio(®) (150 g ha$^{-1)}$were carried out on May 8, May 19, May 29, June 9, June 19, June 30, and July 10, 2020.

The harvest was carried out on July 23, 2020, in the conventional system area and in the areas with MOMFS 1 and MOMFS 2 management, 87 days after plant emergence.

3. Rice

Mechanized rice sowing took place on November 9, 2020 (conventional management) and November 11, 2020 (MOMFS 1 and MOMFS 2 management), using the BRS A 502 cultivar, with a spacing of 0.35 m and a density of 70 kg $^{ha^{-1}\ of}$seeds, aiming to obtain 180 plants per m(2) . In the conventional system, the seeds were treated with the fungicide Standak Top(®) (2mL kg(-1) ofseeds). In the MOMFS 1 and MOMFS 2 treatments, the seeds were treated in the same way as in the conventional treatment and inoculated with Brutal Plus(®)(200 mL 40 kg($^{-1)}$ of seeds).

Mineral fertilization in the seed furrows in the conventional system was 200 kg $^{ha^{-1}}$of the 08-28-16 (NPK) formulation, calculated according to the chemical characteristics of the soil, considering the expected yield of 4.5 to 5.0 t $^{ha^{-1}\ and}$taking into account the recommendations of Cantarella and Furlani (1996). In MOMFS 1 and MOMFS 2 management, fertilization in the seed furrow was 120 kg $^{ha^{-1}\ of}$the 08-28-16 formulation and no fertilization, respectively. Seedling emergence occurred five days after sowing.

Weed control was performed pre-emergence with the herbicide pendimethalin (1,400 g $^{ha^{-1}}$ of active ingredient) and post-emergence using the herbicide metsulfuron methyl (2.0 g $^{ha^{-1}}$ of active ingredient). In MOMFS 1 and 2 management, 100 mL $^{ha^{-1}}$of Brutal $^{Plus®}$was added to the herbicide mixture.

In the conventional system area, two applications of insecticide (thiamethoxam 37.5 g $^{ha^{-1}}$ of active ingredient) and fungicide (trifloxystrobin 75 g $^{ha^{-1}}$ of active ingredient + tebuconazole 150 g $^{ha^{-1}}$ of active ingredient) were made to control pests and diseases. In the areas managed with MOMFS 1 and 2, no insecticide or fungicide was applied to the aerial parts of the plants.

In MOMFS 1 and MOMFS 2 management, foliar applications of Brutal Plus®(250 mL $^{ha^{-1}}$), Ultrasal®(200 g $^{ha^{-1}}$), and Brutal Calcium(®) (150 g ha(-1))were applied on 09/12; 21/12; 04/01; 12/01; 21/01, 02/02, 15/02 and 22/02/2021.

Harvesting was carried out on February 26, 2021, in the conventional system area and on March 1, 2021, in the MOMFS 1 and MOMFS 2 management areas, 104 days after plant emergence.

4. Wheat

Mechanized sowing of wheat took place on April 24, 2021, using the ORS 1403 cultivar with a spacing of 0.17 m and a density of 65 seeds $^{m^{-1}}$(350 plants per $^{m^2}$). In the conventional system, the seeds were treated with the fungicide Standak Top(®)(2 mL $^{kg^{-1}}$of seeds). In the MOMFS 1 and MOMFS 2 treatments, the seeds received the same treatment as in the conventional area and were inoculated with Brutal Plus(®)(200 mL ^{per} 40 kg of seeds) before sowing.

Mineral fertilization applied by broadcasting in the conventional system was 250 kg $^{ha^{-1}}$ of the 08-28-16 (NPK) formulation, calculated according to the chemical characteristics of the soil, considering the expected yield of 3.5 to 5 t $^{ha^{-1}\ and}$taking into account the recommendations of Camargo and Freitas (1996). In MOMFS 1 and MOMFS 2 management, broadcast fertilization at sowing was 125 kg $^{ha^{-1}\ of}$the 08-28-16 formulation and no fertilization, respectively. Seedling emergence occurred five days after sowing, on April 25, 2021.

Weed control was performed pre-emergence using the herbicide pendimethalin (1,400 g $^{ha^{-1}}$of active ingredient) and post-emergence using the herbicide metsulfuron methyl (3.3 g $^{ha^{-1}}$of active ingredient). In MOMFS 1 and 2 management, 100 mL $^{ha^{-1}}$of Brutal $^{Plus®}$was added to the herbicide mixture.

In the conventional system area and in the areas with MOMFS 1 and 2 management, only one application of Moddus®(etil trinexapac at a dose of 0.4 L $^{ha^{-1}}$of the commercial product) was used on June 1, 2021, 37 days after plant emergence, at the beginning of the elongation phase of the culms. One hundred mL $^{ha^{-1}}$of Brutal $^{Plus®}$was added to the application mixture in MOMFS 1 and MOMFS 2 management.

In MOMFS 1 and MOMFS 2 management, foliar applications of Brutal Plus® (250 mL $^{ha^{-1}}$), Ultrasal® (200 g $^{ha^{-1}}$) and Brutal Calcio(®) (150 g $^{ha^{-1})}$were carried out on May 7, May 18, May 28, June 8, June 18, and June 30, 2021. Harvesting was carried out on July 12, 2021, 109 days after plant emergence.

