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INSTITUTO DE CIÊNCIAS AGRÁRIAS
PROGRAMA DE PÓS-GRADUAÇÃO EM AGRONOMIA

DINAMAR MÁRCIA DA SILVA VIEIRA

AVALIAÇÃO AGRONÔMICA E QUALIDADE BROMATOLÓGICA DO BRÓCOLIS SOB CULTIVOS SUCESSIVOS, FONTES E DOSES DE FERTILIZANTES ESPECIAIS PARA FORNECIMENTO DE FÓSFORO NO CERRADO

UBERLÂNDIA
2025

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Tese apresentada à Universidade Federal de Uberlândia, como parte das exigências do Programa de Pós-graduação em Agronomia, área de concentração em Fitotecnia, para obtenção do título de Doutora em agronomia.

Prof. Dr. Reginaldo de Camargo
Orientador

Dr. Miguel Henrique Rosa Franco
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Reuniu-se na sala 1CCG 212A - Campus Glória, da Universidade Federal de Uberlândia, a Banca Examinadora, designada pelo Colegiado do Programa de Pós-graduação em Agronomia, assim composta: Professores Doutores: Araína Hulmann Batista - UFU; Beno Wendling - UFU; Fausto Antônio Domingos Júnior - IFTM; Daniel Pena Pereira - IFTM; Reginaldo de Camargo - UFU orientador(a) do(a) candidato(a).

Iniciando os trabalhos o(a) presidente da mesa, Dr. Reginaldo de Camargo, apresentou a Comissão Examinadora e o(a) candidato(a), agradeceu a presença do público, e concedeu ao(à) Discente a palavra para a exposição do seu trabalho. A duração da apresentação do(a) Discente e o tempo de arguição e resposta foram conforme as normas do Programa.

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APROVADA Uberlândia, 28 de Agosto de 2025.

Profª. Drª. Araína Hulmann Batista - UFU Campus Gloria

Prof. Dr. Beno Wendling - UFU Campus Gloria

Prof. Dr. Daniel Pena Pereira - IFTM Campus Uberaba

Prof. Dr. Fausto Antônio Domingos Júnior - IFTM Campus Uberaba

Prof. Dr. Reginaldo de Camargo
ICIAG-UFU
(Orientador)

UBERLÂNDIA
2025

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Prof. Dr. Daniel Pena Pereira - IFTM Campus Uberaba

Prof. Dr. Fausto Antônio Domingos Júnior - IFTM Campus Uberaba

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Avaliação agronômica e qualidade bromatológica do brócolis sob cultivos sucessivos, fontes e doses de fertilizantes especiais para fornecimento de fósforo no cerrado

Dinamar Márcia da Silva Vieira[1]; Reginaldo de Camargo[2]; Miguel Henrique Rosa Franco[3]

RESUMO GERAL

Os fertilizantes organominerais (FOs) e os minerais revestidos (FMRs) com polímeros vêm sendo apresentado como uma nova opção para reduzir as perdas por lixiviação e adsorção do fósforo (P) nos solos intemperizados das regiões tropicais para culturas de ciclo mais longo, contudo para hortaliças ainda precisam ser melhor avaliados. O objetivo deste estudo foi avaliar o desempenho agronômico, o estado nutricional da planta e as características físico-químicas do brócolis cultivado sob diferentes doses e fontes de fertilizantes especiais para o fornecimento de P em Uberaba, MG. O estudo foi conduzido no delineamento de blocos casualizados, em parcelas subdivididas, nas quais foram avaliadas três fontes de P: 1 - Fosfato monoamônico convencional (MAPConv); 2 - Fosfato monoamônico polimerizado (MAPPol); 3 – Fertilizante organomineral granulado (Org). Foram avaliadas quatro doses: 0 (Sem P), 50 (200 kg ha^{-1} de P_2O_5), 75 (300 kg ha^{-1} de P_2O_5) e 100% (400 kg ha^{-1} de P_2O_5) da dose recomendada de P para a cultura do brócolis, em três ciclos consecutivos, com 4 repetições. Foram avaliados o estado nutricional da planta, a fertilidade do solo na colheita, o número de folhas (NF), a massa fresca (MFC) e massa seca da cabeça (MSC) e a produtividade (PROD) do brócolis. No terceiro ciclo também foi avaliado a qualidade físico-química da produção. Observou-se que no primeiro ciclo, o brócolis apresentou maiores valores para NF (24), MFC (1,05 kg planta^{-1}), MSC (0,27 kg planta^{-1}) e PROD (18,81 Mg ha^{-1}) onde foi aplicado o MAPPol, que foi, respectivamente, 5, 25, 8 e 23% superior ao Org e 20, 25, 14 e 34% superior ao MAPConv; No segundo ciclo, os maiores valores para NF (23), MFC (1,85 kg planta^{-1}), MSC (0,26 kg planta^{-1}) e PROD (33,01 Mg ha^{-1}) ocorreu onde foi aplicado o Org, que foi superior 4, 15, 8 e 5% quando comparado ao MAPConv e em 2, 24, 4 e 14% quando comparado ao MAPPol, respectivamente; No terceiro ciclo, os maiores valores para MFC (0,91 kg planta^{-1}), MSC (0,29 kg planta^{-1}) e PROD (22,82 Mg ha^{-1}) ocorreu onde foi aplicado o Org, que foi superior em 5, 10 e 6% quando comparado ao MAPPol e em 24, 10 e 10% quando comparado ao MAPConv, respectivamente; O melhor desempenho agronômico, o maior teor de fosforo no solo e na planta e a melhor qualidade físico-química do brócolis ocorreram na dose de 100% (400 kg ha^{-1} de P_2O_5) da recomendação para a cultura, nos três fertilizantes avaliados; Os teores de umidade, cinzas, proteínas, lipídios, ácidos totais tituláveis e ácido ascórbico não foram afetados significativamente pelos fertilizantes utilizados, por outro lado, os sólidos solúveis totais e o pH apresentaram os maiores e os menores valores no MAPConv, respectivamente; O ORG foi o que proporcionou o melhor desempenho agronômico do brócolis e o maior efeito residual no solo no segundo e terceiro ciclos em comparação com o MAPPol e ao MAPConv.

Palavras-chave: *Brassica oleracea* var. *itálica*; atributos físico-químicos; produção.

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Agronomic evaluation and bromatological quality of broccoli under successive crops, sources and doses of special phosphorus fertilizers in the Cerrado.

Dinamar Márcia da Silva Vieira[1]; Reginaldo de Camargo[2]; Miguel Henrique Rosa Franco[3]

GENERAL ABSTRACT

The Organomineral fertilizers (FOs) and polymer-coated minerals (FMRs) have been presented as a new option for reducing losses due to leaching and adsorption of phosphorus (P) in weathered soils in tropical regions for longer-cycle crops, but they still need to be better evaluated for vegetables. The objective of this study was to evaluate the agronomic performance, nutritional status of the plant, and physicochemical characteristics of broccoli grown under different doses and sources of special fertilizers for P supply in Uberaba, MG. The study was conducted in a randomized block design, in subdivided plots, in which three sources of P were evaluated: 1 - conventional monoammonium phosphate (CMP); 2 - polymer-coated monoammonium phosphate (PCMP); 3 - Granulated organomineral fertilizer (GOF). Four doses were evaluated: 0 (no P application), 50 (200 kg ha^{-1} of P_2O_5), 75 (300 kg ha^{-1} of P_2O_5), and 100% (400 kg ha^{-1} of P_2O_5) of the recommended dose of P for broccoli cultivation, in three consecutive cycles, with four replicates. The nutritional status of the plant, soil fertility at harvest, number of leaves (NL), fresh mass (HFM) and dry mass of the head (HDM), and yield (YLD) of broccoli were evaluated. In the third cycle, the physical-chemical quality of the production was also evaluated. It was observed that in the first cycle, broccoli presented higher values for NL (24), HFM (1.05 kg plant^{-1}), HDM (0.27 kg plant^{-1}), and YLD (18.81 Mg ha^{-1}) where PCMP was applied, which was, respectively, 5, 25, 8, and 23% higher than the GOF and 20, 25, 14, and 34% higher than the CMP; In the second cycle, the highest values for NL (23), HFM (1.85 kg plant^{-1}), HDM (0.26 kg plant^{-1}), and YLD (33.01 Mg ha^{-1}) occurred where GOF was applied, which was 4, 15, 8, and 5% higher when compared to CMP and 2, 24, 4, and 14% higher when compared to PCMP, respectively; In the third cycle, the highest values for HFM (0.91 kg plant^{-1}), HDM (0.29 kg plant^{-1}) and YLD (22.82 Mg ha^{-1}) occurred where GOF was applied, which was 5, 10 and 6% higher when compared to PCMP and 24, 10 and 10% higher when compared to CMP, respectively; The best agronomic performance, the highest phosphorus content in the soil and plant, and the best physical-chemical quality of broccoli occurred at the dose of 100% (400 kg ha^{-1} of P_2O_5) of the recommendation for the crop, in the three fertilizers evaluated; The moisture, ash, protein, lipid, total titratable acid, and ascorbic acid contents were not significantly affected by the fertilizers used. On the other hand, total soluble solids and pH presented the highest and lowest values in CMP, respectively; GOF provided the best agronomic performance of broccoli and the greatest residual effect on the soil in the second and third cycles compared to PCMP and and CMP.

Keywords: *Brassica oleracea* var. itálica; production ; physical-chemical attributes.

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1 INTRODUÇÃO GERAL

O cultivo de hortaliças ocupa importante destaque no cenário do agronegócio brasileiro, atividade esta que na maioria das propriedades são consideradas de base familiar, especialmente na região Sul e Sudeste do país, onde o setor vem se profissionalizando, sendo que nas últimas três décadas a produção e a produtividade praticamente dobraram sem que houvesse relativo aumento de área, devido ao desenvolvimento de novas tecnologias para esta atividade e, nos últimos 10 anos, o consumo cresceu e o consumidor está sendo cada vez mais exigente por hortaliças de melhor qualidade (Clemente et al., 2015, CONAB, 2024).

Dentre estas hortaliças, as brássicas estão incluídas entre as mais consumidas no país, pois são plantas que apresentam alto valor nutritivo e comercial, são excelentes fontes de vitamina A, potássio (K), ferro (Fe), cálcio (Ca) e fibras, entretanto, são plantas com elevada capacidade de extração de nutrientes do solo, principalmente de nitrogênio (N), fósforo (P) e K, que são os que mais influenciam a produção (Kano et al., 2010). Dentre estes nutrientes, o P é aquele que mais limita a produtividade das culturas, pois está em baixa disponibilidade nos solos tropicais por serem acentuadamente intemperizados, com capacidade de troca catiônica reduzida e alta adsorção aniônica, condição esta que proporciona redução na saturação de bases, aumento gradual na retenção de ânions, como o fosfato e o sulfato dentre outros, em decorrência disto, os solos mudam gradualmente de fonte para dreno de P inorgânico (Pi) (TORRES et al, 2023).

De forma geral, a produção de hortaliças quase sempre está associada ao preparo convencional do solo, onde ocorre uso intensivo de implementos agrícolas com arações e gradagens constantes, aplicação de elevadas quantidades de fertilizantes minerais que são complementadas por uso de estercos orgânicos, uso de agroquímicos e irrigação por aspersão, que podem causar desequilíbrios nutricionais, aumento da erosão hídrica e lixiviação de nutrientes (Altieri e Nicholls, 2011; Fayad et al., 2019), sendo que este manejo convencional favorece a deterioração dos atributos do solo comprometendo a sustentabilidade da produção (Santos et al., 2017).

As formas de manejo do solo nestas áreas de produção de hortaliças vêm evoluindo e, dentre as inovações tecnológicas introduzidas nas áreas produtivas, o sistema de plantio direto de hortaliças tem se destacado, quando utilizado em substituição ao sistema convencional de cultivo, pois é um tipo de sistema que aportam elevadas quantidades de matéria orgânica no solo após cada ciclo de cultivo, pode melhorar os atributos físicos, químicos e biológicos do solo, aumentando o rendimento das culturas (Massan et al., 2019; Torres et al., 2021).

Os fertilizantes também estão evoluindo tecnologicamente, disponibilizando produtos no mercado que também aportam matéria orgânica no solo, com o objetivo melhorar os atributos do solo, reduzir perdas, ciclar nutrientes, manter ou aumentar a produção das hortaliças (Vieira et al., 2020), dentre estas inovações estão os fertilizantes organominerais (FOs) e os minerais revestidos (FMRs) ou protegidos (Almeida et al., 2016). Estes fertilizantes são denominados também de especiais, que são produtos resultantes da mistura física ou combinação de fertilizantes minerais com orgânicos que promovem o aproveitamento de diferentes resíduos orgânicos (Portugal et al., 2016).

O ideal para uma produção de hortaliças elevada e de boa qualidade é aplicar uma adubação completa, que reúna adubos orgânicos (estercos) e químicos em um mesmo fertilizante, de maneira a ocorrer substituição gradativa do fertilizante exclusivamente químico (Andrade et al., 2012). Com base nesta premissa, os FOs se constituem na mistura do fertilizante mineral e do orgânico no mesmo grânulo, que tendem liberar os nutrientes lentamente durante todo o ciclo da cultura, favorecendo seu melhor aproveitamento através do sincronismo de liberação ao longo do crescimento das plantas, além de diminuir as perdas por lixiviação, volatilização e adsorção de N, P e K no solo (Vieira et al., 2023).

Os FMRs também são de liberação mais lenta e controlada, pois atrasam a disponibilidade inicial dos nutrientes por meio de diferentes mecanismos, com a finalidade de disponibilizá-los para as culturas por maior período de tempo e otimizar a absorção pelas plantas, reduzindo perdas (Zavaschi, 2010). No mercado existem diversos tipos de FMRs, os que possuem uma molécula orgânica presente no fertilizante que promoveria a proteção do elemento P da fixação com o Al, Fe e Ca, tornando este nutriente mais disponível no solo, e outros fertilizantes fosfatados recobertos por polímeros de liberação controlada, que disponibilizam o nutriente lentamente no solo (Figueiredo et al., 2012).

O uso dos FOs e FMRs tem surgido como uma nova opção na redução da adsorção do P pelos coloides do solo, porém por serem novos produtos, é necessária uma avaliação aprofundada em campo para diversas culturas, pois ainda há pouco conhecimento sobre seu comportamento em solos ácidos e precisam ser avaliados de forma mais detalhada.

2 HIPÓTESE TESTADA

A hipótese testada neste estudo é sobre os fertilizantes minerais associados à matéria orgânica ou protegidos por polímeros que proporcionam maior disponibilidade de fósforo e influenciam positivamente a produção e a qualidade físico-química das brássicas.

3 OBJETIVO GERAL

Neste estudo objetivou-se avaliar a disponibilização de fósforo no solo através de diferentes fontes e doses de fertilizantes e sua influência nos atributos agronômicos da planta, químicos do solo e na qualidade nutricional das plantas.

4 REVISÃO DE LITERATURA

4.1. A produção de hortaliças no país

O cultivo de hortaliças no Brasil, em sua grande maioria, é feito sob sistema convencional de plantio, que caracterizado pelo intenso revolvimento do solo após cada ciclo de cultivo, iniciando-se por uma aração e posteriormente por um destorroamento utilizando enxadas rotativas ou gradagens sucessivas (Aradora e niveladora), que pulveriza o solo e incorpora a matéria orgânica existente, o que provoca alterações nos atributos físicos, químicos e biológicos (Loss et al. 2015) e com o tempo pode reduzir a quantidade de matéria orgânica do solo (Souza et al., 2014), deixando o solo susceptível às formas de erosão, que acarretam perdas de solo, água e a lixiviação de nutrientes (Santos et al., 2017).

O revolvimento e a intensa utilização do solo em plantios sucessivos de hortaliças, em longo prazo proporcionam o seu empobrecimento, comprometendo a sustentabilidade ambiental e produtiva, contudo, as formas de manejo do solo evoluíram para sistemas mais conservacionistas de cultivo, onde o sistema de plantio direto (SPD) de hortaliças (SPDH) tem se destacado, devido ao revolvimento mínimo, a rotação de culturas e a manutenção dos resíduos na superfície do solo, que aportam quantidades consideráveis de material orgânico ao solo após cada ciclo de cultivo (Silva et al., 2018; Massan et al., 2019).