5. Soybeans

Mechanized sowing of soybeans took place on December 14, 2021, using the TMG 7063 IPRO cultivar, with a spacing of 0.45 m and a density of 16 seeds m^{-1}. In the conventional system, the seeds were treated with the fungicide Derosal(®) and inoculated with *Bradyrhizobium japonicum.* In MOMFS 1 and MOMFS 2 management, the seeds were not treated with fungicide, only inoculated with Brutal Plus(®) (200 mL 40 kg$^{(-1)}$ of seeds).

Mineral fertilization in the seed furrows in the conventional system was 300 kg $^{ha^{-1}}$of the 02-20-20 (NPK) formulation, calculated according to the chemical characteristics of the soil, considering the expected yield of 3.0 to 3.4 t $^{ha^{-1}\ and}$taking into account the recommendations of Mascarenhas and Tanaka (1996). In MOMFS 1 and MOMFS 2 management, fertilization in the seed furrow was 150 kg $^{ha^{-1}\ of}$the 02-20-20 formulation and no fertilization, respectively. Seedling emergence occurred five days after sowing.

Weed control was performed post-emergence using glyphosate + chlorimuron ethyl herbicides. In MOMFS 1 and 2 management, 100 mL $^{ha^{-1}}$of Brutal $^{Plus®}$was added to the herbicide mixture.

In the conventional system area, two applications of insecticides and fungicides registered for the crop were made to control pests and diseases. In the areas with MOMFS 1 and 2 management, no insecticides or fungicides were applied.

In MOMFS 1 and MOMFS 2 treatments, foliar applications of Brutal Plus®(250 mL ha^{-1}), Ultrasal(®) (200 g ha(-1$^{)}$) ^{and}Brutal Calcio(®) (200 g ha(-1$^{)}$)were carried out on January 11, January 25, February 6, February 17, and March 3, 2022. In the applications carried out on March 2 and March 11, Brutal Calcio(®) (150 g ha$^{(-1)}$)was also added. The harvest was carried out on April 5, 2022, 107 days after plant emergence.

6. Common Bean

Mechanized sowing of beans took place on May 3, 2022, using the IAC 1850 cultivar, with a spacing of 0.45 m and a density of 12 seeds $^{m^{-1}}$. In the conventional system, the seeds were treated with the fungicide Standak Top(®)(2 mL $^{kg^{-1}}$of seeds) and inoculated with *Rhizobium tropici (*200 mL $^{ha^{-1})}$. In the MOMFS 1 and MOMFS 2 treatments, the seeds were not treated with insecticide or fungicide, but only inoculated with Brutal Plus(®)(200 mL 40 kg$^{(-1)}$of seeds).

Mineral fertilization in the seed furrows in the conventional system was 250 kg $^{ha^{-1}}$ of the 08-28-16 (NPK) formulation, calculated according to the chemical characteristics of the soil, considering the expected yield of 2.5 to 3.5 t $^{ha^{-1}\ and}$taking into account the recommendations of Wutke et al. (2022). In MOMFS 1 and MOMFS 2 management, fertilization in the seed furrow was 136 kg $^{ha^{-1}\ of}$the 08-28-16 formulation and no fertilization, respectively. Seedling emergence occurred six days after sowing.

Weed control was performed post-emergence using herbicides registered for the crop (Podium EW® - 0.7 L $^{ha^{-1}}$ and Flex® - 0.85 L $^{ha^{-1}}$). In MOMFS 1 and 2 management, 100 mL $^{ha^{-1}}$of Brutal $^{Plus®}$was added to the herbicide mixture.

In the conventional system area, four applications of insecticides and fungicides registered for the crop were carried out to control pests and diseases. In the areas with MOMFS 1 and 2 management, no insecticides or fungicides were used.

In MOMFS 1 and MOMFS 2 management, foliar applications of Brutal Plus® (250 mL ha^{-1}), Ultrasal(®) (200 g $ha^{-1)}$ andBrutal Calcio® (200 g $ha^{-1)}$were performed on May 25, May 30, May 13, June 23, June 30, July 7, and July 18, 2022. Harvesting was carried out on August 1, 2022, in the conventional system area and in the areas with MOMFS 1 and MOMFS 2 management, 85 days after plant emergence.

7. Grain sorghum

Mechanized sowing of sorghum took place on October 25, 2022, using the Agromen 70G70 cultivar, with 90% germination, spacing of 0.50 m, and a density of 12 seeds m^{-1}. In the conventional system, the seeds were treated with the fungicide Standak Top(®) (2 mL kg$^{(-1)}$ of seeds). In the MOMFS 1 and MOMFS 2 treatments, the seeds were not treated and, before sowing, were inoculated only with Brutal Plus(®)(200 mL per 40 kg of seeds).

Mineral fertilization applied by broadcasting in the conventional system was 240 kg $ha^{-1}$of the 08-28-16 (NPK) formulation, calculated according to the chemical characteristics of the soil, considering the expected yield of 4 to 6 t $ha^{-1}$and taking into account the recommendations of Duarte et al. (2022). In MOMFS 1 and MOMFS 2 management, sowing fertilization was 122 kg ha^{-1} of the 08-28-16 formulation and no fertilization, respectively. Seedling emergence occurred six days after sowing.