Outro problema observado nas áreas cultivadas com hortaliças é a elevada capacidade de extração de nutrientes do solo em um curto espaço de tempo, que exigem aplicações de elevadas quantidades de fertilizante minerais de alta solubilidade (Silva et al., 2020), pois os solos do cerrado brasileiro são altamente intemperizados, pobres em fertilidade, onde a quantidade expressiva da fração argila na composição mineral do solo e o tipo de mineral constituinte desta fração, com predomínio de minerais como os óxidos de ferro (Fe) e alumínio (Al), propiciam correlações significativas com a capacidade máxima de adsorção de fósforo (P), principalmente óxidos de ferro (Fontana et al., 2008). Ainda apresentam baixos teores de matéria orgânica no solo, que desempenha um papel ambivalente, já que tanto poderia adsorver o P, como também bloquear os sítios de adsorção que ocorrem nas superfícies das argilas e óxidos de Fe e Al (Bezerra et al., 2015).

Uma das maneiras de favorecer a conservação do solo é aumentando sua fertilidade via diferentes formas de adubação e, conjuntamente, criar condições de manter ou aumentar o teor de matéria orgânica do solo (Loss et al., 2015; Torres et al., 2021). Entretanto, neste ambiente, a matéria orgânica ao ser revolvida e incorporada no solo é mineralizada mais rapidamente, que pode proporcionar algumas vantagens de forma imediata, pois promove maior disponibilização de nutrientes no solo, aumenta a capacidade de troca de cátions, a atividade microbiana do solo, neutraliza íons tóxicos do solo, entretanto em longo prazo empobrecem o solo em termos de fertilidade, a reestruturação física é mais lenta, reduz a atividade microbiológica e o teor de matéria orgânica no solo a níveis mínimos, que irá favorecer a erosão do solo e a lixiviação, com isso pode aumentar a dependência externa de fertilizantes minerais (Fernandes et al., 2015, Higashikawa et al., 2017).

Uma das tecnologias adotadas para minimizar os baixos teores de matéria orgânica nos solos do cerrado brasileiro é o uso de fertilizantes organominerais (FOs), isso ocorre devido à formulação, que possibilita a mistura física ou associação de fertilizantes minerais e orgânicos de diversas origens (Magela et al., 2019).

Essa tecnologia dos FOs vem sendo utilizada com sucesso em algumas culturas, que têm apresentado resultados promissores na cana de açúcar (Almeida Junior et al., 2011), cafeeiro (Fidalski et al., 2010), feijão (Oliveira et al., 2014; Rodrigues et al., 2016), com milho, aveia, melão, café, trigo, batata, cana-de-açúcar, feijão e interação lavoura-pecuária-floresta (Sousa et al., 2014).

Alguns estudos comprovaram que a utilização dos FOs como alternativa de adubação em algumas hortaliças tem proporcionado maior rendimento e melhor qualidade do produto na colheita (Luz et al., 2010; OliveirA et al., 2010; Morais; Gatiboni, 2015), entretanto, os resultados ainda são inconsistentes e precisam ser melhor avaliados.

4.2. A família das brássicas

A família botânica Brassicaceae (Cruciferae) possuem vários representantes, dentre eles pode-se destacar o repolho, brócolis, couve-flor, rabanete, rúcula, agrião, mostarda e nabo, sendo que estas são mais cultivadas nas regiões Sul e Sudeste do Brasil (Cecilio Filho et al., 2012), principalmente por ser produzida em pequenas áreas do cinturão verde e em hortas domésticas enriquecendo a alimentação diária da população (Filgueira, 2013).

De forma geral, as brássicas são plantas que apresentam alto valor nutritivo e comercial, tem grande importância socioeconômica em alguns estados brasileiros e estão incluídas entre as hortaliças mais consumidas no país, pois são plantas apresentam alto valor nutritivo e comercial, são excelentes fontes de vitamina A, K, Fe, Ca, fibras e fitoquímicos, ricas em ácido cítrico e ascórbico e sais de cálcio (Kano et al., 2010; Silva et al., 2012).

Entretanto, são plantas que apresentam elevada capacidade de extração de nutrientes do solo, com isso necessitam de grandes aportes de nutrientes, em períodos de tempo relativamente curtos, que é feito através do uso de fertilizantes minerais, que para os macronutrientes são absorvidos na sequência K>N>Ca>S>Mg>P, enquanto que para os micronutrientes ocorre a sequência de absorção de Fe>Zn>Mn>B>Cu>Mo, respectivamente (May et al., 2007; Torres et al., 2017a; 2021). Castoldi et al. (2009) e Aquino et al. (2009) destacam ainda que a maior demanda de nutrientes nas brássicas ocorre nos últimos 10 a 20 dias do ciclo da cultura.

De acordo com Hochmuth et al. (1991) e Diniz et al. (2008), os valores de referência ou faixa de suficiências dos teores de macronutrientes no tecido foliar de brócolis são: N: 2,4-4,0%; P: 0,2-0,4%; K: 1,6-2,5%; Ca: 0,81,5% e Mg: 0,23-0,4%.

Segundo Blind et al. (2015), as exigências nutricionais e de cultivo do brócolis são similares ao do repolho, em que as doses podem variar de 200 a 350 kg ha^{-1} de N nítrico ou amoniacal, 250 a 400 kg ha^{-1} de P na forma de superfosfatos e 250 a 350 kg ha^{-1} de K na forma de cloretos, em áreas com pH variando entre 6,2 a 6,8. Além desses macronutrientes, Kotur et al (1998) e Pizetta et al. (2005), destacam ainda que as brássicas estão no grupo das hortaliças mais exigentes em boro (B) e molibdênio (Mo) em solos de clima tropical, pois sua deficiência determina o aparecimento de medula oca, necrose na parte central do caule e aberrações no limbo foliar causados pela diferenciação celular.

Avaliando os parâmetros agronômicos do brócolis em sistema convencional e orgânico, Otutami et al. (2001) evidenciaram que produtividade de cultivares do brócolis, são influenciadas pelas fontes e doses de adubação, principalmente para fornecer N, P e K no plantio. Dependendo do espaçamento utilizado, Melo (2015) destaca que as produtividades do brócolis podem variar de 7 a 22 Mg ha^{-1}, de acordo com as doses de N, P e K aplicadas e o espaçamento utilizado. Ferreira Júnior et al. (2023) trabalhando com espaçamento menor que o recomendado (0,50 x 0,50 m), obtiveram produtividade total variando entre 15 a 37 Mg ha^{-1}, que comprova a influência positiva das doses de fertilizantes minerais aplicadas e da utilização do menor espaçamento de plantio.

Avaliando as características agronômicas dos brócolis, repolho e couve-flor cultivado em sucessão as plantas de cobertura, Torres et al. (2017b) observaram que onde havia uma Fabácea presente em cultivo isolado ou em consorcio, que a massa fresca da cabeça (MFC) e produtividade (PROD) do brócolis apresentava valores significativamente superiores, quando comparado às outras coberturas, justificaram que este comportamento era decorrente da maior disponibilidade de No solo, contudo, que o mesmo não ocorria para o repolho e a couve-flor, que apresentavam os valores de quando cultivados sobre qualquer cobertura.

Uma das alternativas utilizadas para minimizar os desbalanços nutricionais que podem ser causados pelo excesso de fertilizantes utilizados nas brássicas é associar a adubação mineral a orgânica, via adição de esterco animal, vermicompostagem, pois essas culturas apresentam boa resposta à adubação orgânica (Fontanétti et al., 2006), pois os nutrientes disponibilizados pela matéria orgânica ocorrem de forma gradual e variam de acordo com a cultivar e a fonte de adubo utilizada (Brito e Santos, 2010).

Em áreas sob sistema de plantio direto de hortaliças (SPDH), onde ocorre aporte continuo de matéria orgânica após cada ciclo cultivo, as brássicas tem mostrado melhoria no rendimento e na qualidade da produção, pois tem aproveitado os nutrientes que está sendo liberado lentamente dos resíduos deixados no solo (Torres et al., 2021).

Os resíduos depositados sobre o solo após o cultivo de diferentes coberturas promovem a elevação do teor de matéria orgânica (MO) e da capacidade de troca catiônica (CTC) no solo causando maior disponibilidade de nutrientes ao entrar em decomposição (Leite et al., 2010), entretanto, esses efeitos são bastante variáveis, pois depende da espécie utilizada, manejo dado à biomassa, época de semeadura, persistência dos resíduos sobre o solo, condições locais e da interação entre esses fatores (Teixeira et al., 2012).

4.3. Os fertilizantes minerais, minerais protegidos e os organominerais

No cerrado brasileiro predominam os Latossolos, que são altamente intemperizados, são ácidos, apresentam óxidos de ferro (Fe) e alumínio (Al) e argilas do grupo da caulinita como principais constituintes da fração argila, tem alta adsorção de fosfatos devido à presença de cargas positivas na superfície desses óxidos, que nas condições de reação ácida apresentam-se preferencialmente com cargas positivas, sendo capazes de reter em sua superfície vários ânions com predomínio de íons fosfatos (Valladares et al., 2003).

Esse solo predominante no cerrado brasileiro apresenta características que dificultam o manejo de P, pois tem baixo teor natural deste nutriente (Novais; Smyth, 1999), sendo necessária a aplicação de elevadas doses para que a necessidade da planta seja suprida e ao se adicionar matéria orgânica pode-se ter a sua fixação diminuída, além de disponibilizar nutrientes com a decomposição do material (Silva et al., 2017). Há diversos estudos que relatam que os principais fatores que influenciam a adsorção de fósforo no solo são pH, alumínio trocável, teor e mineralogia da fração argila, teor de coloides amorfos e matéria orgânica (Fontana et al., 2008; Broggi et al., 2010; Lana et al., 2014).

O P é um dos macronutrientes menos exigidos pelas plantas, entretanto, é aquele que tem limitado a produção agrícola nas condições brasileiras com mais frequência, pois, de forma geral, o teor total deste elemento no solo varia entre 200 a 3000 mg kg^{-1}, sendo que menos de 0,1 % desse total (0,002 a 2,0 mg L^{-1}) encontra-se na solução do solo (Novais e Smyth, 1999). Essa baixa disponibilidade de P nos solos tropicais é decorrente dos seus baixos teores, da baixa solubilidade dos compostos de P encontrados nos solos e da sua imobilização devido as fortes interações que apresentam com os constituintes destes solos, sendo estas interações conhecidas como sorção, adsorção ou fixação de P (Rolim Neto et al., 2004).

Mesmo sendo um dos nutrientes menos exigido, ainda assim desempenha um papel fundamental em todo o metabolismo da planta, auxiliando o desenvolvimento inicial, favorecendo toda a parte aérea da planta (Prates et al., 2012), além de ser essencial na divisão celular, reprodução, metabolismo, fotossíntese, respiração, síntese de substâncias orgânicas e na geração de energia, como a adenosina triptofano (Malavolta, 1985).

No mercado há diferentes fontes de P, dentre eles o fosfato diamônico, fosfato monoâmonico, fosfato natural, hiperfosfato, superfosfato simples, superfosfato triplo, termofosfato magnesiano, fosfato bicálcico, fosfato natural reativo, fosfato decantado e organominerais (Gitti e Roscoe, 2017). Contudo, o setor agrícola do Brasil a cada ano cresce mais e com isso a demanda por insumos para a sua condução, com isso, atualmente a importação de fertilizantes corresponde a mais de 80% dos fertilizantes utilizados no país e, analisando somente a demanda de fertilizantes fosfatados, a importação é de cerca de 55% da demanda do país (Anda, 2023). No ano de 2021, o Brasil apresentou recorde de importação de fertilizantes, acima de 85% do total demandado no país, reforçando a dependência do mercado internacional (CONAB, 2024), situação que pode ser revertida com a utilização de novas tecnologias que disponibilizem mais P no solo, minimizando problema da adsorção.

Os fertilizantes organominerais representam uma nova tecnologia que vem sendo introduzida nas áreas cultivadas com hortaliças, esse produto é produzido a partir da mistura física ou pela combinação de fertilizantes minerais e orgânicos. Em sua composição é necessário que contenha no mínimo de 8% de carbono orgânico, um máximo de 30% de umidade, uma capacidade de troca de cátions (CTC) mínima de 80 $mmol_c\ kg^{-1}$ e no mínimo 10% de macronutrientes declarados para os produtos com macronutrientes primários (MAPA, 2009).

A legislação brasileira que trata sobre o tema de fertilizantes, descrita na Lei Federal 6.894, de 16/12/1980 (BRASIL, 1980), regulamentada pelo Decreto 4.954, de 14/01/2004 (Brasil, 2004), define fertilizante mineral como aquela substância fornecedora de nutrientes para plantas obtidas de um processo físico, químico ou físico-químico. O fertilizante orgânico é definido como todo aquele produto essencialmente orgânico obtido a partir de matérias-primas de indústria rural ou urbana, vegetal ou animal, ou seja, o fertilizante organomineral é aquele que resultante da mistura de fertilizante mineral e orgânico.

Segundo Kamogawa e Rodrigues (2024), o desempenho do setor de FOs na safra 2019/20 registrou crescimento de 80,5% nas vendas, em sua maioria são produtos acabados da indústria de fertilizantes especiais resultado de produção nacional, no futuro esses produtos podem se tornar uma fonte alternativa de fertilização altamente viável que prioriza principalmente o uso de matéria prima nacional, reduzindo a dependência de fertilizantes do mercado externo.

O resíduo orgânico como matéria-prima para a fabricação de FOs possui uma grande diversidade, podendo ser proveniente até mesmo de resíduos orgânicos domésticos (Almeida, et al. 2020). Entretanto, um dos compostos orgânicos que vem sendo utilizados de forma exponencial na agricultura é a torta de filtro, devido à elevada quantidade gerada nas agroindústrias, uma vez que tal resíduo apresenta cerca de 1,2 a 1,8% de P e a sua utilização apresenta aumentos de produtividades (Oliveira et al., 2014; Mota et al., 2019).

A utilização de fontes organominerais vem sendo considerada mais eficiente no fornecimento de nutrientes em comparação às fontes minerais (Magela et al., 2019; Silva et al., 2020), por apresentar uma solubilização gradual, permitindo que a cultura absorva nutriente de forma constante e gradual durante o ciclo (Chávez et al., 2019).

Segundo Rodrigues et al. (2016), a adição de matéria orgânica ao fertilizante mineral faz com que a aplicação do fertilizante organomineral garanta maior uniformidade nas concentrações e disponibilidade de nutrientes no produto final, pois aumenta a concentração do nutriente, minimizando as taxas de aplicação no campo. Pauletti et al. (2003) afirmam que no decorrer do tempo, acontece a estabilização dos nutrientes e consequentes aumentos da produtividade, visto que nos fertilizantes organominerais, quando há o ataque dos microrganismos do solo à matriz orgânica, ocorre a liberação gradual dos nutrientes.

O Nitrogênio (N) e o potássio (K) são os nutrientes com maior mobilidade no solo, que apresentam elevadas perdas por lixiviação, o qual está diretamente relacionado com as condições de água, textura do solo e CTC, ressaltando a importância da escolha da fonte e manejo do nutriente que irá ser aplicado (Rosolem et al., 2006). Garcia et al. (2015) verificaram que o processo de lixiviação de K foi reduzido quando se utilizou o fertilizante organomineral como fonte de K, comparado ao fertilizante mineral, principalmente quando realizadas aplicações de grandes doses.

Os solos tropicais apresentam baixa disponibilidade de P, uma condição decorrente dos seus baixos teores, da baixa solubilidade dos compostos de P normalmente encontrados nos solos e da sua imobilização devido as fortes interações que apresentam com os constituintes destes solos, sendo estas interações conhecidas como sorção, adsorção ou fixação de P (Rolim Neto et al., 2004). Dick et al. (2009) destacam que a presença da matéria orgânica no solo altera a disponibilidade de nutrientes de outras fontes, tanto pela sua influência nas reações de troca, adsorção, sorção e solubilização, pois serve como fonte direta de N, P, enxofre (S) e alguns metais, por meio do processo de mineralização e por ser fonte de energia para microrganismos.

A adição de matéria orgânica no solo (MOS) via fertilizante organomineral pode amenizar o problema da sorção do P, pois esta MOS irá atuar no bloqueio dos sítios de adsorção do fosfato, protegendo o P do contato direto com os coloides do solo (Novais e Smyth, 1999; Vieira et al., 2020). Segundo Luz et al. (2010), a utilização dos FOs no cultivo de hortaliças pode amenizar o problema da deficiência e a adsorção de P nos solos o cerrado brasileiro, pois o enriquecimento de adubos orgânicos com fertilizantes minerais pode diminuir a taxa de mineralização da MOS, sorção de P e lixiviação dos nutrientes.

A presença de maior quantidade de ânions orgânicos nos grânulos destes FOs proporciona maior competição pelos sítios de adsorção de P, com isso aumenta a interação planta-mineral, reduzindo a fixação do P e diminuindo a transformação do P em formas indisponíveis para a planta (Sousa et al., 2014).

Nas áreas de produção de grãos, onde geralmente tem ciclos de cultivo mais longo, os fertilizantes organominerais vem sendo utilizado há mais tempo e tem apresentado resultados promissores (Oliveira et al., 2014; Rodrigues et al., 2016), entretanto em hortaliças ainda existe uma grande carência de estudos e informações sobe a eficiência do uso deste produto. Isso se deve ao fato de que muitas das hortaliças cultivadas apresentam um ciclo mais curto e a liberação dos nutrientes presentes nos organominerais pode não acompanhar a demanda das plantas. Portanto, é necessário o melhor entendimento da dinâmica deste tipo de fertilizante, porém alguns resultados promissores já foram evidenciados (Luz et al., 2010; Vieira et al., 2020).

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CAPÍTULO 1

CULTIVO DO BRÓCOLIS SOB FONTES E DOSES DE FERTILIZANTES ESPECIAIS PARA FORNECIMENTO DE FÓSFORO NO CERRADO BRASILEIRO[11]

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Broccoli Cultivation Under Different Sources and Rates of Specialty Phosphorus Fertilizers in the Brazilian Cerrado

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Abstract: This study aimed to evaluate the agronomic performance and yield of broccoli grown under different sources and rates of specialty phosphorus (P) fertilizers in Uberaba, Minas Gerais, Brazil. The experiment was conducted in a randomized block design arranged in a split-plot scheme, testing three P sources: (1) conventional monoammonium phosphate (CMP); (2) polymer-coated monoammonium phosphate (PCMP); and (3) organomineral fertilizer (Org). Four application rates were evaluated: 0 (no P applied), 50% (200 kg ha^{-1} of P_2O_5), 75% (300 kg ha^{-1} of P_2O_5), and 100% (400 kg ha^{-1} of P_2O_5) of the recommended phosphorus rate for broccoli, with four replications. The parameters assessed included plant nutritional status, soil fertility at harvest, number of leaves (NL), fresh head weight (FHW), dry head weight (DHW), and broccoli yield (YLD). In the first growing cycle, broccoli showed the highest NL (24), FHW (1.05 kg plant^{-1}), DHW (0.27 kg plant^{-1}), and YLD (18.81 Mg ha^{-1}) values when PCMP was applied, which was 5, 25, 8 and 23% higher than Org and 20, 25, 14 and 34% higher than CMP. In the second cycle, broccoli showed higher values of NL (23), FHW (1.85 kg plant^{-1}), DHW (0.26 kg plant^{-1}), and YLD (33.01 Mg ha^{-1}) where Org was applied, which was 4, 15, 8 and 5% higher than CMP and 2, 24, 4 and 14% higher than PCMP, respectively. All the variables evaluated showed the highest values at the 100% dose. Broccoli yield in the same area was 124%, 53%, and 115% higher in the second cycle compared to the first for CMP, PCMP, and Org, respectively. The greatest residual effect on soil fertility was observed in the area treated with the Org.

Keywords: *Brassica oleracea* var. *italica*; soil fertility; leaf nutrient content; broccoli yield; fertilizer efficiency

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1. Introduction

Plants belonging to the Brassicaceae family are among the most widely consumed vegetables in Brazil, owing to their high nutritional and commercial value, as well as their adaptability to cultivation across all regions of the country [1,2]. Among brassicas, broccoli cultivation has emerged as one of the most promising, with national production and consumption increasing by approximately 63% over the past decade [3].

This exponential growth is associated with the intensive use of soil and irrigation water and the application of large amounts of highly soluble mineral fertilizers, pH-correcting agents, and agrochemicals. These practices can lead to nutrient imbalances and losses through volatilization, leaching, and adsorption [4,5]. Daily irrigation is required due to prolonged dry periods when broccoli is cultivated in the Brazilian Cerrado. This biome is characterized by weathered, acidic soils with mineralogy dominated by iron (Fe) and aluminum (Al) oxides and kaolinite. The presence of positively charged sites on the surfaces of these oxides promotes high phosphate adsorption. Consequently, nutrient losses through leaching and adsorption tend to be high in this environment [6,7].

To minimize nutrient losses, particularly phosphorus (P), specialty fertilizers have been developed, among which organomineral fertilizers (OMFs) and polymer-coated phosphate fertilizers (PCFs) stand out. These fertilizers are designed to release nutrients in a more controlled and gradual manner, which can enhance nutrient uptake by plants and reduce overall losses [8–13].

Organomineral fertilizers (OMFs) result from the physical blending or association of mineral and organic fertilizers from various sources. The organic matter (OM) in the granules contributes to an increase in the soil's cation exchange capacity [14,15], promoting the proliferation of soil microorganisms. These microorganisms help solubilize mineral fertilizers, enhancing the residual effect of phosphorus fertilization. This is achieved through competition between the organic acids released by microbial activity and phosphate ions for adsorption sites in the soil [6,16,17].

Polymer-coated fertilizers (PCFs) are fertilizers covered with polymer layers that reduce the initial release of nutrients through various mechanisms, aiming to extend their availability to crops and optimize plant uptake, thereby minimizing nutrient losses [8]. According to Figueiredo et al. [18], the gradual release promoted by the nutrient coating reduces its contact with Fe and Al oxides and clay minerals, thereby preventing the formation of stable compounds that would otherwise limit P availability in the soil.

The edaphoclimatic conditions for vegetable cultivation in the Cerrado, particularly those related to soil fertility, have been corrected or maintained primarily through highly soluble mineral sources [19]. Generally, fertilization recommendations for crops have been established based on studies conducted in low-fertility soils managed under conventional tillage systems [20]. Under these conditions, using slow-release specialty fertilizers has shown a potential to improve nutrient uptake efficiency, especially P [15,21,22].

In vegetable cultivation areas, fertilization with OMFs and PCFs can offer new prospects for production and improvements in soil chemical quality. However, since these are slow-release products and vegetables are short-cycle crops, their use requires further evaluation to avoid nutrient deficiencies or excesses in the plants [23–25].

In this context, the hypothesis tested in this study is whether special fertilizers (OMFs and PCFs) are more efficient in supplying phosphorus for broccoli production in the weathered soils of the Cerrado, when compared to traditional mineral fertilizers. This study aimed to evaluate the agronomic performance of broccoli grown under different rates and sources of specialty P fertilizers in Uberaba, Minas Gerais, Brazil.

2. Materials and Methods

2.1. Characterization of the Experimental Area

The study was conducted in an experimental area in the municipality of Uberaba, Minas Gerais, Brazil, which is located between the geographical coordinates 19°39′19″ S and 47°57′27″ W, at an approximate altitude of 800 m, in two consecutive cycles. The first cycle took place from March to June and the second cycle from September to December 2023, in an area that had been fallow for a year, where plants from the Poaceae family predominate, and the last crop that was grown in the area was cabbage (*Brassica oleracea* var. *capitata*), also grown in the same area with a conventional management system.

The experimental area had been used for over 10 years as a pasture for *Urochloa brizantha* cv. *Marandu*, followed by two successive cropping cycles of soybean (*Glycine max* L.) and maize (*Zea mays* L.) for dry grain production in rotation. The area was then left fallow for five years, during which it was mowed occasionally, until the implementation of this experiment. At that point, soil samples were collected from the 0–20 cm layer for chemical characterization. Two disking operations were carried out: deep disking using a harrow with 18 disks (76.2 cm in diameter), followed by superficial disking with a light harrow equipped with 44 disks (60.96 cm in diameter). Finally, planting holes were prepared for transplanting the broccoli seedlings (*Brassica oleracea* var. *italica* L.).

The soil in the experimental area was classified as Typic Oxisol [26], with a medium texture and the following particle size distribution at the 0–20 cm layer: 260 g kg^{-1} of clay, 700 g kg^{-1} of sand, and 40 g kg^{-1} of silt. The corresponding chemical properties are presented in Table 1.

Table 1. Chemical attributes of the 10–20 cm soil layer of the experimental area at the beginning of broccoli planting in Uberaba, MG, Brazil.

Layer	pH		Ca	Mg	Al	H + Al	P	K	S	SOC
cm	H_2O	SMP		cmol$_c$ dm^{-3}				mg dm^{-3}		g dm^{-3}
0–20	6.00	5.40	0.47	0.26	0.00	1.40	10.33	66.30	1.50	23.50
			B	Cu	Fe	Mn	Zn			
						mg dm^{-3}				
			0.20	1.61	14.71	13.20	14.73			

pH H_2O determined in a soil to water ratio of 1:1; SOC = soil organic carbon; H+Al determined based on the Shoemaker, Mac Lean, and Pratt (SMP) index, which is a method for analyzing and correcting soil acidity, based on the buffering power of the soil.

The climate of the region is classified as Aw-type, a tropical savanna with a hot climate according to the updated Koppen classification [27], characterized by hot, rainy summers and cool, dry winters. The region has an accumulated annual rainfall of 1600 mm, an average annual temperature of 22.6 °C and relative humidity of 68% [28]. During the experiment, the total rainfall was 796 mm and the average temperature was 21 °C during the first cycle (March to June 2023), and 456 mm with an average temperature of 24 °C during the second cycle (September to December 2023) (Figure 1).

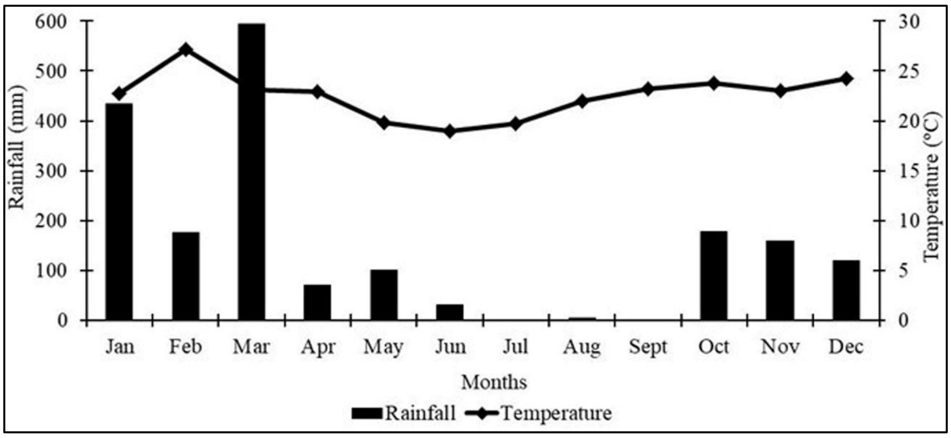

Figure 1. Monthly rainfall and average temperature recorded at the weather station of the Federal Institute of Education, Science and Technology of Triângulo Mineiro (IFTM), Uberaba Campus, Minas Gerais, from January to December 2023.

2.2. Experimental Design and Treatments

The experiment was conducted in a randomized block design, arranged in a split-plot scheme with four replications. In the main plots, three phosphorus sources were evaluated: (1) conventional monoammonium phosphate (CMP) (formula 11-52-00); (2) polymer-coated monoammonium phosphate (PCMP) (formula 11-52-00); and (3) granular organomineral fertilizer (Org) (formula 05-26-00). In the subplots, four phosphorus application rates were tested: 0 (no P applied), 50% (200 kg ha^{-1} of P_2O_5), 75% (300 kg ha^{-1} of P_2O_5), and 100% (400 kg ha^{-1} of P_2O_5) of the recommended rate for broccoli, as proposed by Ribeiro et al. [29].

The granulated organomineral fertilizer (Org) used, based on filter cake, was formula 05-26-00 (N-P-K), which contained 8% total organic carbon (0.14 g dm^{-3} of organic matter).

The study was conducted over two consecutive cropping cycles in the same experimental area, with broccoli seedlings (*Brassica oleracea* var. *italica* L.) transplanted successively approximately 30 days after the harvest of the previous crop.

Soon after completing the harvest of the first cycle, two harrowing operations were carried out again (medium plow harrow and light harrow), to incorporate residues and level the soil in the area, followed by hoeing and the subsequent transplanting of seedlings for the second cycle.

2.3. Additional Information

2.3.1. Production, transplanting, and cultural practices for broccoli seedlings

Single-head broccoli seedlings were grown in 128-cell polystyrene trays filled with Bioplant commercial substrate, using the seed of the hybrid broccoli cultivar Avenger from the Sakata company, which has an average cycle of 100 days, an average mass of 700 g per head, and an average yield of 20 Mg ha^{-1}. The seedlings were produced in a greenhouse covered with plastic and enclosed sidewalls by a commercial nursery in Uberaba, Minas Gerais.

Before planting the broccoli, weed regrowth in the area following soil preparation was controlled using glyphosate (Gliz® 480 SL, 960 g ha^{-1} of a.i.) (São Paulo, SP, Brazil) and 2,4-D dimethylamine (Aminol® 806, 1612 g ha^{-1} of a.i.) (Londrina, PR, Brazil). The herbicides were applied using a Jacto sprayer mounted on a 75 HP Agrale tractor (Caxias do Sul, RS, Brazil), operating at a maximum 6 km h^{-1} speed. The sprayer had a 2000 L tank, delivering 200 L ha^{-1} spray volume.

After transplanting the seedlings, weed management was carried out through the application of fluazifop-p-butyl (Fusilade® 250 EW, 175 g ha^{-1} of a.i.) (São Paulo. SP, Brazil), supplemented, when necessary, by manual hoeing or mowing using a motorized handheld brush cutter to keep the area free of weeds.

Approximately 15 days after desiccation, the seedlings broccolis were transplanted to the field on 5 March 2023 (first cycle), when they had reached a height of 10 to 15 cm. The seedlings were planted in previously dug holes using manual post-hole diggers, with an approximate diameter of 0.15 m and a depth of 0.18 m at a spacing of 0.80 × 0.50 m, targeting a plant density of 25,000 plants per hectare. Harvesting began on 28 May 2023.

In the second cycle, seedling transplanting took place on 12 September 2023, using a spacing of 0.80 × 0.50 m to achieve a plant density of 25,000 plants per hectare. Harvesting began on 6 December 2023. No raised beds were constructed in the area. Each plot consisted of four, 4.0 m in length, with six plants per row, 24 plants per plot, and 1.0 m alleys between blocks. The eight central plants were considered the usable area for evaluating fresh head weight (FHW), dry head weight (DHW), and crop yield (YLD).

The plants were irrigated daily using a fixed conventional sprinkler system equipped with sectorial sprinklers with a 560 L h^{-1} flow rate, spaced 9 m apart. Irrigation was applied between 20 to 30 min daily to maintain soil moisture near field capacity.

2.3.2. Planting, fertilization, and application of top-dressing fertilizers

All planting and topdressing fertilization was applied directly into the planting holes, where the seedlings were subsequently transplanted. Fertilizer rates were determined based on soil chemical analysis and under the recommendations of the Soil Fertility Commission of the State of Minas Gerais [29].

The recommended rates of N, P, and K for broccoli were 150 kg ha^{-1} of N, 400 kg ha^{-1} of P_2O_5, and 100 kg ha^{-1} of K_2O, based on an expected yield of 20 Mg ha^{-1}, for the state of Minas Gerais, according to Ribeiro et al. [29]. The full rate of phosphorus was applied at planting, while nitrogen and potassium were split into four applications: 20% at planting and the remaining amounts at 20 days (20%), 40 days (30%), and 60 days (30%) after transplanting.

At the same time points as the split applications, three foliar sprays were carried out to supply boron (B), molybdenum (Mo), and cobalt (Co) at 20, 40, and 60 days after transplanting. The solution applied contained 1 g L^{-1} of boric acid (17% B) and 2.7 mL of Vitaphol CoMo®, a product containing 10% Mo and 2% Co. Applications were performed to ensure full leaf coverage without runoff, using a solution composed of 1 g L^{-1} of boric acid plus 0.5 g L^{-1} of ammonium molybdate [30].

2.3.3. Broccoli harvest

Broccoli was harvested as the inflorescences reached commercial maturity when the floral buds were fully developed but still tightly closed, forming compact and firm heads. Harvesting began 85 days after transplanting the seedlings to the field.