Weed control was performed post-emergence with the herbicide atrazine (3 L ha^{-1} of p.c.). In MOMFS 1 and 2 treatments, 100 mL ha^{-1} of Brutal Plus® was added to the herbicide mixture.

Nitrogen fertilization in all treatments was performed once when the plants had an average of five fully formed leaves, using 80 kg $ha^{-1}$of N in the form of urea. After application, irrigation was performed with a 12.6 mm water depth to minimize losses due to volatilization.

In the MOMFS 1 and MOMFS 2 treatments, foliar applications of Brutal Plus®(250 mL ha^{-1}), Ultrasal(®) (200 g $ha^{-1)}$ andBrutal Calcio® (200 g $ha^{-1)}$were performed on 11/23, 12/01, 12/14, 12/22, 01/02, 01/12, and 01/22/2022. The harvest was scheduled to take place in mid-February 2023, but due to a large attack by maritacas, there were significant losses and it was decided not to harvest.

On August 11, 2022, new liming was carried out in the total area involving the three soil management practices. Two tons per hectareof dolomitic limestone with 80% PRNT was applied by broadcasting without incorporation. On October 15, 2022, a new application of Brutal Rocks(®)was made with 1.7 t ha$^{(-1)}$in MOMFS Management 1 and 2.5 t ha$^{(-1)}$in MOMFS Management 2.

8. Second corn crop

In April 2023, the entire area was scarified, involving the three soil management practices, followed by light harrowing to break up clods and level the soil. Mechanized corn sowing took place on April 13, 2023, using the AG 7098 cultivar, a simple hybrid with good resistance to leafhoppers and caterpillars. The spacing was 0.85 m between rows and a density of 5.4 seeds m$^{(-1)}$. The seeds had already been industrially treated with insecticides and fungicides. In areas MOMFS 1 and MOMFS 2, the seeds were inoculated with Brutal Plus(®)(200 mL per 40 kg of seeds) and 6 g of Brutal Calcium(®) per kg of seeds before sowing.

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Mineral fertilization in the conventional system was 250 kg ha⁻¹ of the 08-28-16 (NPK) formulation, calculated according to the chemical characteristics of the soil, considering the expected yield of 6 to 8 t ha⁻¹ and taking into account the recommendations of Duarte et al. (2022). In MOMFS 1 and MOMFS 2 management, sowing fertilization was 136 kg ha⁻¹ of the 08-28-16 formulation and no fertilization, respectively. Seedling emergence occurred five days after sowing, on April 18, 2023.

Weed control was performed post-emergence with the herbicide atrazine (3 L ha⁻¹ of p.c.) and Soberan®(0.2 L ha⁻¹), when the plants had six fully formed leaves (May 8, 2023). In MOMFS 1 and 2 treatments, 100 mL ha⁻¹ of Brutal Plus® was added to the herbicide mixture.

Nitrogen fertilization in all treatments was performed on May 4, 2023, using 80 kg ha⁻¹ of N in the form of urea. After application, the area was irrigated using a 12.6 mm water depth to minimize losses due to volatilization.

In MOMFS 1 and MOMFS 2 treatments, foliar applications of Brutal Plus®(250 mL ha⁻¹), Ultrasal®(200 g ha⁻¹), Brutal Calcium(®) (200 g ha⁻¹) and *Bacillus thuringensis (0*.5 kg ha⁻¹) were carried out on April 25 (plants with two fully formed leaves); May 2 (four leaves); May 8 (six leaves) and May 16 (eight leaves). In conventional management, applications were made on April 25 with Perito (®)(1.0 kg ha⁻¹)+ Lanate (®)(0.8 L ha⁻¹)+ spreader (2 leaves); May 2 with Sperto (®)(300 g ha⁻¹)+ Prêmio (®) (100 mL ha⁻¹) +spreader (4 leaves); May 8 with Sperto® (300 g ha⁻¹) +spreader (6 leaves); May 16 with Esalt® (100 mL ha⁻¹) +Magnum® (1kg ha⁻¹) +spreader (8 leaves). The harvest was carried out on September 6, 2023, 141 days after emergence.

9. Soybeans

Mechanized sowing of soybeans took place on December 14, 2023, using the BMX Desafio RR cultivar, with a spacing of 0.45 m and a density of 14.2 seeds m⁻¹. In the conventional area, the seeds were treated with Standak Top(®)fungicide (2 mL kg⁻¹ of seeds) and inoculated with *Bradyrhizobium japonicum (1*.2 mL kg⁻¹ of seeds). In the MOMFS 1 and MOMFS 2 areas, the seeds were not treated with fungicide and insecticide, only inoculated with Brutal Plus®(200 mL per 40 kg of seeds) and Brutal Calcium®(6 g per kg of seeds) .

Mineral fertilization in the seed furrows in the conventional system was 300 kg ha⁻¹ of the 02-20-20 (NPK) formulation, calculated according to the chemical characteristics of the soil, considering the expected yield of 3.0 to 3.4 t ha⁻¹ and taking into account the recommendations of Quaggio et al. (2022). In MOMFS 1 and MOMFS 2 management, fertilization in the seed furrow was 150 kg ha⁻¹ of the 02-20-20 formulation and no fertilization, respectively. Seedling emergence occurred seven days after sowing (December 21, 2023).