2.4. Evaluations

2.4.1. Agronomic attributes

Immediately after harvest, the number of leaves (NL) and fresh head weight (FHW) was determined on an analytical scale, and crop yield (YLD) was determined by quantifying the number of heads produced in the area. Part of the harvested material was taken to the laboratory, chopped into smaller pieces to facilitate drying, and placed in a forced-air circulation oven at 65 °C for 72 h or until reaching a constant weight to determine the dry head weight (DHW). The FHW and DHW results were expressed in kilograms per plant (kg $plant^{-1}$) and the productivity of marketable broccoli heads in megagrams per hectare (Mg ha^{-1}).

2.4.2. Leaf sampling and nutritional status analysis

Samples of recently matured leaves were collected at the broccoli head formation stage to analyze the nutritional status of the plants, following the methodology proposed by Martinez et al. [31].

Total N was analyzed using the Kjeldahl distillation method, P using colorimetry, and potassium using flame atomic emission spectrophotometry [14]. Calcium and magnesium were determined through atomic absorption spectrophotometry [32] and sulfur through turbidimetry [33]. The total content of each nutrient was estimated by multiplying the percentage of the nutrient in each sample by the total dry weight.

2.4.3. Soil sampling and chemical analysis

After the broccoli harvest, a Dutch auger collected individual soil samples from the eight planting holes where the usable area plants had been harvested. These samples were combined to form a composite sample per plot, with four replications, collected at a depth of 15 cm to quantify the residual effect of the fertilizers used after each cropping cycle.

After soil sampling, the samples were air-dried, crushed, and sieved through a 2.0 mm mesh to obtain the air-dried fine earth fraction (ADFE), which was used for fertility analyses following the analytical methods described by Teixeira et al. [14].

Soil pH in water was determined using a 1:2.5 soil-to-solution ratio. The soil was left in contact with distilled water for one hour, after which the pH was measured using a benchtop pH meter. Exchangeable Ca^{2+}, Mg^{2+}, and $Al^{3+}$and potential acidity (H^+ + Al) were extracted using 1 mol L^{-1} KCl solution and quantified through titration. Phosphorus (P) and potassium (K^+) were extracted using a double-acid solution (0.05 mol L^{-1} HCl + 0.0125 mol L^{-1} H_2SO_4) following the Mehlich-1 method and analyzed with colorimetry (P) and flame photometry (K^+), respectively, according to the methodology described by Teixeira et al. [14].

2.5. Statistical Analysis

The residual normality assumptions, variance homogeneity, and block additivity were tested using the Shapiro–Wilk and Bartlett tests, respectively. The values of the evaluated variables were subjected to an analysis of variance (ANOVA) using the F-test. Significant, quantitative factors (fertilizer rates) were further analyzed by regression using SigmaPlot software, version 2012. Means of qualitative factors (soil treatments) were grouped using the Scott–Knott test at a 5% significance level ($p < 0.05$).

A joint analysis of variance was performed using data from both broccoli cropping cycles. When a significant effect was observed, means were grouped using the Scott–Knott test at a 5 and 1% significance level ($p < 0.05$; $p < 0.01$) with the aid of the Agroestat software, version 2024, developed by Barbosa and Maldonado Júnior [34].

3. Results and Discussion

3.1. Agronomic, Soil, and Plant Chemical Attributes in the First Cropping Cycle

The results obtained after the first cropping cycle showed that broccoli exhibited significantly higher values ($p < 0.05$) for the number of leaves (NL) (24.00), fresh head weight (FHW) (1.05 kg plant^{-1}), dry head weight (DHW) (0.27 kg plant^{-1}), and yield (YLD) (18.01 Mg ha^{-1}) where the polymer-coated monoammonium phosphate (PCMP) was applied when compared to 22.87, 0.84 g plant^{-1}, 0.25 g plant^{-1}, and 15.34 Mg ha^{-1} where the organomineral fertilizer (Org) was applied and to the 19.12, 0.67 g plant^{-1}, 0.22 g plant^{-1}, and 14.02 Mg ha^{-1} obtained with the conventional monoammonium phosphate (CMP). It is worth noting that the highest values for all parameters consistently occurred at the rate corresponding to 100% of the recommended fertilization for the crop (Table 2).

Phosphorus (P) is one of the macronutrients required in the smallest amounts by plants; however, it is often the most limiting factor for agricultural production under Brazilian conditions [35]. This was confirmed in the present study, as the lowest yield values were observed in the treatment with no P application (zero rate) compared to the other application rates (50%, 75%, and 100%) across all three fertilizers evaluated.

Initial soil chemical analysis showed a phosphorus (P) content of 10.33 mg dm^{-3}, which is below the critical level for crop production of 15.1 mg dm^{-3} of P, according to Alvarez et al. [13]. This result explains the lower broccoli yield observed at the zero rate, as the available phosphorus was insufficient to support normal plant development.

In general, the total phosphorus content in soil ranges from 200 to 3000 mg kg^{-1}, with less than 0.1% of this total (0.002 to 2.0 mg dm^{-3}) present in the soil solution [36]. According to Rolim Neto et al. [37], the low availability of P in tropical soils is due to its low overall content, the low solubility of the P compounds typically found in these soils, and its immobilization resulting from strong interactions with soil constituents.

Table 2. Agronomic attributes of broccoli during the first cropping cycle under different phosphorus fertilizers and application rates in Uberaba, MG, Brazil, in 2023.

Treatment	Agronomic Attributes			
	NL	FHW	DHW	YLD
	--	kg plant^{-1}		Mg ha^{-1}
		Fertilizer (F)		
CMP	19.12 c	0.67 c	0.22 c	14.02 c
PCMP	24.00 a	1.05 a	0.27 a	18.81 a
Org	22.87 b	0.84 b	0.25 b	15.34 b
%		Rate (R)		
Zero	19.25 c	0.46 c	0.22 b	8.21 c
50	20.67 b	0.90 b	0.24 a	17.05 b
75	24.00 a	0.98 b	0.25 a	17.21 b
100	24.08 a	1.22 a	0.26 a	21.76 a
F-test for F	70.81 *	16.38 **	15.47 *	77.50 *
F-test for R	26.16 *	92.52 *	9.47 *	163.71 *
F-test for P × R	21.72 *	13.12 *	22.75 *	27.97 *
CV% for F	5.51	16.3	10.1	6.99
CV% for R	7.47	12.8	8.4	9.56

Means followed by the same lowercase letters belong to the same group by the Scott–Knott test (* = $p < 0.05$; ** = $p < 0.01$). ^{ns} = Not significant; CV = coefficient of variation; CMP = conventional monoammonium phosphate; PCMP = polymer-coated monoammonium phosphate; Org = organomineral fertilizer; NL = number of leaves; FHW = fresh head weight; DHW = dry head weight; YLD = Yield.

Fertilization efficiency does not depend solely on the application rates or amounts applied, as phosphorus availability from soluble phosphate fertilizers is influenced by the chemical reactions that control nutrient supply to the soil solution, particularly chemical adsorption or precipitation, the pH around the fertilizer granule, and the type of precipitate that predominates [7,25].

A significant interaction between fertilizer types and application rates was analyzed through regression to determine the maximum yield and the optimal fertilizer rate. The curves showed a linear fit for the number of leaves (NL) with CMP, PCMP, and Org fertilizers, indicating that increasing the application rate led to an increase in NL to support greater plant development (Figure 2A).

Regarding fresh head weight (FHW), the regression curve showed a polynomial fit for PCMP, and using the equation of the curve, it can be calculated that MFC reached a maximum value of 1.35 kg at a rate of 376 kg ha^{-1} of P_2O_5 (94.5%). Beyond this point, FHW progressively declined. For CMP and Org, the regression curves showed a linear fit, with FHW increasing as fertilizer rates increased (Figure 2B).

The regression curve for dry head weight (DHW) showed a polynomial fit for CMP, PCMP, and Org. Maximum DHW values of 0.29, 0.32, and 0.27 kg were reached at application rates of 370, 450, and 500 kg ha^{-1} of P_2O_5, respectively, after which DHW progressively declined (Figure 2C).

For yield (YLD), the regression curve showed a linear fit for CMP and Org, with values increasing as the application rates increased. For PCMP, the curve exhibited a polynomial fit, with YLD increasing up to 21 Mg ha^{-1} at a rate of 93 kg ha^{-1} of P_2O_5, after which it declined with further increases in application rate (Figure 2D).

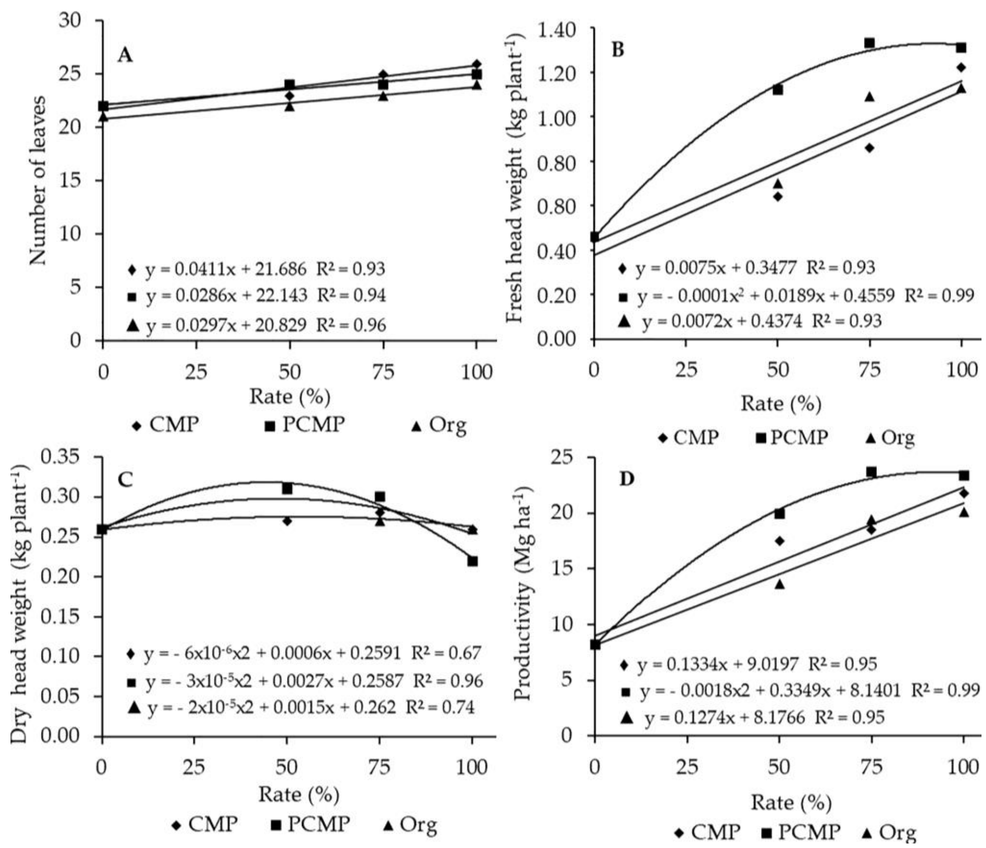

Figure 2. Regression analysis of the interactions for number of leaves (NL) (**A**), fresh head weight (FHW) (**B**), dry head weight (DHW) (**C**), and yield (YLD) (**D**) during the first broccoli cropping cycle (mean values), in Uberaba, MG, Brazil, in 2023.

According to Figueiredo et al. [18], the potential unavailability of P under high pH conditions can affect the efficiency of polymer-coated phosphate fertilizers (PCMP) and other controlled-release formulations. However, this behavior was not observed in the present study, as the highest values for NL, FHW, DHW, and YLD (Table 2) were recorded in the areas where PCMP was applied, in contrast to the results observed with CMP and Org.

Soil chemical analysis conducted immediately after harvest showed that the experimental areas had similar pH values at planting, ranging from 5.68 to 5.76. Phosphorus (P) levels ranged from 99.49 to 108.02 mg dm^{-3}, potassium (K) from 217.85 to 218.31 mg dm^{-3}, calcium (Ca) from 1.62 to 1.63 $cmol_c$ dm^{-3}, magnesium (Mg) from 0.47 to 0.49 $cmol_c$ dm^{-3}, aluminum (Al) from 0.01 to 0.03 $cmol_c$ dm^{-3}, and potential acidity (H + Al) from 4.17 to 4.18 $cmol_c$ dm^{-3}. These results indicate that nutrient levels were significantly higher and more consistent in the treatments where PCMP and Org were applied, compared to CMP, which showed wider variation in P (71.62 to 201.34 mg dm^{-3}), Ca (1.42 $cmol_c$ dm^{-3}), Mg (0.40 $cmol_c$ dm^{-3}), and H + Al (4.08 $cmol_c$ dm^{-3}). The highest nutrient concentrations in the soil occurred at the 100% application rate for all three fertilizers (Table 3), following Ribeiro et al. [29].

The P, K, Ca, and Mg levels measured immediately after harvest were higher than the initial soil values of 10.33 mg dm^{-3} for P, 66.30 mg dm^{-3} for K, 0.47 $cmol_c$ dm^{-3} for Ca, and 0.26 $cmol_c$ dm^{-3} for Mg, and the initial H + Al value of 1.40 $cmol_c$ dm^{-3} (Table 1). These results indicate that fertilization with all three fertilizers improved the chemical quality of the soil by the end of the cropping cycle.

Table 3. Soil chemical analysis immediately after the harvest of the first broccoli cropping cycle under different phosphorus fertilizers and application rates in Uberaba, MG, Brazil, in 2023.

Treatment	Chemical Attributes						
	pH	P	K	Ca	Mg	Al	H + Al
	H_2O	mg dm^{-3}		cmol$_c$ dm^{-3}			
	Fertilizer (F)						
CMP	5.66 a	71,62 b	201.34 b	1.42 b	0.40 a	0.01 a	4.08 a
PCMP	5.69 a	108.02 a	218.31 a	1.63 a	0.47 a	0.02 a	4.17 a
Org	5.68 a	99.49 a	217.85 a	1.62 a	0.49 a	0.03 a	4.28 a
%	Rate (R)						
Zero	5.70 a	48.03 b	175.24 b	1.39 b	0.42 a	0.02 a	4.05 a
50	5.65 a	102.69 a	198.66 a	1.39 b	0.45 a	0.02 a	4.18 a
75	5.70 a	107.65 a	207.35 a	1.69 a	0.45 a	0.01 a	4.19 a
100	5.65 a	113.81 a	215.42 a	1.75 a	0.50 a	0.01 a	4.28 a
F-test for F	1.31^{ns}	0.39**	1.22**	0.65**	0.09^{ns}	0.91^{ns}	4.59 ^{ns}
F-test for R	0.24^{ns}	23.52**	10.57*	4.86*	4.31^{ns}	1.58 ^{ns}	2.75 ^{ns}
F-test for F × R	0.48^{ns}	30.53**	9.06**	4.12**	1.20^{ns}	0.91 ^{ns}	0.28 ^{ns}
CV% for F	2.66	16.87	12.55	13.90	21.90	33	12.58
CV% for R	2.62	12.12	10.84	13.76	24.16	25	13.66

Means followed by the same lowercase letters belong to the same group by the Scott–Knott test (* = $p < 0.05$; ** = $p < 0.01$); ^{ns} = Not significant; CV = coefficient of variation; CMP = conventional monoammonium phosphate; PCMP = polymer-coated monoammonium phosphate; Org = organomineral fertilizer.

In general, foliar analysis showed no significant differences among the fertilizers evaluated for nitrogen (N) and potassium (K). However, for phosphorus (P), the highest value was recorded with CMP at the 100% rate, which was significantly higher ($p < 0.05$) compared to the values observed with PCMP and Org. No significant differences were found among the fertilizer rates for N, whereas the highest K value was observed at the 100% application rate (Table 4).

In their study evaluating different phosphorus sources combined with organic compost in broccoli production, Cardoso et al. [19] observed that the addition of organic compost increased P, K, and Ca levels, as well as cation exchange capacity, base sum, and base saturation (V%). They also demonstrated that using low-solubility phosphorus sources, when combined with organic fertilization, can result in yields comparable to those obtained with highly soluble sources.

This finding confirms the efficiency of the fertilizers used in supplying nutrients for plant development and indicates that the faster release of P from CMP resulted in higher foliar concentrations of this nutrient.

Nitrogen (N) and potassium (K) are the nutrients most required by most crops and, consequently, are also the most abundant in plant tissues, often occurring at levels four to five times higher than phosphorus (P) in plant residues [35]. This was confirmed in the present study, as the amounts of N and K accumulated in broccoli residues were approximately six times higher than that of P. In their study on the uptake dynamics of macro- and micronutrients in brassicas, Alves et al. [38] found that P was the fifth most accumulated macronutrient, surpassing only sulfur (S).

Foliar analysis of broccoli at harvest during the first cropping cycle showed values ranging from 48.53 to 49.97 g kg^{-1} for nitrogen (N), 7.46 to 8.10 g kg^{-1} for phosphorus (P), and 49.61 to 51.23 g kg^{-1} for potassium (K) (Table 4). All of these nutrients fell within the sufficiency ranges considered adequate for plant development, which are 30 to 55 g kg^{-1} for N, 3 to 8 g kg^{-1} for P, and 25 to 50 g kg^{-1} for K, according to Trani and Raij [30].

Table 4. Foliar analysis of broccoli at harvest during the first cropping cycle under different phosphorus fertilizers and application rates in Uberaba, MG, Brazil, in 2023.

Treatment	Nutritional Composition		
	N	P	K
		$g\ kg^{-1}$	
		Fertilizer (F)	
CMP	48.53 a	8.10 a	51.23 a
PCMP	48.53 a	7.49 b	51.16 a
Org	49.97 a	7.46 b	49.61 a
		Rate (R)	
Zero	48.04 a	7.38 b	48.43 b
50	48.95 a	7.46 b	50.24 b
75	49.84 a	7.70 b	50.59 b
100	51.83 a	8.19 a	53.41 a
F-test for F	2.32 ^{ns}	10.40 **	2.21 ^{ns}
F-test for R	3.17 ^{ns}	12.61 **	0.98 *
F-test for F × R	1.18 ^{ns}	7.57 *	1.04 ^{ns}
CV% for F	4.00	4.58	6.33
CV% for R	6.12	6.05	5.82

Means followed by the same lowercase letters belong to the same group by the Scott–Knott test (* = $p < 0.05$; ** = $p < 0.01$). ^{ns} = Not significant; CV = coefficient of variation; CMP = conventional monoammonium phosphate; PCMP = polymer-coated monoammonium phosphate; Org = organomineral fertilizer.

One of the benefits provided by the use of organomineral fertilizers (OMFs) and polymer-coated fertilizers (PCFs) is the reduced loss of nutrients through leaching and adsorption, which generally occurs because their cation exchange capacity is typically much higher than that of clay minerals. As a result, nutrient release is slower [9]. In this study, nutrient availability appears to have been slower with PCMP, which may have influenced agronomic attributes (NL, FHW, DHW, and YLD) when compared to Org (Table 2, Figure 2), despite similar values being observed in soil (Table 3) and foliar analysis (Table 4) at harvest between the Org and PCMP treatments.

3.2. Agronomic, Soil, and Plant Chemical Attributes in the Second Cropping Cycle

In the second cropping cycle, the values for the number of leaves (NL), fresh head weight (FHW), dry head weight (DHW), and yield (YLD) were significantly higher in the treatment where the Org fertilizer was applied compared to PCMP and CMP. However, a reversal in performance was observed among the fertilizers: CMP outperformed PCMP in terms of FHW, DHW, and YLD (Table 5), in contrast to the first cropping cycle, where PCMP had shown superior results across all evaluated parameters (Table 2, Figure 2).

Regarding the application rates, no significant differences were observed in the NL across the three fertilizer rates (50%, 75%, and 100%) and in DHW at both the lower (0% and 50%) and higher (75% and 100%) rates, where values were similar. However, for FHW and YLD, the values were significantly higher at the highest application rate, showing an increasing trend as the applied rates increased (Table 5).

The positive effect of the Org fertilizer is directly related to its composition, as these products contain fulvic and humic components within their organic fractions. In general, these components enhance nutrient uptake from the product, stimulate microbial activity around the root system, improve nutrient retention and release, water retention, aeration, and soil aggregation, and contribute to residual nutrient effects in the soil [6,12,24]. Aguiar et al. [39] also emphasized that adding organic biomass (OB) through the Org fertilizer reduces phosphorus sorption in the soil, as the OB blocks phosphate adsorption sites, thereby protecting P from direct contact with soil colloids.

Table 5. Agronomic attributes of broccoli during the second cropping cycle under different phosphorus fertilizers and application rates in Uberaba, MG, Brazil, in 2023.

Treatment	Agronomic Attributes			
	NL	FHW	DHW	YLD
	-	kg		Mg ha^{-1}
		Fertilizer (F)		
CMP	22.25 b	1.61 b	0.24 b	31.51 b
PCMP	22.69 b	1.49 c	0.21 c	28.85 c
Org	23.19 a	1.85 a	0.26 a	33.01 a
		Rate (R)		
Zero	21.00 b	0.98 d	0.20 b	17.46 d
50	23.25 a	1.71 c	0.21 b	31.78 c
75	23.58 a	1.97 b	0.26 a	37.73 b
100	23.00 a	2.21 a	0.26 a	39.53 a
F-test for F	1.96 *	5.82 **	3.10 *	11.40 *
F-test for R	6.49 *	74.23 *	8.59 *	120.21 *
F-test for F × R	1.47 ^{ns}	14.38 *	3.63 *	22.63 *
CV% F	5.91	12.55	10.1	8.03
CV% R	6.97	12.46	8.4	9.79

Means followed by the same lowercase letters belong to the same group by the Scott–Knott test (* = $p < 0.05$; ** = $p < 0.01$). ^{ns} = Not significant; CV = coefficient of variation; CMP = conventional monoammonium phosphate; PCMP = polymer-coated monoammonium phosphate; Org = organomineral fertilizer; NL = number of leaves; FHW = fresh head weight; DHW = dry head weight; YLD = yield.

The PCMP can alter the hydrogenic potential (pH) of the soil, but this occurs to a lesser extent than CMP, because the polymerization that coats the fertilizer helps delay the release of nutrients, including ammonia, which can acidify the soil over time, whereas this does not occur with CMP, where the release of this ammonia into the soil occurs immediately, which will contribute to the acidification of the environment [18], while Org fertilizer, which contains organic matter, releases nutrients more slowly when decomposed and tends to have a less acidifying effect [15], which justifies the inversion that occurred in the NL, FHW, DHW, and YLD values in the second cycle, since Org fertilizer showed the best values, followed by CMP and PCMP in the second cycle.

Over time, Magela et al. [40] emphasize that there is a gradual improvement in soil fertility, with nutrient stabilization and increased yield, since in Org fertilizers, the microbial breakdown of the organic matrix leads to the gradual release of nutrients. In this study, the Org fertilizer appears to have provided some degree of residual effect in the soil for the second cropping cycle, which was not observed with PCMP.

In their study, Ferrari et al. [12] selected promising phosphate sources and formulations for phosphorus supply and observed that the combination of nutrients from organic and mineral sources in organomineral fertilizers proved effective in minimizing adsorption issues commonly found in the weathered soils of the Cerrado. They reported linear increases in soil phosphorus content over the evaluation period, both in quantity and in trend, as a result of the proposed mixtures compared to the control treatment and the application of isolated sources.

In tropical soils, acidity limits plant development, but it is known that the action of organic matter reduces its negative effects, as well as reducing the effects of aluminum toxicity in experimental or field conditions, promoting better crop performance, even under adverse conditions [9,23].

When evaluating the residual effect of phosphorus sources with and without organic compost on the production of other vegetables grown in succession to broccoli, Cardoso et al. [25] observed that fertilization with organic compost combined with phosphorus sources provided the residual effect necessary for satisfactory yields in the subsequent crops.

Aguilar et al. [10] evaluated the effect of mineral fertilizers, Org fertilizers, and growth regulators on broccoli seedling production in their study. They observed that except for the number of leaves (NL), the other agronomic parameters evaluated showed no significant differences among the treatment results from those observed in this study.

Depending on the spacing used, Melo [41] noted that broccoli yield (YLD) can range from 7 to 22 Mg ha^{-1}, which is consistent with the total yields observed in this study across both cropping cycles. In the first cycle, total YLD ranged from 14.02 to 18.81 Mg ha^{-1} (Table 2), while in the second cycle, it ranged from 28.85 to 33.01 Mg ha^{-1}, based on a planting density of 25,000 plants per hectare (Table 5).

Based on the breakdown of significant interactions through regression analysis, the regression curve for fresh head weight (FHW) under CMP showed a linear fit, with FHW increasing as the fertilizer rate increased. However, this was not the case for PCMP and Org, whose regression curves showed a polynomial fit. FHW increased up to a maximum of 1.83 and 2.11 kg at application rates of 221 kg ha^{-1} of P_2O_5 (55.3%) and 307 kg ha^{-1} of P_2O_5 (76.7%), respectively, and then declined with further increases in rate (Figure 3A).

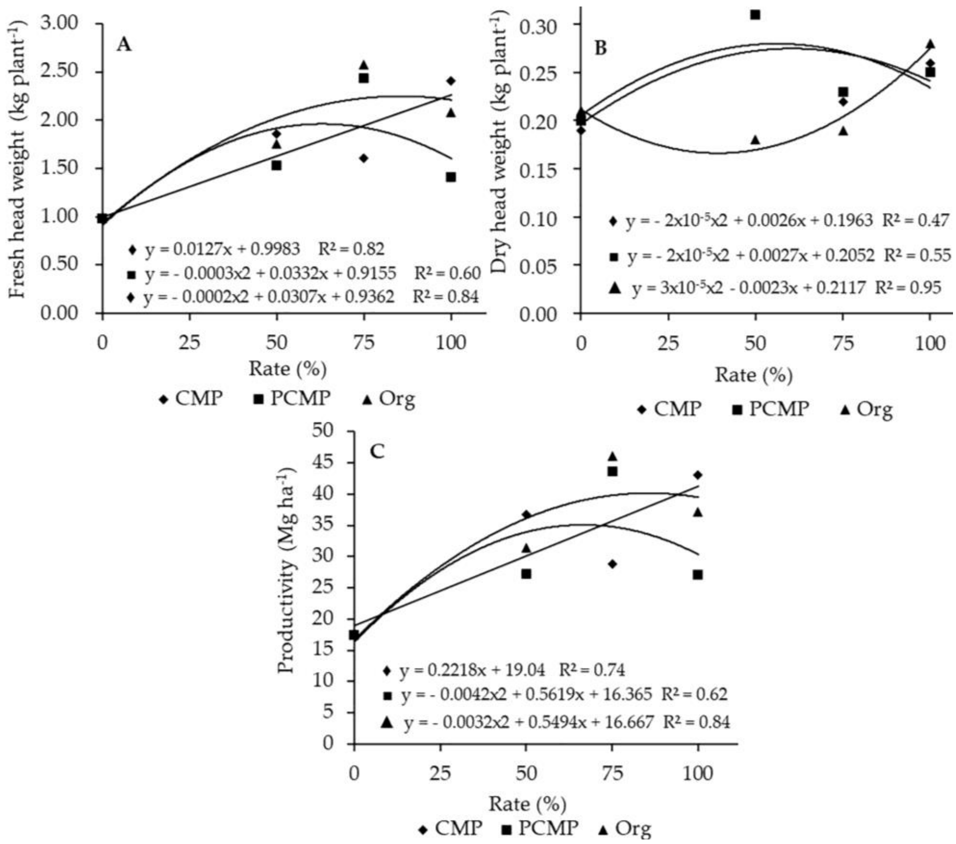

Figure 3. Regression analysis of the interactions for fresh head weight (FHW) (**A**), dry head weight (DHW) (**B**), and yield (YLD) (**C**) during the second broccoli cropping cycle (mean values), in Uberaba, MG, Brazil, in 2023.

For dry head weight (DHW), the values increased with CMP and PCMP applications until reaching maximum values of 0.28 and 0.30 kg at application rates of 260 and 270 kg ha^{-1} of P_2O_5 (65.0% and 67.5%, respectively), after which they declined as the rates increased further. In contrast, the regression curve for Org showed an inverse pattern: DHW decreased until reaching a minimum of 0.17 kg at 153 kg ha^{-1} of P_2O_5 (38.3%) and then increased as the application rates continued to rise (Figure 3B).

For yield (YLD), the regression curve showed a linear fit for CMP, with YLD increasing as the application rates increased. For PCMP and Org, the curves showed a polynomial fit, with YLD increasing up to 35.2 and 40.2 Mg ha^{-1} at application rates of 268 kg ha^{-1} of P_2O_5 (66.9%) and 343 kg ha^{-1} of P_2O_5 (85.8%), respectively, followed by a decline as the rates continued to increase (Figure 3C).

In the second cycle, soil chemical analysis conducted immediately after harvest showed that the areas where fertilizers were applied had similar pH values, ranging from 5.56 to 5.60. The values for phosphorus (P = 105.99 mg dm^{-3}), potassium (K = 116.68 mg dm^{-3}), and calcium (Ca = 1.48 cmol$_c$ dm^{-3}) were significantly higher in the Org treatment. In contrast, the values for magnesium (Mg), aluminum (Al), and potential acidity (H + Al) were similar and did not differ among CMP, PCMP, and Org treatments. The highest concentrations of nutrients in the soil were always observed at the recommended rate of 100%, according to Ribeiro et al. [29], for the three fertilizers (CMP, PCMP, and Org) (Table 6).

Table 6. Soil chemical analysis immediately after the harvest of the second broccoli cropping cycle under different phosphorus fertilizers and application rates in Uberaba, MG, Brazil, in 2023.

Treatment	Chemical Attributes						
	pH	P	K	Ca	Mg	Al	H + Al
	H_2O	mg dm^{-3}		cmol$_c$ dm^{-3}			
	Fertilizer (F)						
CMP	5.56 a	75.92 c	100.47 b	1.26 c	0.38 a	0.02 a	4.38 a
PCMP	5.61 a	94.16 b	96.85 b	1.43 b	0.42 a	0.02 a	4.47 a
Org	5.60 a	105.99 a	116.68 a	1.48 a	0.44 a	0.03 a	4.67 a
%	Rate (R)						
Zero	5.52 b	52.99 c	86.47 b	1.04 d	0.32 c	0.03 a	4.05 b
50	5.54 b	83.90 b	109.09 a	1.34 c	0.39 b	0.02 a	4.51 a
75	5.59 b	114.09 a	110.26 a	1.51 b	0.46 a	0.01 a	4.73 a
100	5.71 a	117.13 a	112.85 a	1.66 a	0.49 a	0.01 a	4.74 a
F-test for F	2.55 ^{ns}	0.03 *	6.33 **	5.83 **	0.74 ^{ns}	0.94 ^{ns}	4.59 ^{ns}
F-test for R	1.34 *	41.59 *	44.47 *	28.38 *	1.98 *	1.30 ^{ns}	2.75 *
F-test for F × R	0.69 ^{ns}	21.63 *	4.30 *	26.74 *	8.84 *	0.86 ^{ns}	0.28 ^{ns}
CV% for F	1.79	10.21	6.05	6.12	21.60	31	7.87
CV% for R	3.24	13.56	11.93	6.47	11.65	28	14.13

Means followed by the same lowercase letters belong to the same group by the Scott–Knott test (* = $p < 0.05$; ** = $p < 0.01$); ^{ns} = Not significant; CV = coefficient of variation; CMP = conventional monoammonium phosphate; PCMP = polymer-coated monoammonium phosphate; Org = organomineral fertilizer.

Soil chemical analysis also revealed improvements in soil chemical quality in the areas where CMP, PCMP, and Org fertilizers were applied, with Org standing out due to its higher P and K levels and a greater residual effect after harvest. This effect is likely related to the addition of organic matter to the soil alongside the mineral fertilizer, as demonstrated in the studies by Fernandes et al. [42], Higashikawa and Menezes Júnior [16], Silva et al. [17], and Teixeira et al. [15].

When evaluating the agronomic efficiency and phosphorus recovery of Org and CMP fertilizers in sandy and clay soils, Sá et al. [21] observed that, at the tested rates, the residual effects did not differ significantly between the phosphorus sources. However, plants showed greater agronomic efficiency when Org fertilizer was used than CMP.

Soil pH and P, Ca, Mg, and H + Al levels were similar between the first (Table 3) and second cropping cycles (Table 6). However, the available K content in the soil was 50% lower in the second cycle. This lower availability of K can be attributed to its higher susceptibility to leaching during periods of increased rainfall (Figure 2), as it is not a structural component of any organic molecule and is found primarily as a free or adsorbed cation. This makes it easily exchangeable within cells or tissues, with high intracellular mobility. Moreover, it is the most abundant cation in plant tissues and is absorbed from the soil solution in large quantities by roots in the form of K^+ ions [43].