Weed control was performed post-emergence using the herbicides glyphosate (1.5 kg ha⁻¹) + chlorimuron ethyl (30 g ha⁻¹). In MOMFS 1 and 2 management, 100 mL ha⁻¹ of Brutal Plus® was added to the herbicide mixture.

In the conventional system, two applications of insecticides and fungicides registered for the crop were made to control pests and diseases. In the areas with MOMFS 1 and 2 management, no insecticides or fungicides were applied.

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In MOMFS 1 and MOMFS 2 treatments, foliar applications of Brutal Plus® (250 mL ha⁻¹), Ultrasal(®) (200 g ha⁻¹) and Brutal Cálcio® (200 g ha⁻¹), *Bacillus thuringiensis* (200 g ha⁻¹) and Brutal Citrus® (150 mL ha⁻¹) were carried out on January 12, January 22, January 29, February 9, February 19, February 28, March 12, and March 20, 2024. The harvest was carried out on May 6, 2024, 138 days after emergence.

10. Wheat

Mechanized sowing of wheat took place on May 21, 2024, using the ORS Feróz cultivar with a spacing of 0.17 m and a density of 65 seeds m^{-1} (350 plants per m^2). In the conventional system, the seeds were treated with the fungicide Standak Top(®) (2 mL kg^{-1} of seeds). In the MOMFS 1 and MOMFS 2 treatments, the seeds were inoculated before sowing with Brutal Plus® (200 mL per 40 kg of seeds) and Brutal Cálcio® (120 g per 40 kg of seeds).

Mineral fertilization applied by broadcasting in the conventional system was 250 kg ha^{-1} of the 08-28-16 (NPK) formulation, calculated according to the chemical characteristics of the soil, considering the expected yield of 4 to 6 t ha^{-1} and taking into account the recommendations of Cantarella et al. (2022). In MOMFS 1 and MOMFS 2 management, broadcast fertilization at sowing was 125 kg ha^{-1} of the 08-28-16 formulation and no fertilization, respectively. Seedling emergence occurred six days after sowing, on May 27, 2024.

Weed control was performed pre-emergence with the herbicide pendimethalin (1,400 g ha^{-1} of active ingredient) and post-emergence using the herbicide metsulfuron methyl (5.0 g ha^{-1} of active ingredient). In MOMFS 1 and 2 management, 100 mL ha^{-1} of Brutal Plus® was added to the herbicide mixture.

In MOMFS 1 and MOMFS 2 treatments, foliar applications of Brutal Plus® (250 mL ha^{-1}), Ultrasal® (200 g ha^{-1}), Brutal Calcium(®) (200 g ha^{-1}) and *Bacillus thuringensis* (200 g ha^{-1}) were carried out on June 20, June 28, July 9, July 19, July 31, and August 8, 2024. The harvest was carried out on September 2, 2024, 99 days after emergence.

Evaluations:

For each crop, grain yield (kg ha^{-1}) was determined by collecting plants (soybeans and beans), panicles (rice), and ears (wheat and corn) from the usable area of the plots, disregarding the side rows and half a meter at the ends of each row. After mechanical threshing, the grains obtained were weighed and the data transformed into kg ha^{-1} (13% moisture basis), with the values extrapolated to kg ha^{-1}. In the statistical analysis of productivity, the data were submitted to analysis of variance and the means were compared by Tukey's test at 5% probability, according to Pimentel Gomes and Garcia (2002). The statistical analyses were processed using the statistical analysis program SISVAR(®) (Ferreira, 2000).

In August 2020, September 2022, and September 2024, after the harvest of beans, beans, and wheat, respectively, soil sampling was performed at a depth of 0–0.20 m to determine the chemical characteristics in each of the treatments, according to the method proposed by Raij et al. (2001). Also in September 2024, another soil sampling was carried out, removing 20 samples in each treatment, at a depth of 0–0.10 m, which, after homogenization, obtained a composite sample, where the enzymes Arylsulfatase and β-Glycosidase were determined, according to the methodology of Mendes et al. (2021) and Acid Fostase, according to the methodology of Tabatabai and Bremner (1969).

Results and Discussion

Before the start of the project, a soil analysis of the experimental area (0.0 to 0.20 m) was performed, and the chemical characteristics are presented in Table 1.

Based on the values obtained, it can be seen that the pH ($_{CaCl_2}$) was 5.0 and the base saturation was 54% (Table 1). On October 24, 2019, 1.3 t $^{ha^{-1}}$ (1) of dolomitic limestone, with 80% PRNT, was applied by broadcasting, with the aim of increasing base saturation to 70%. After the soybean and bean crops, a new sampling was performed, individually for each management practice, and the chemical characteristics are presented in Table 2. The results indicate an increase in pH and base saturation (V%), as well as a reduction in aluminum (Al) and potential acidity (H+Al) (Table 2).

According to Malavolta (1981), the application of limestone raises the soil pH by reducing the concentration of hydrogen ions (H^+). This is due to the presence of calcium ($CaCO_3$) and magnesium ($MgCO_3$) carbonates, which, when reacting with soil water, release calcium (Ca^{2+}), magnesium (Mg^{2+}), hydroxyl (OH^-), and bicarbonate (HCO_3^-) ions. The Ca^{2+} and Mg^{2+} cations increase base saturation (V%), while the OH^- and HCO_3^- anions neutralize soil acidity by reacting with H^+. Additionally, the hydroxyl ion (OH^-) contributes to the neutralization of aluminum (Al^{3+}), an element that is toxic to plants and predominant in low acidity conditions.