Foliar analysis of broccoli at harvest during the second cropping cycle showed values ranging from 42.55 to 48.06 g kg^{-1} for nitrogen (N), 6.02 to 6.59 g kg^{-1} for phosphorus (P), and 42.63 to 45.07 g kg^{-1} for potassium (K) (Table 7). All values fall within the sufficiency range for the crop, considered adequate for plant development: 30 to 55 g kg^{-1} for N, 3 to 8 g kg^{-1} for P, and 25 to 50 g kg^{-1} for K, according to [30].

Table 7. Foliar analysis of broccoli immediately after harvest during the second cropping cycle under different phosphorus fertilizers and application rates in Uberaba, MG, Brazil, in 2023.

Treatment	Nutritional Composition		
	N	P	K
		g kg^{-1}	
		Fertilizer (F)	
CMP	47.48 a	6.02 b	44.53 a
PCMP	42.55 a	6.14 b	42.63 a
Org	48.06 a	6.59 a	45.07 a
%		Rate (R)	
Zero	43.45 a	4.50 b	41.60 a
50	45.65 a	6.40 a	42.41 a
75	46.23 a	6.73 a	46.03 a
100	48.79 a	7.39 a	46.27 a
F teste for F	0.19 ^{ns}	69.31 **	17.82 ^{ns}
F test for R	2.81 ^{ns}	13.63 *	1.79 ^{ns}
F test for F × R	1.87 ^{ns}	1.12 ^{ns}	0.26 ^{ns}
CV% F	13.57	4.47	7.51
CV% R	12.79	13.59	14.75

Means followed by the same lowercase letters belong to the same group by the Scott–Knott test (** = $p < 0.05$; * = $p < 0.01$); ^{ns} = Not significant; CV = coefficient of variation; CMP = conventional monoammonium phosphate; PCMP = polymer-coated monoammonium phosphate; Org = organomineral fertilizer.

The highest foliar P content was observed with the Org fertilizer, while no significant differences were found among the 50% (6.40 g kg^{-1}), 75% (6.73 g kg^{-1}), and 100% (7.39 g kg^{-1}) application rates, which were statistically equal and higher than the value observed at the zero rate (4.59 g kg^{-1}). These results confirm the importance of phosphate fertilizer application in this study and demonstrate its residual effect in the soil at harvest time.

In general, nitrogen (N) is the nutrient most required by most crops and, consequently, is also the most abundant in plant tissues. In the Org fertilizer, this N is retained in the organic matrix and gradually released into the soil. However, for this organic N to become available to plants, soil microorganisms must first mineralize the organic matter. These microorganisms use N as an energy source and carbon (C) from plant residues to build their own biomass, meaning that only the excess N is released into the soil and made available to plants for growth and production [44]. In this study, this release of N appears to have occurred naturally, as described by those authors, since the soil N content was within the sufficiency range (30 to 55 g kg^{-1}) for optimal plant development.

3.3. Joint Analysis of Data from the Two Cycles

This residual effect was more evident in the soil where the Org fertilizer was applied, as shown by the joint analysis of the data. There was an improvement in soil chemical quality in this area during the second cropping cycle, where the highest values for NL, FHW, DHW, and YLD of broccoli were observed. This may be explained by the presence of organic matter combined with mineral fertilizer, which promotes slow nutrient release and reduces losses through leaching and adsorption.

According to Kiehl [45], the addition of organic material provided by the Org fertilizer enhances the residual effect of phosphorus fertilization through the gradual release of the nutrient into the soil. Fernandes et al. [42] emphasized that this increase in residual soil P occurs due to competition for adsorption sites between phosphate ions and the organic acids generated during the mineralization of the organic biomass added to the soil.

Analyzing broccoli production in response to different N and K rates applied via fertigation, with all P applied at planting, Silva et al. [46] observed a linear increase in dry head weight (DHW) with increasing N rates, ranging from 19 to 28 g $plant^{-1}$. However, these values are lower than those obtained in the present study, which range from 32 to 81 g $plant^{-1}$.

The potassium (K) requirements for optimal plant growth range from 25 to 50 g kg^{-1} of the dry mass of vegetative plant parts. However, plants have the ability to absorb more K than they actually need—a phenomenon commonly referred to as the luxury consumption of potassium [47].

In evaluating the nutrient uptake of brassicas, Silva [48] observed that macronutrient absorption followed the decreasing order of export: K > N > Ca > P > S > Mg, with the highest uptake rates occurring during the final 10 days of the crop cycle. Aquino et al. [49] and Correa et al. [50], in turn, reported the following sequences: K > N > Ca > S > P > Mg and K > N > S > Ca > P > Mg, respectively.

4. Conclusions

The polymer-coated monoammonium phosphate (PCMP) and granular organomineral (Org) fertilizers used as phosphorus sources resulted in the highest fresh and dry head weights and yield at the 100% rate (400 kg ha^{-1} of P_2O_5).

In the first growing cycle, broccoli showed the highest values for leaf number (NL) (24), fresh head mass (FHW) (1.05 kg $plant^{-1}$), dry head mass (DHW) (0.27 kg $plant^{-1}$), and productivity (YLD) (18.81 Mg ha^{-1}) when PCMP was applied, which were 5, 25, 8, and 23% higher than Org and 20, 25, 14, and 34% higher than conventional monoammonium phosphate (CMP). In the second cycle, broccoli showed higher values of NL (23), FHW (1.85 kg $plant^{-1}$), DHW (0.26 kg $plant^{-1}$), and YLD (33.01 Mg ha^{-1}) where Org was applied, which were 4, 15, 8, and 5% higher than CMP and 2, 24, 4, and 14% higher than PCMP, respectively.

Broccoli yield in the same area was 124%, 53%, and 115% higher in the second cropping cycle compared to the first cycle for the CMP, PCMP, and Org fertilizers, respectively.

The greatest residual effect in the soil was observed in the area where the Org fertilizer was applied.

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Data Availability Statement: The original data presented in the study will be openly available at https://repositorio.ufu.br, as soon as the doctoral thesis is defended in the Postgraduate Program in Agronomy.

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Conflicts of Interest: The author Miguel Henrique Rosa Franco was employed by the company AGROCP Company. The remaining 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.

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CAPÍTULO II

QUALIDADE AGRONÔMICA E FÍSICO-QUÍMICA DO BRÓCOLIS CULTIVADO SOB DIFERENTES FERTILIZANTES E DOSES DE FÓSFORO[11]

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Article

Agronomic and Physicochemical Quality of Broccoli Cultivated Under Different Fertilizers and Phosphorus Rates

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Abstract

The aim of this study was to evaluate the agronomic performance and physicochemical characteristics of broccoli grown under different doses and sources of special phosphorus (P) fertilizers and their residual effect on the soil, in Cerrado mineiro. A randomized block design arranged in a split-plot scheme was employed, where three P sources—T1 = Conventional monoammonium phosphate (CMP); T2 = Polymerized monoammonium phosphate (PCMP); T3 = Granulated organomineral fertilizer (GOF)—along with four P_2O_5 rates—1–0 (No P); 2–50% (200 kg ha^{-1} P_2O_5); 3–75% (300 kg ha^{-1} P_2O_5); and 4–100% (400 kg ha^{-1} P_2O_5)—were assessed. Evaluations included the number of leaves (NL), head fresh (HFM) and dry mass (HDM), yield (YLD), soil fertility at harvest, plant nutritional status, and the physicochemical quality of the harvested broccoli. It was observed that GOF provided the best agronomic performance (HFM, HDM and YLD) of the broccoli and the greatest residual effect in the soil compared to PCMP and CMP. The moisture, ash, protein, lipid, total titratable acid and ascorbic acid contents were not significantly ($p < 0.05$) affected by the fertilizers used, on the other hand, total soluble solids and hydrogen potential showed the highest and lowest values, respectively, with CMP. The best agronomic performance, the highest phosphorus content in the soil and plant and the best physical–chemical quality of the broccoli occurred at a dose of 100% (400 kg ha^{-1} of P_2O_5) of the recommendation for the crop in all three fertilizers evaluated.

Keywords: special fertilization; polymerized fertilizer; organomineral; production

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1. Introduction

Broccoli (*Brassica oleracea* var. italica) has a high nutritional and commercial value and can be grown in any region of Brazil, having become one of the most consumed vegetables in the country [1–3]. Global broccoli production has reached over 19 million megagrams per year, with China, India, and the United States being the largest producers, in a planted area exceeding 1.0 million hectares [4,5].

Brazil stands out as the largest producer of broccoli in South America, with an estimated cultivated area of 15,000 hectares, accounting for approximately 48% of the region's total, and more than 290,000 megagrams per year. Consumption of this vegetable has grown exponentially in recent decades, with a 63% increase in the area cultivated in the country in the last 10 years. However, the largest producers are still concentrated in the Southeast region of the country, with the state of São Paulo leading production (30,045 megagrams), closely followed by Minas Gerais (27,659 megagrams) [6,7].

Broccoli cultivated in Brazil is produced using cultivars with high genetic potential, which are part of a technological package that is highly dependent on industrialized inputs, as these plants have a high capacity for extracting nutrients from the soil, requiring the use of large amounts of fertilizers for their cultivation [8]. Furthermore, it remains a conventionally grown crop, involving two harrowing operations after each cycle and highly soluble mineral fertilizers, which increases the potential for erosion and nutrient leaching [9,10]).

When broccoli is cultivated in the Brazilian Cerrado, where acidic soils with low natural fertility predominate and the mineralogy is rich in iron (Fe) and aluminum (Al) oxides, with a predominance of kaolinite, phosphate adsorption tends to be high due to the presence of positive charges on the surface of these clay minerals. As a result, a considerable part of the inorganic P added to the soil via fertilizers is retained with so much energy that its balance with the P in the solution disappears, and it is no longer useful for the plant's immediate growth. In this scenario, leaching and adsorption losses tend to be higher, maximizing the need for proper management [11–16]. Filgueira [17] and Oliveira et al. [18] emphasize that brassicas can extract, on average, about 180 kg ha^{-1} of N, 40 kg ha^{-1} of P_2O_5, and 150 kg ha^{-1} of K_2O during the entire cultivation cycle.

Among the technological innovations being used to reduce nutrient leaching and phosphorus (P) adsorption in the Cerrado and other regions of the country, granular organomineral fertilizer (GOFs) and polymer-coated phosphate fertilizers (PCMPs) have stood out, as these products are formulated to release nutrients in a controlled and gradual manner throughout the crop cycle [19,20].

GOFs are created through the physical mixing or combination of mineral and organic fertilizers of various origins, as the organic matter present in the granule increases the soil cation exchange capacity, reducing nutrient losses through leaching and adsorption [21,22]. On the other hand, PCMPs, coated with polymers, provide a slower initial release of nutrients through different mechanisms. The nutrient coating reduces its contact with Fe and Al oxides and clay minerals, preventing the formation of stable compounds and decreasing P adsorption in the soil. Consequently, this allows the nutrient to remain available in the soil for longer and optimizes its plant absorption, reducing losses, as well as having a considerable residual effect on the soil [20,23,24].

Some studies using GOFs and PCMPs as a source of P have already been conducted with broccoli and other crops, which have shown them to be more appropriate fertilizers for use in tropical soils, as they are formulated to release nutrients in a controlled and slower manner, resulting in better utilization by plants and reduced losses due to adsorption [13,19–21,25].

According to Altiere and Nicholls [26], agricultural practices and the intensive use of inorganic fertilizers can cause nutritional imbalances in plants and alter the physicochemical quality of the product. In their study, Storck et al. [27] analyzed the physicochemical composition of the edible part of cauliflower and broccoli and observed the following values for carbohydrates, crude fiber, protein, lipids, ash, and moisture, respectively: 4.5, 2.4, 1.9, 0.2, 0.6, and 92.8% for cauliflower and 4.0, 2.9, 3.6, 0.3, 0.8, and 91.2% for broccoli. In cabbage, Ferreira et al. [28] reported values of 1.03% for total titratable acidity, 2.77% for carbohydrates, and 5.56°Brix for total soluble solids. According to Ornellas [29], broccoli and cauliflower are morphologically similar plants, with a nutritional value that varies depending on the plant part, averaging from 1% to 3% protein, 4% to 24% carbohydrates, and lipids present in small amounts.

Several studies have already evaluated the agronomic performance of broccoli grown conventionally using highly soluble mineral fertilizers [8,9,18,30]. However, studies evaluating the use of special fertilizers in combination with the physicochemical composition of broccoli are nonexistent, making this study unique.

In this context, the hypothesis tested in this study is that special fertilizers (GOFs and PCMPs) are more efficient in providing P in the weathered soils of the Cerrado and can alter the nutritional composition of broccoli. The aim of this study was to evaluate the agronomic performance and physicochemical characteristics of broccoli grown under different doses and sources of special phosphorus fertilizers and their residual effect on the soil, in Uberaba, Minas Gerais, Brazil.

2. Materials and Methods

2.1. Characterization of the Area

The study was conducted in an experimental area in Uberaba, Minas Gerais, Brazil, located at 19°39′19″ S and 47°57′27″ W, at approximately 800 m, from March to June 2024.

In this same area, the previous year (2023), two consecutive cycles of broccoli were grown, after which the area was left fallow for three months, where the spontaneous vegetation developed naturally, and then the area was prepared again for another cycle of cultivation. The soil preparation in the area consisted of two harrowings, one deep harrowing with an 18-disk harrow (76.2 cm in diameter), followed by a shallow harrowing with a light harrow equipped with 44 disks (60.96 cm in diameter).

The soil in the experimental area was classified as Oxisol [31], with a sandy loam texture and the following particle-size distribution at the 0–20 cm layer—260, 700, and 40 g kg^{-1} of clay, sand and silt, respectively—as well as the following chemical attributes (Table 1).

Table 1. Chemical attributes of the 10–20 cm soil layer in the experimental area at the beginning of broccoli planting in Uberaba, Minas Gerais, Brazil.

Layer	pH		Ca	Mg	Al	H + Al	P	K	S	SOM
cm	H_2O	SMP	cmol$_c$ dm^{-3}				mg dm^{-3}			g dm^{-3}
0–20	5.70	5.10	0.47	0.26	0.00	2.20	21,70	66.30	1.50	20.20
			B	Cu	Fe	Mn	Zn			
			mg dm^{-3}							
			0.20	1.61	14.71	13.20	14.73			

pH of H_2O determined in a soil to water ratio of 1:1; SOM = soil organic matter; H + Al determined based on the Shoemaker, Mac Lean, and Pratt (SMP) index, which is a method for analyzing and correcting soil acidity, based on the buffering power of the soil.

The climate is classified as Aw-type, a tropical savanna with a hot climate according to the updated Koppen classification [32], characterized by hot, rainy summers and cool, dry winters. The region has an accumulated annual rainfall of 1600 mm, an average annual temperature of 22.6 °C and relative humidity of 68% [33]. During the experiment, cumulative precipitation totaled 456 mm, and the average temperature was 21 °C from March to June 2024 (Figure 1).

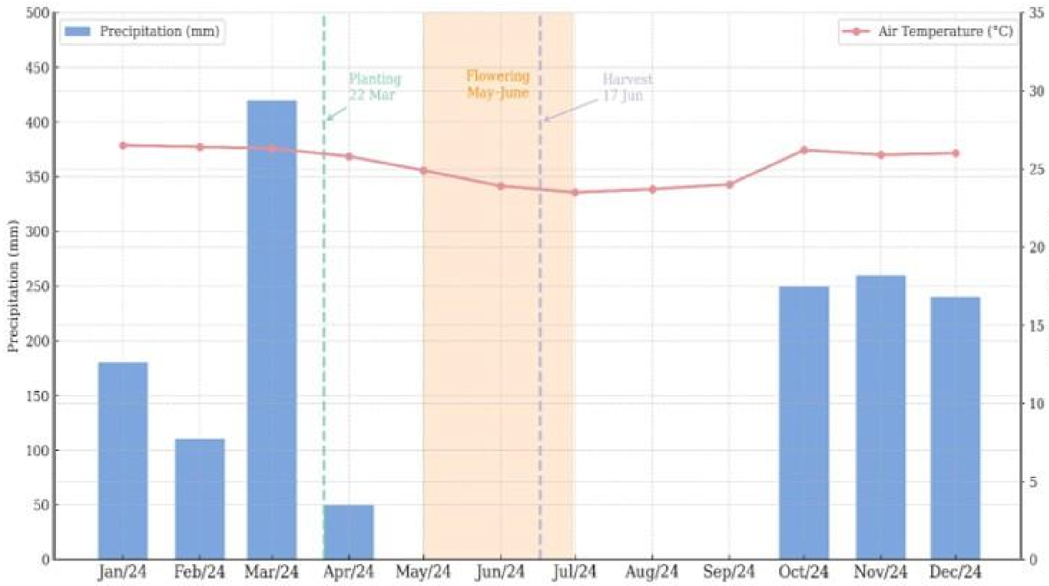

Figure 1. Monthly rainfall and average temperature recorded at the weather station of the Federal Institute of Education, Science and Technology of Triângulo Mineiro (IFTM), Uberaba Campus, Minas Gerais, from January to December 2024.