With the reduction in potential acidity ($H^+ + Al^{3+}$), soil colloids, previously occupied by H^+ and Al^{3+}, become predominantly associated with Ca^{2+} and Mg^{2+} cations, which are essential for plant development (Malavolta, 1981; Malavolta, 2006). However, a reduction in CTC is observed after liming (Table 2), possibly due to the decrease in H^+ and Al^{3+} levels, which previously occupied the exchange sites.

Regarding phosphorus (P) levels, MOMFS 2 and, especially, MOMFS 1 stand out, with 39 mg dm^{-3}, while conventional management recorded 23 mg dm^{-3}. This increase in MOMFS 1 and 2 management may be associated with the pplication of the Brutal Rocks® soil remineralizer, whose nutrients were possibly solubilized by the action of microorganisms present in the Brutal $^{Plus®}$ bioinput.

Tables 3 and 4 show the grain yields obtained in the 2019/20 to 2023/24 harvests for the different crops grown in a rotation system in the first and second harvests of each agricultural year (soybean/bean; rice/wheat; soybean/bean; sorghum/corn, and soybean/wheat). In the sorghum crop, it was not possible to evaluate productivity due to the large attack of maritacas at the end of the crop cycle (Table 4).

Means followed by the same letter in the columns do not differ according to Tukey's test at 5% probability; C.V.: coefficient of variation.

For soybean productivity, there was no significant difference between conventional management and MOMFS 2 for the last two crops (Tables 3 and 4). Conventional management and MOMFS 2 were also statistically equal for bean productivity in the first year (Table 3). For rice, there was no difference between conventional management

P	M.O	pH	K	Ca	Mg	H+Al	Al	CTC	V	$S\text{-}SO_4^{2-}$	B	Cu	Fe	Mn	Zn
mg dm^{-3}	mg dm^{-3}	$CaCl_2$	----------- mmol$_c$ dm^{-3} ---------						%	---------- mg dm^{-3} ----------					
23[1]	22	5.8	1.4	28	26	25	0	35	69	25	0.12	2.1	2.1	21.7	1.1
39[2]	21	5.9	1.5	27	22	22	0	37	70	19	0.14	2.1	17	19.9	1.2
27[3]	21	5.8	1.1	26	21	20	0	31	71	10	0.16	2.1	17	19.4	1.1

Table 2. Values of the chemical characteristics of the soil in the experimental area of the 0–0.20 m layer after bean cultivation. Selvíria (MS), 2020.

OM: Organic matter; $S\text{-}SO_4^{2-}$: Extractable sulfur; P: Phosphorus; K: Potassium; Ca: Calcium; Mg: Magnesium; H+Al: Hydrogen + Aluminum (exchangeable acidity); CTC: Cation exchange capacity; V%: Base saturation; B: Boron; Cu: Copper; Fe: Iron; Mn: Manganese; Zn: Zinc. Extraction methods: P – Resin; B – Hot water; Cu, Fe, Mn, and Zn – DTPA. ([1] (:) Conventional management; ([2:]) MOMFS 1 management and ([3:]) MOMFS 2 management.

Management	2019/2020		2020/2021		2021/2022	
	Soy	Beans	Rice	Wheat	Soybeans	Beans
Conventional	63.6 to	54.0 to	121.9 to	59.3	65.8	46.9 to
MOMFS 1	51.6 b	50.8 b	117.8 a	60.0	53.0 b	34.2 b
MOMFS 2	53.8 b	52.6 a	94.7 b	55.6	55.2 a	35.6 b
F values	6.10*	4.45*	12.90**	2.01^{ns}	14.01**	27.34**
CV (%)	12.13	5.76	14.65	11.63	13.19	9.02

Table 3. Crop productivity (bags ha^{-1}) as a function of different management practices. Selvíria (MS), 2019/20 to 2021/22.

* , ** and $^{ns:}$ significant at 1%, 5% probability and not significant by the F test, respectively.

Management	2022/2023		2023/2024	
	Sorghum	Corn 2nd Harvest	Soybeans	Wheat
Conventional	-	144.9	70.6 to	70.2 a
MOMFS 1	-	120.0	60.1 b	66.7 a
MOMFS 2	-	129.7	70.6 a	69.1 a
F values	-	2.97^{ns}	4.03*	0.95^{ns}
CV (%)	-	15.77	17.84	13.43

Table 4. Crop productivity (bags ha^{-1}) as a function of different management practices. Selvíria (MS), 2022/22 to 2023/24.

* , ** and $^{ns:}$ significant at 1%, 5% probability and not significant by the F test, respectively.

Means followed by the same letter in the columns do not differ by Tukey's test at 5% probability; C.V.: coefficient of variation.

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and MOMFS 1 (Table 3), while in the two years of wheat cultivation (Tables 3 and 4) and the second corn crop (Table 4), productivity was statistically equal in the three management systems.

In general, it can be observed that conventional management showed higher productivity in a wide variety of crops (Figure 1). Adding up the yields of all crops, they were 697.2 bags $^{ha^{-1}}$in conventional management, compared to 614.7 bags $^{ha^{-1}}$in MOMFS 1 and 616.0 bags $^{ha^{-1}}$in MOMFS 2 (Figure 1). Despite the superiority of conventional management in most crops, Tables 3 and 4 show positive results obtained in MOMFS 1 and 2 management.

These values may be associated with the conditions provided by the no-till system (SPD), which, combined with the application of organic compost and MPCP (Brutal Plus®), possibly favored soil microbiological activity. The action of microorganisms, through the decomposition of organic material, cycling, and solubilization of nutrients, may explain the positive performance observed in these management practices (Hungria, 2011; Cardoso and Andreote, 2016).

Figure 2 illustrates the amounts of fertilizer used in each management system when sowing crops, with emphasis on MOMFS 1, with half the mineral fertilization, and MOMFS 2, which had no mineral fertilization. According to Vieira (2017), nitrogen fertilizers, when used in excess, can contaminate groundwater through nitrate ($^{NO_3^-}$) leaching and the atmosphere through nitrous oxide ($_{N_2O}$) emissions. Urea is the most widely used nitrogen fertilizer due to its low cost and high N content. However, its efficiency can be impaired by the volatilization of ammonia ($^{NH_4^+}$).

Nitrogen fertilizers such as urea, ammonium nitrate, and ammonium sulfate are based on ammonia ($_{NH_3}$). To obtain NH($_{3)}$ through the Haber- Boch process, tons of CO($_{2)}$ are emitted into the atmosphere, which is characterized as a greenhouse gas, intensifying global warming (Vieira, 2017). According to Silva (2014), nitrogen fertilizers can acidify and salinize soils. Soil salinization can also occur with the use of potash fertilizers, as they are most often supplied in the form of potassium chloride (KCl) (Marschner, 1997).

In addition to the environmental impacts associated with fertilizer use, its application in crops represents a significant cost (Figure 3). It can be observed that, in MOMFS 2 management, the cost per hectare was less than 50% compared to conventional management. Thus, although MOMFS 2 showed lower yields in certain crops, this limitation can be offset by the significant reduction in implementation costs.

Observing the values of the chemical characteristics of the soil in samples taken in August 2022, in the three management practices used (Table 5), there was a notable increase in the values of P, CTC, and V% when compared to Table 2. However, it is important to note that on August 11, 2022, a new liming was carried out, applying 2 t $^{ha^{-1}}$of dolomitic limestone, broadcast and without incorporation. The changes from this application, added to the application of Brutal $^{Rocks®,}$organic compound, Brutal $^{Plus®,}$Brutal $^{Calcium®,,and}$Ultrasal($^{®)}$ in each crop were positive and can be seen in the chemical characteristics presented in Table 6, wher , soil collection was performed immediately after the wheat harvest (last crop) in September 2024.

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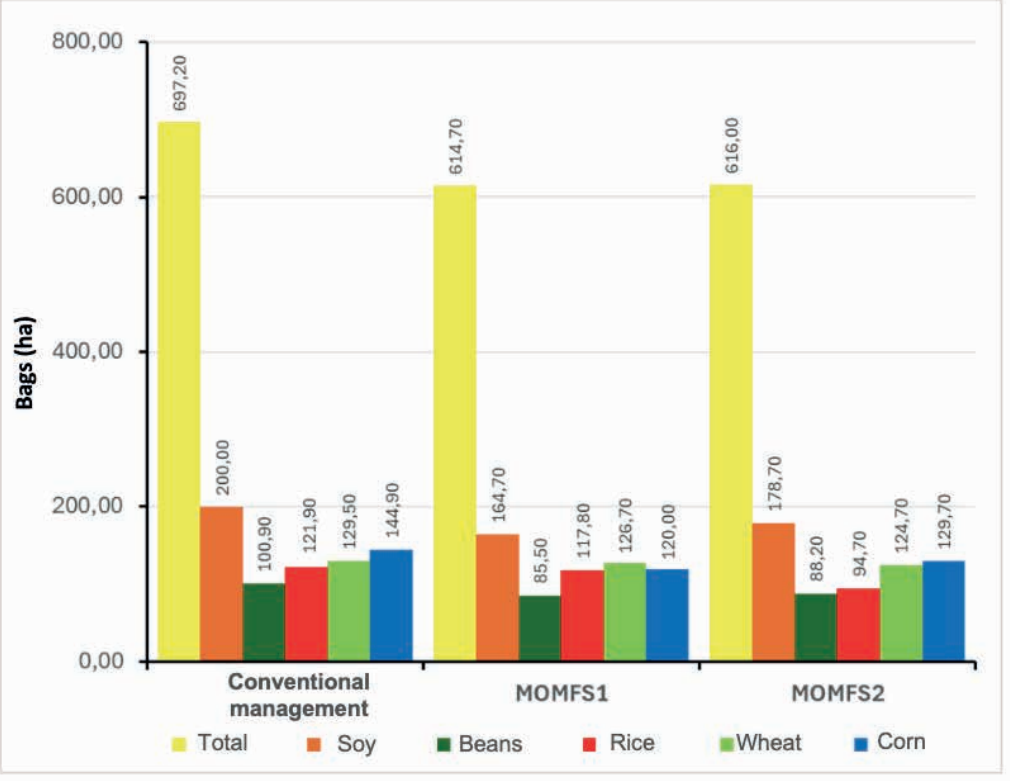

Figure 1. Amount of grain produced (bags ha^{-1}) in each management system during the ten crops. Selvíria (MS), 2021-2024.