2.2. Experimental Design and Treatments

The experiment was conducted in a randomized block design, arranged in a split-plot scheme with four replications. In the main plots, three P sources were evaluated: (1) conventional monoammonium phosphate (CMP) (formula 11-52-00); (2) polymer-coated monoammonium phosphate (PCMP) (formula 11-52-00); and (3) granular organomineral fertilizer (GOF) (formula 05-26-00). In the subplots, four phosphorus application rates were tested: 0 (no P applied), 50% (200 kg ha^{-1} of P_2O_5), 75% (300 kg ha^{-1} of P_2O_5), and 100% (400 kg ha^{-1} of P_2O_5) of the recommended rate for broccoli [34].

During its growth cycle, broccoli extracts a significant amount of P from the soil, which can vary from 30 to 60 kg of P_2O_5 [17]. However, in Oxisol, the availability of P in the soil is minimal and there is still high adsorption of this element. In this scenario, Ribeiro et al. [34] recommend doses of phosphate fertilizers ranging from 250 to 400 kg ha^{-1} of P_2O_5 to meet the crop's demand.

The distribution of these plots (main treatment) and subplots (secondary treatment) in the field were all randomly selected, and all sampling was carried out in each subplot, always with four replicates.

The GOF used, based on filter cake, was formula 05-26-00 (N–P–K), which contained 8% total organic carbon (0.14 g dm^{-3} of organic matter).

2.3. Additional Information

Single-head broccoli seedlings were grown in 128-cell polystyrene trays filled with Bioplant commercial substrate, using the seed of the hybrid broccoli cultivar Avenger from the Sakata company, which has an average cycle of 100 days, an average mass of 700 g per head and an average yield of 20 Mg ha^{-1} [19,32].

The seedlings were produced in 128-cell trays in a greenhouse covered with plastic and enclosed sidewalls, irrigated by micro-sprinklers, at a commercial nursery specializing in brassica seedlings in Uberaba, Minas Gerais, Brazil.

After transplanting the seedlings, weed management was carried out through the application of fluazifop-p-butyl (Fusilade® 250 EW, 175 g ha^{-1} of a.i.) (São Paulo, SP, Brazil), supplemented, when necessary, by manual hoeing or mowing using a motorized handheld brush cutter to keep the area free of weeds.

The broccoli seedlings were transplanted to the field on 22 March 2024, into holes previously prepared with the help of hand diggers, with an approximate diameter of 0.15 m and a depth of 0.18 m, at a spacing of 0.80 × 0.50 m, to achieve a final stand of 25,000 plants per hectare.

The harvesting began on 17 June 2024, when the plants reached the point of commercial maturity, when the crowns are large, green and firm, with tightly closed edges.

No raised beds were built in the area, and the experimental plots consisted of four rows, each four meters long, with six plants per row, totaling twenty-four plants per plot, and the eight central plants were considered useful for evaluations of fresh head weight (FHW), dry head weight (DHW) and crop yield (YLD). Tracks 1.0 m wide were left throughout the area to separate the blocks and make harvesting easier.

All the planting and top-dressing fertilizer was applied directly to the holes on 20 March 2024, where the seedlings were later transplanted. The fertilizer doses were determined based on the chemical analysis of the soil and according to the recommendations of the Minas Gerais State Soil Fertility Commission [34], with 150 kg ha^{-1} of N, 400 kg ha^{-1} of P_2O_5 and 100 kg ha^{-1} of K_2O being applied for an expected yield of 20 Mg ha^{-1}. The entire dose of P was applied at planting, while N and K were divided four times, with 20% applied at planting and the rest applied at 20 (20%), 40 (30%), and 60 (30%) days after transplanting.

At the same time as the fertilizer splits, three foliar sprays were applied to provide boron (B), molybdenum (Mo), and cobalt (Co) at 20, 40, and 60 days after transplanting the seedlings. The solution contained 1 g L^{-1} of boric acid (17% B) and 2.7 mL of Vitaphol CoMo®, a product containing 10% Mo and 2% Co. Applications were carried out to completely cover the leaves without runoff of the boric acid solution at a concentration of 1 g L^{-1}, plus 0.5 g L^{-1} of ammonium molybdate [35].

The plants were irrigated daily using a fixed conventional sprinkler system equipped with sectorial sprinklers with a 560 L h^{-1} flow rate, spaced 9 m apart. Irrigation was applied for approximately 20 to 30 min daily to maintain soil moisture near field capacity.

2.4. Evaluations

The broccoli was harvested when the inflorescences were fully developed with flower buds still attached and compact, firm heads. Harvesting lasted 30 days, during which evaluations were carried out every three days, starting 80 days after transplanting.

In the harvested material, the number of leaves (NL) and fresh head weight (FHW) were determined on an analytical scale and crop yield (YLD) was determined by quantifying the number of heads produced in the area. Part of the harvested material was taken to the laboratory, chopped into smaller pieces to facilitate drying, and placed in a forced-air circulation oven at 65 °C for 72 h or until reaching constant weight to determine dry head weight (DHW). The FHW and DHW results were expressed in kilograms per plant (kg plant^{-1}) and productivity of broccoli heads in megagrams per hectare (Mg ha^{-1}).

Samples of recently matured leaves were collected at the broccoli head formation stage to analyze the nutritional status of the plants [36]. Total nitrogen was analyzed using the Kjeldahl distillation method, P by colorimetry, and K by flame atomic emission spectrophotometry. Ca and Mg were determined by atomic absorption spectrophotometry, and S by turbidimetry [37]. The total content of each nutrient was estimated by multiplying the percentage of the nutrient in each sample by the total dry weight.

After the broccoli harvest, a Dutch auger collected individual soil samples from the eight planting holes where the usable area plants had been harvested. These samples were combined to form a composite sample per plot, with four replications, collected at a depth of 15 cm to quantify the residual effect of the fertilizers used after each cycle.

After soil sampling, the samples were air-dried, crushed, and passed through a 2.0 mm mesh sieve, thus obtaining the air-dried fine earth fraction (ADFE), which was used for fertility analyses, following the analytical methods described by Teixeira et al. [35].

Soil pH in water was determined using a 1:2.5 soil-to-solution ratio. The soil was left in contact with distilled water for one hour, after which the pH was measured using a benchtop pH meter. Exchangeable Ca^{2+}, Mg^{2+}, and $Al^{3+}$and potential acidity (H^{+} + Al) were extracted using 1 mol L^{-1} KCl solution and quantified by titration. P and K were extracted using a double-acid solution (0.05 mol L^{-1} HCl + 0.0125 mol L^{-1} H_2SO_4) following the Mehlich-1 method and analyzed by colorimetry (P) and flame photometry (K^{+}), respectively [37].

A portion of the harvested plants was taken to the Food Analysis Laboratory of IFTM, where chemical analyses were conducted using the following methods: moisture by the gravimetric method; protein by the Kjeldahl method, through the determination of the nitrogen content in the food; lipids by the Soxhlet method (gravimetric), based on the amount of material solubilized by the solvent; ascorbic acid by the Tillmans method [38]. The fixed mineral residue (ash) was determined by calcining the sample in a muffle furnace at 550 °C until light-colored ash was obtained. The pH was measured with a pH meter with the sample at 25 °C. Total soluble solids were measured by electronic refractometry, carbohydrates were calculated as the difference between the values of each food component, and the total caloric value was calculated based on the caloric content of each food constituent [39].

Crude fiber was determined using the gravimetric method after acid digestion, while total titratable acidity and the acidity due to the predominant organic acid were determined according to the methodology described by IAL [40].

The analyses of protein, crude fiber, and lipids were performed on dry samples, and the indices for fresh mass were calculated later. The remaining analyses were conducted on fresh samples 24 h after harvest, which were kept refrigerated and stored in five layers of nylon bags during the entire period, according to AOAC methodology [39].

2.5. Statistical Analysis

The residual normality assumptions, variance homogeneity, and block additivity were tested using the Shapiro–Wilk and Bartlett tests, respectively. The values of the evaluated variables were subjected to analysis of variance using the F-test. When significant, quantitative factors (fertilizer rates) were further analyzed by regression using SigmaPlot software, version 2012. The means of qualitative factors (soil treatments) were grouped using the Scott–Knott test ($p < 0.05$; 0.01) with the aid of the Agroestat software, version 2024, developed by [41].

The figures were produced using the Python version 3.12 and the Matplotlib package version 3.8.2 [42], using linear or polynomial regressions adjusted by the least squares method.

3. Results and Discussion

3.1. Agronomic Attributes

When analyzing the agronomic attributes, in general, no significant differences ($p <$ 0.05) were observed in the NL among the fertilizers used. However, this was not the case for the other parameters, as the values for HFM (0.91 kg), HDM (0.29 kg), and YLD (22.82 Mg ha^{-1}) were higher ($p < 0.05$) with the organomineral fertilizers (GOFs), followed by polymer-coated phosphate fertilizers (PCMPs) (0.86 kg; 0.26 kg and 21.43 Mg ha^{-1}), using conventional monoammonium phosphate (CMP) (0.69 kg; 0.22 kg and 20.62 Mg ha^{-1}), respectively (Table 2).

Table 2. Agronomic traits of broccoli plants during the third cultivation cycle as affected by different fertilizer types and phosphorus application rates in Uberaba, MG, 2024.

Treatments	Agronomic Attributes			
	NL	**HFM**	**HDM**	**YLD**
	-	**kg plant^{-1}**		**Mg ha^{-1}**
		Fertilizer (F)		
CMP	25.81	0.69 c	0.22 c	20.62 c
PCMP	26.19	0.86 b	0.26 b	21.43 b
GOF	25.37	0.91 a	0.29 a	22.82 a
%		Rate (R)		
0	23.50 b	0.46 c	0.21 c	19.26 b
50	25.34 a	0.80 b	0.24 b	20.59 a
75	26.33 a	0.97 a	0.27 a	21.04 a
100	27.00 a	0.98 a	0.28 a	21.85 a
F-test for F	0.80 ^{ns}	12.58 **	8.02 *	8.46 *
F-test for R	7.05 **	359.05 **	189.98 **	3.02 *
F-test for F × R	0.79 ^{ns}	18.76 **	4.47 **	17.86 **
CV% F	5.91	9.22	10.15	7.11
CV% R	6.97	4.76	10.39	4.80

Means followed by the same lowercase letters in the column do not differ according to the Scott–Knott test (** = $p < 0.05$; * = $p < 0.01$). ^{ns} = Not significant; CV = Coefficient of variation; CMP = Conventional monoammonium phosphate; PCMP = Polymerized monoammonium phosphate; GOF = Granulated organomineral fertilizer; NL = Number of leaves; HFM = Head fresh mass; HDM = Head dry mass; YLD = Yield.

The higher production observed with the application of the GOF can be explained by the presence of organic matter combined with minerals in the same granule, which protects the P and releases the nutrient more slowly, compared to PCMP and CMP, reducing the issue of P adsorption and providing a greater amount of P available for plant absorption throughout its entire growth cycle.

The GOF result from the physical mixing or combination of mineral and organic fertilizers of various origins, as the organic matter present in the granule contributes to increasing the soil cation exchange capacity [22]. It also promotes the proliferation of beneficial soil microorganisms, which solubilize mineral fertilizers, providing a greater residual effect of the applied phosphate fertilization through competition between the organic acids released and phosphate ions for adsorption sites in the soil [8,13,21].

According to Figueiredo et al. [43] and Cardoso et al. [44], the gradual release of nutrients promoted by the polymer coating of PCMP reduces its contact with Fe and Al oxides and clay minerals; thus, there is no formation of stable compounds, which would reduce the adsorption of P in the soil. This explains why PCMP treatment yields better results than CMP. Among the fertilizers used, CMP has the highest solubility and availability of P in the soil, as this nutrient is not protected by polymers or organic matter.

The P is one of the macronutrients least required by plants; however, it has the most frequently limited agricultural production in the Brazilian Cerrado [45]. This is due to the predominance of Oxisols in the region—highly weathered and acidic soils—where most of the applied phosphate fertilizer tends to precipitate as aluminum- and iron-bound phosphorus (P-Al and P-Fe). In more alkaline soils, the predominant precipitation occurs in P-Ca [46].

The low natural availability of P in tropical soils, as occurs in the Brazilian Cerrado, leads to the application of this macronutrient in production systems, mainly via soluble inorganic fertilizers in larger quantities, which in a way are necessary for the system as an alternative to circumvent the problem of strong nutrient adsorption [47].

The initial chemical analysis of this soil showed a P content of 21.7 mg dm^{-3}, higher than the critical level for crop production, established by Alvarez et al. [48] at 15.1 mg dm^{-3} of P. This likely explains the 19.26 Mg ha^{-1} yield at the zero P rate (No P), which was only 12% lower than the highest yield obtained (21.85 Mg ha^{-1}).

Regarding application rates, similar values of NL, HFM, HDM, and YLD were observed at the 100% (400 kg ha^{-1} P_2O_5) and 75% (300 kg ha^{-1} P_2O_5) rates. These values were higher than those recorded at the 50% rate and in the control treatment (no P). However, this difference was significant only for HFM and HDM when using the phosphate fertilizer recommended for the crop. These results confirm the importance of using these phosphate fertilizer sources, which mitigate the problem of adsorption that occurs in these Cerrado soils, as the values obtained for HFM, HDM, and YLD were significantly higher with GOF and PCMP fertilizers, whose main characteristic is the protection of P by organic matter and by the polymer used, as well as the slow release of nutrients.

Some studies show that for growing broccoli in poor soils with adsorption problems, the recommended doses of phosphate fertilizers range from 250 to 400 kg ha^{-1} of P_2O_5 in the form of superphosphates, in areas with a pH ranging from 6.0 to 6.8 [7,17,34], a condition that justifies the best yields observed at the 100% dose (400 kg ha^{-1} of P_2O_5) applied to the three fertilizers evaluated.

The Oxisol that predominates in the study area has a low clay content (260 g kg^{-1}) but high levels of Fe and Al, making it a soil with a high capacity for P adsorption, thus reducing its availability to plants, as observed by Loss et al. [49]. Torres et al. [14] and Silva et al. [16] highlight that additions of P to the soil beyond the amounts absorbed by plants increase the fractions of inorganic P, leading to a saturation process of adsorption sites.

According to Cardoso et al. [15] and Vieira et al. [50, 51], fertilizer efficiency does not depend solely on the doses of fertilizer being applied, as the availability of phosphorus from the application of soluble phosphates depends on the reaction that controls the amount of the nutrient in the soil solution, mainly chemical adsorption or precipitation, the pH around the fertilizer granule, and the type of precipitate that predominates.

However, it is known that acidity limits plant development in tropical soils. Nevertheless, adding organic matter to the system reduces the negative effects caused by acidity, as well as reducing the effects of aluminum toxicity in experimental or field conditions, promoting better crop performance, even in adverse conditions [25].

Based on the analysis of significant interaction breakdowns using regression curves (Table 2), it was observed that for the CMP, PCMP, and GOF, a linear regression model best fit the data for HFM (Figure 2A), HDM (Figure 2B), and YLD (Figure 2C). Increasing fertilizer rates resulted in corresponding increases in these parameters, reaching maximum values of 0.98 kg, 0.28 kg, and 21.85 Mg ha^{-1}, respectively, at the 100% recommended fertilization rate for the crop.

The beneficial effect of P is directly linked to the plant's ability to accumulate biomass during its initial growth phase, thereby increasing the leaf area exposed to light, as demonstrated by Oliveira et al. [18], who correlated increasing P rates with an increase in the leaf area index, resulting in greater photosynthetic capacity.

This linear increase in production with increasing fertilizer rates is consistent with studies conducted by Fageria [52], Aguilar et al. [19,24], and Sousa et al. [53], who identified a direct relationship between increasing P rates and HDM accumulation in vegetables. These authors highlighted that P is essential in biomass production, especially in intensive cultivation systems. These results reflect the efficiency of phosphate fertilization in broccoli cultivation and align with Malavolta [54], who emphasizes that P optimizes nutrient uptake and plant development when applied at adequate rates.