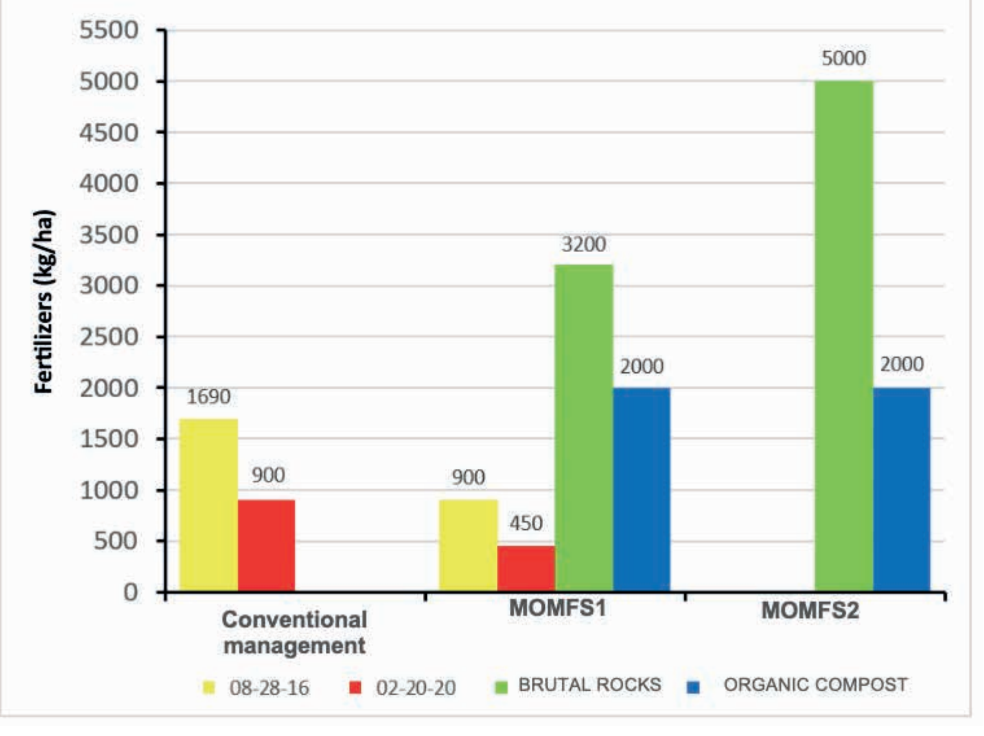

Figure 2. Amount of fertilizer (kg ha^{-1}) used in each management system for crop establishment during the ten crops. Selvíria (MS), 2021-2024.

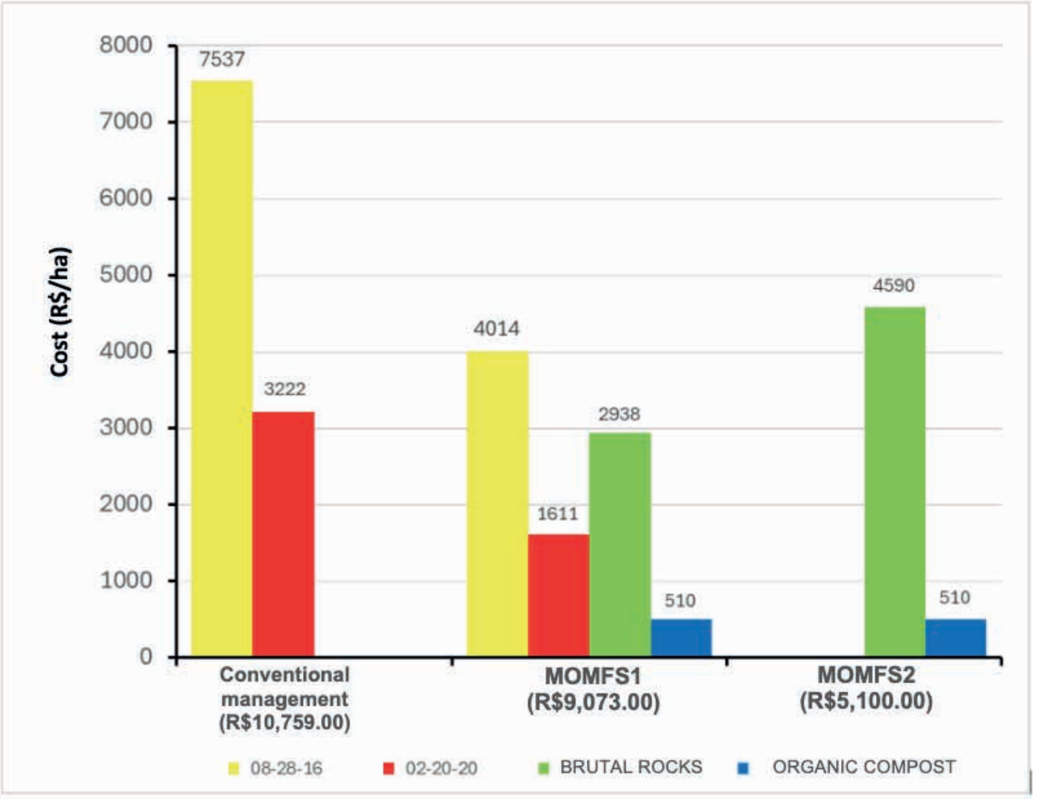

Figure 3. Cost([1]) of fertilizers (R$ ha($^{-1)}$)in each management system during the ten crops. Selvíria (MS), 2021-2024.

[1] – values per ton of each fertilizer obtained in R$, obtained in August/2025.

P	M.O	pH	K	Ca	Mg	H+Al	Al	CTC	V	$S\text{-}SO_4^{2-}$	B	Cu	Fe	Mn	Zn
mg dm^{-3}	mg dm^{-3}	$CaCl_2$	----------- mmol$_c$ dm^{-3} ----------						%	---------- mg dm^{-3} ----------					
37[1]	18	5.1	1.6	26	20	25	1	72.6	66	7	0.22	1.6	17	19.3	0.8
62[2]	17	5.2	1.0	27	20	25	0	73.0	66	5	0.21	1.8	16	19.1	0.8
65[3]	18	5.9	1.0	29	32	18	0	80.0	82	6	0.10	1.6	10	15.8	0.5

Table 5. Values of the chemical characteristics of the soil in the experimental area of the 0-0.20 m layer after bean cultivation. Selvíria (MS), 2022.

OM: Organic matter; $S\text{-}SO_4^{2-}$: Extractable sulfur; P: Phosphorus; K: Potassium; Ca: Calcium; Mg: Magnesium; H+Al: Hydrogen + Aluminum (exchangeable acidity); CTC: Cation exchange capacity; V%: Base saturation; B: Boron; Cu: Copper; Fe: Iron; Mn: Manganese; Zn: Zinc. Extraction methods: P – Resin; B – Hot water; Cu, Fe, Mn, and Zn – DTPA. ([1] (:) Conventional management; ([2:]) MOMFS 1 management and ([3:]) MOMFS 2 management.

P	M.O	pH	K	Ca	Mg	H+Al	Al	CTC	V	$S\text{-}SO_4^{2-}$	B	Cu	Fe	Mn	Zn
mg dm^{-3}	mg dm^{-3}	$CaCl_2$	----------- $mmol_c\ dm^{-3}$ ------------						%	---------- mg dm^{-3} ----------					
37[1]	22	5.8	3.4	34	17	23	0	80.4	75	6	0.40	3.3	46	15.9	5.2
44[2]	21	6.1	3.0	37	15	27	0	83.0	81	7	0.22	3.0	41	15.4	3.8
52[3]	22	6.4	1.9	45	18	27	0	86.9	85	5	0.25	2.8	27	14.9	3.2

Table 6. Values of the chemical characteristics of the soil in the experimental area of the 0–0.20 m layer after wheat cultivation. Selvíria (MS), 2024.

OM: Organic matter; $S\text{-}SO_4^{2-}$: Extractable sulfur; P: Phosphorus; K: Potassium; Ca: Calcium; Mg: Magnesium; H+Al: Hydrogen + Aluminum (exchangeable acidity); CTC: Cation exchange capacity; V%: Base saturation; B: Boron; Cu: Copper; Fe: Iron; Mn: Manganese; Zn: Zinc. Extraction methods: P – Resin; B – Hot water; Cu, Fe, Mn, and Zn – DTPA. ([1] [(:)] Conventional management; ([2:]) MOMFS 1 management and ([3:]) MOMFS 2 management.

Management	Arylsulfatase (µg/g.h)	β-Glycosidase (µg/g.h)	Acid phosphatase (µg/g.h)
Soil management			
Conventional	297.04	690.00	852.59
MOMFS 1	523.70	5,136.15	6,608.15
MOMFS 2	426.67	4,586.15	6,119.26

Table 07 – Values for analysis of soil enzyme activity of the enzymes arylsulfatase, β-glycosidase, and acid phosphatase. Selvíria (MS), September/2024.

Source: Plant Nutrition Laboratory, UNESP – Ilha Solteira.

Looking at the results described in Table 6, it can be observed that MOMFS 1 and MOMFS 2 management presented higher values than conventional management for several soil characteristics evaluated (P, pH, Ca, CTC, and V%), indicating that MOMFS 2, in particular, is an interesting management strategy, considering the savings in fertilizers, the grain productivity obtained in most of the crops used, and environmental sustainability.

The values obtained in the analysis of soil enzyme activity after a period of 5 years, during which 10 crops were grown, are presented in Table 07. When comparing these data, an increase in enzyme activity in general can be observed after five years of cultivation in this study. For the enzyme arylsulfatase, this increase was 60%, while for β-glycosidase it was 604% and for acid phosphatase, 646%, comparing Conventional Management with the average of MOMFS 1 and MOMFS 2 Management. Soils with higher levels of arylsulfatase and β-glycosidase store more water, have a lower nematode population, are more efficient in nutrient use, have greater bioremediation potential, and produce grains with higher nutritional quality (Mendes, 2024).

Conclusions

- Brutal Plus® combined with Brutal Calcium® and Ultrasal® foliar fertilizers resulted in healthy plants, avoiding the use of insecticides and fungicides;

- MOMFS 1 and MOMFS 2 management showed similar performance to conventional management in terms of grain yield, but with healthier soils, lower costs, and greater environmental sustainability.

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