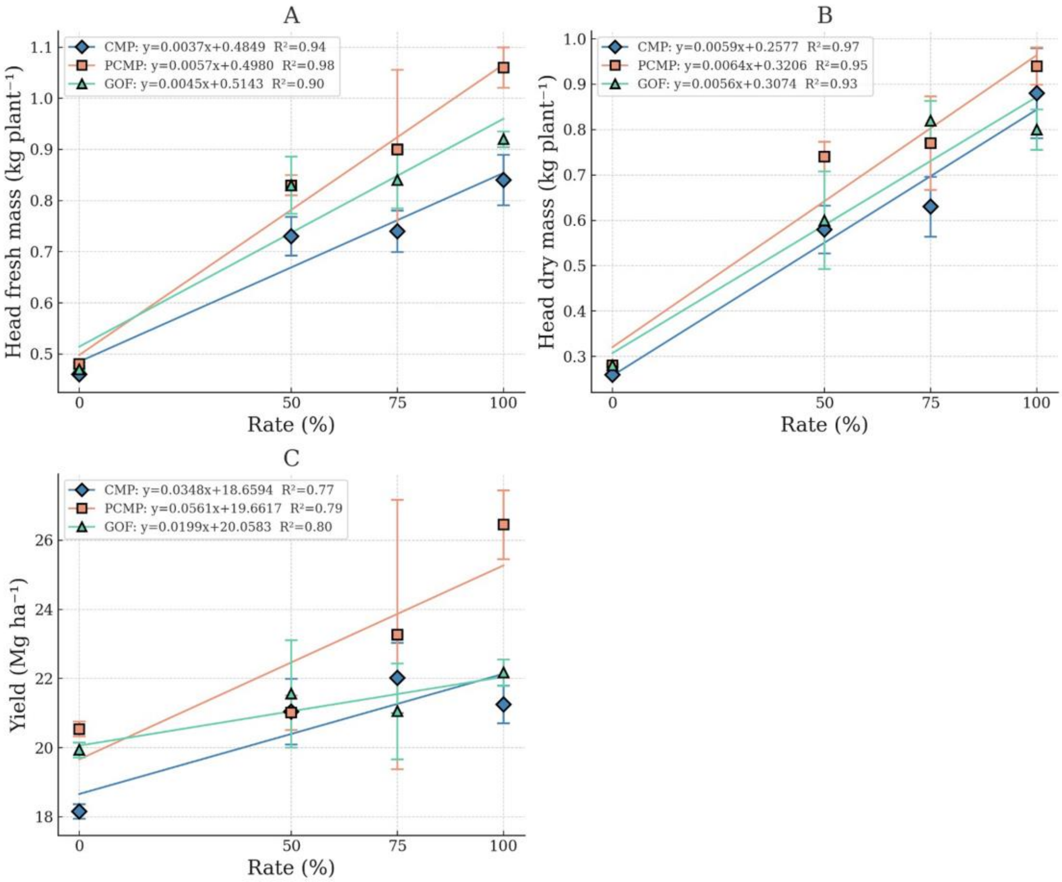

Figure 2. Linear regression analysis of the interaction effects on head fresh mass (HFM) (**A**), head dry mass (HDM) (**B**), and yield (YLD) (**C**) of broccoli grown in Uberaba, MG, 2024.

The chemical analysis of the soil immediately after harvest showed that the soil in the three areas had similar pH values, ranging from 5.62 to 5.65 among the fertilizers used, with the highest values recorded at the 100% rate (5.70). For P (101.09 mg dm^{-3}) and K (167.50 mg dm^{-3}) contents in the soil were significantly higher where GOF was applied, when compared to the values observed in PCMP (88.81 and 135.35 mg dm^{-3}) and CMP (87.71 and 150.91 mg dm^{-3}), while for Ca, Mg, and H + Al, the nutrient levels in the soil were similar for PCMP and GOF. However, for CMP, Ca and Mg were lower than the others. For the doses, the highest nutrient levels in the soil always occurred where the 75% and 100% doses were applied for three fertilizers (CMP, PCMP, and GOF) (Table 3).

The initial P content in the soil was 21.7 mg dm^{-3}, which, when compared with the levels observed after fertilization with CMP (87.71 mg dm^{-3}), PCMP (88.81 mg dm^{-3}) and GOF (101.09 mg dm^{-3}), showed increases in the P content in the soil of 404%, 409% and 466%, respectively. In other words, the application of different fertilizers provided greater availability of nutrients for plant absorption, especially GOF. In addition, the decomposition and nutrient cycling of organic matter contributed to improving soil fertility in the area.

According to Figueiredo et al. [43], P may be unavailable in the soil in areas with high pH, altering the efficiency of polymer-coated phosphate fertilizers (PCMPs) and controlled-release fertilizers (GOFs). However, this behavior was not observed in this study, as the areas had a pH (in H_2O) ranging from 5.62 to 5.65. Even so, the GOF area had the highest values for all nutrients evaluated, which is probably related to the organic matter present in the fertilizer formulation, which slowly releases these nutrients into the soil solution (Table 3).

Table 3. Chemical analysis of the soil immediately after broccoli harvest under different fertilizers and phosphorus (P) rates in Uberaba, MG, 2024.

Treatment	Chemical Attributes					
	pH	P	K	Ca	Mg	H + Al
	H_2O	mg dm^{-3}		cmol$_c$ dm^{-3}		
	Fertilizer (F)					
CMP	5.63	87.71 b	150.91 b	1.34 b	0.39 b	4.38
PCMP	5.65	88.81 b	135.35 c	1.53 a	0.45 a	4.28
GOF	5.62	101.09 a	167.50 a	1.55 a	0.47 a	4.38
	Rate (R)					
0	5.05 b	50.51 d	142.17 b	1.39 b	0.38 b	4.05 b
50	5.61 b	95.78 c	146.91 b	1.45 b	0.44 a	4.40 a
75	5.62 b	108.39 b	155.76 a	1.52 a	0.45 a	4.45 a
100	5.70 a	115.47 a	162.84 a	1.53 a	0.46 a	4.47 a
F-test for F	0.43 ^{ns}	0.27 **	0.36 **	1.20 **	0.88 **	1.00 ^{ns}
F-test for R	1.09 **	8.96 *	16.31 **	22.10 **	9.76 *	0.79 **
F-test for F x R	0.84 ^{ns}	5.58 **	13.45 **	10.45 **	4.13 **	0.56 ^{ns}
CV% F	1.12	10.74	9.84	6.66	12.10	6.10
CV% R	2.04	8.58	7.61	8.80	14.22	9.71

Means followed by the same lowercase letters in the column do not differ according to the Scott–Knott test (** = $p < 0.05$; * = $p < 0.01$). ^{ns} = Not significant; CV = Coefficient of variation; CMP = Conventional monoammonium phosphate; PCMP = Polymerized monoammonium phosphate; GOF = Granulated organomineral fertilizer.

Regression analysis of the significant interactions revealed a linear trend for P and K (Figure 3A), as well as for Ca and Mg (Figure 3B), indicating that soil nutrient contents increased with higher fertilizer application rates. This behavior is more pronounced for P, likely because a portion of the applied P is adsorbed by the soil, meaning that at higher rates, more P remains available in the soil for subsequent plant uptake.

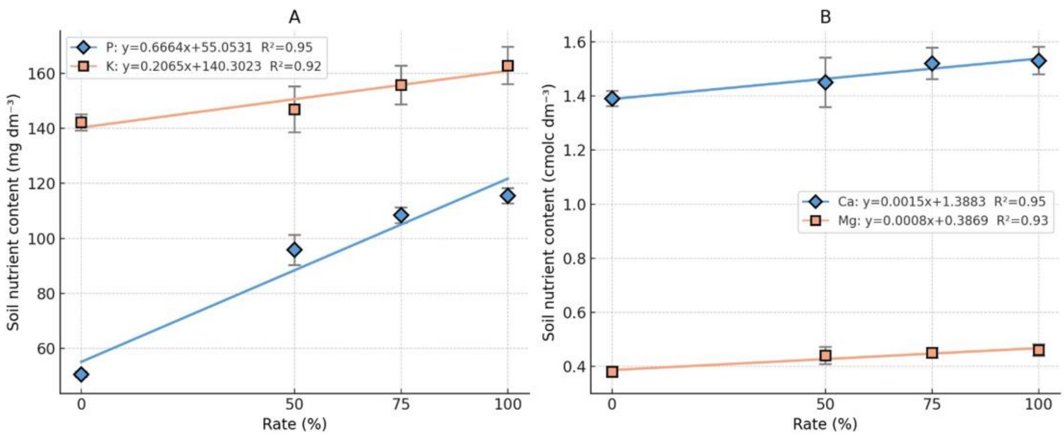

Figure 3. Linear regression analysis of the interaction effects on soil P and K (**A**), and Ca and Mg (**B**) in the broccoli cultivation area in Uberaba, Minas Gerais, Brazil, in 2024.

The combination of nutrients from organic and mineral sources in GOF proved promising in minimizing the issues of adsorption that occur in the weathered soils of the

Cerrado, as increases in soil P were observed in both quantities and a linear trend over the evaluation period due to the proposed mixtures compared to the control and the application of isolated sources [20], results similar to those observed in this study.

The composition of GOF includes fulvic and humic components in the organic fractions, which stimulate microbial flora around the root system, facilitating nutrient retention and release, water retention, aeration, aggregation, as well as providing residual nutrient effects in the soil [13,49,53]. In addition, the authors highlight that these components optimize the absorption of nutrients contained in fertilizers, reducing P adsorption in the soil, as organic biomass acts to block phosphate adsorption sites, protecting P from direct contact with soil colloids.

Foliar analysis showed no significant differences among the fertilizers evaluated for N, P, and K; however, the availability of these nutrients in the plant increased as the fertilizer rates increased, reaching the highest value at the 100% rate (Table 4).

Table 4. Foliar nutrient contents in broccoli immediately after the cycle, under different fertilizer types and phosphorus application rates, in Uberaba, MG, 2024.

Treatment	**Nutritional Composition**		
	N	**P**	**K**
		g kg^{-1}	
		Fertilizer (F)	
CMP	44.92	5.11	33.17
PCMP	46.39	5.08	31.87
GOF	49.19	5.63	33.28
		Rate (R)	
0	41.76 b	4.93 b	29.65 b
50	41.94 b	5.31 a	32.49 a
75	43.39 b	5.35 a	33.67 a
100	60.24 a	5.52 a	35.28 a
F-test for F	0.92 ^{ns}	0.10 ^{ns}	1.43 ^{ns}
F-test for R	6.63 **	2.72 **	2.70 *
F-test for F x R	1.92 ^{ns}	3.98 *	1.62 *
CV% F	6.23	4.47	5.05
CV% R	9.76	13.59	8.72

Means followed by the same lowercase letters in the column do not differ according to the Scott–Knott test (** = $p < 0.05$; * = $p < 0.01$). ^{ns} = Not significant; CV CV = Coefficient of variation; CMP = Conventional monoammonium phosphate; PCMP = Polymerized monoammonium phosphate; GOF = Granulated organomineral fertilizer.

Nitrogen, the most absorbed nutrient by plants, is also the most abundant in plant tissues and tends to be released slowly when this organic matter undergoes decomposition/mineralization. Since GOF contains organic matter and nutrients in the same granule, this nutrient is gradually released and made available to plants [49].

Foliar analysis of broccoli at harvest revealed N contents ranging from 44.92 to 49.19 g kg^{-1}, P from 5.08 to 5.63 g kg^{-1}, and K from 31.87 to 33.28 g kg^{-1} (Table 4). All values fell within the sufficiency range for the crop—30 to 55 g kg^{-1} for N, 3 to 8 g kg^{-1} for P, and 25 to 50 g kg^{-1} for K—considered adequate for plant development, according to Trani and Raij [35], indicating that the plants were well nourished at the time of sampling.

The regression analysis of the significant interactions revealed a linear trend for P (Figure 4A) and K (Figure 4B), indicating that the foliar contents of these nutrients increased with higher soil application rates. This behavior was expected, as P and K are among the nutrients most readily absorbed by plants when available in the soil.

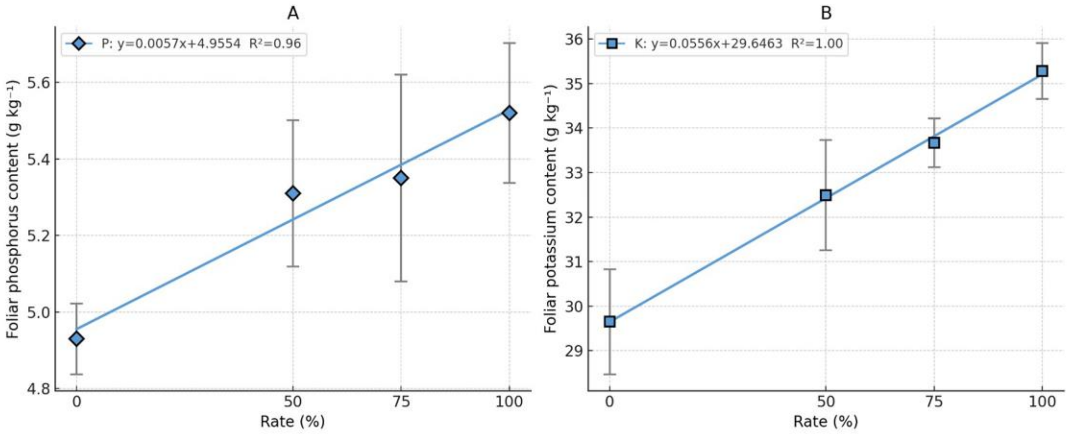

Figure 4. Linear regression analysis of the interaction effects on foliar P (**A**) and K (**B**) contents in broccoli grown in Uberaba, MG, 2024.

According to [45], N and K are the nutrients required in the greatest quantities by most crops and, for this reason, are also the most abundant in plant tissues, reaching values four to five times higher than those accumulated in residues compared to P. In this study, at the 100% rate, the N and K values were 11 and 6 times greater than P, respectively.

In a study evaluating biomass production, macronutrient content, and export in Brassica crops as a function of nitrogen (N) rates, Aquino et al. [55] and Alves et al. [56] reported that macronutrient uptake followed the following decreasing order of export: K > N > Ca > S > P > Mg.

3.2. Physicochemical Attributes

The physicochemical analysis of broccoli revealed no significant differences among the fertilizers and application rates for moisture (MOI), ash (ASH), lipids (LIP), protein (PROT), crude fiber (CF), and amino acids (AA). However, this was not the case for total soluble solids (TSS) and hydrogenionic potential (pH), which showed significantly higher values ($p < 0.05$) where CMP was applied (4.34°Brix) and Org and PCMP (7.18; 7.26), when compared to PCMP and GOF for TSS and CMP for pH, respectively (Table 5).

The P content in the soil can influence several characteristics related to the physical–chemical quality of plants, mainly in the contents of fibers, lipids, proteins, and ascorbic acid, since the deficiency of this nutrient in the soil can reduce plant development, affecting biomass production and, consequently, the concentration of these nutrients [57]. However, this was not observed for these nutrients in this study, as the fertilizers provided P in adequate amounts for plant development.

Analyzing the physicochemical composition of the edible part of broccoli at harvest, Storck et al. [27] reported similar values for MOI (91.2%) and PROT (3.6%), and lower values for ASH (0.8%), LIP (0.03%), and CF (2.9%) compared to those obtained in this study. According to the authors, broccoli is an excellent source of fiber, a condition also observed in this study, where the CF content ranged from 15.02% to 16.25%, further highlighting the common occurrence of high variability in CF content among brassicas (cauliflower and broccoli) and foods in general.

The LIP content in broccoli ranged from 2.27% to 3.54%, PROT from 2.66% to 2.82%, and AA from 15.87% to 20.12%, values that are higher than those obtained by Torres et al. [10] for cauliflower, which reached maximum values of 0.16%, 1.36%, and 5.86%, and for cabbage, which ranged from 0.06%, 1.33%, and 20.0%, highlighting that broccoli is richer in LIP, PROT, and AA compared to cabbage and cauliflower, which together are the most consumed brassicas in the country [6].

Table 5. Bromatological composition of broccoli grown under different fertilizer types and phosphorus application rates in Uberaba, MG, 2024.

Fertilizer	Parameters Evaluated in Broccoli								
	MOI	ASH	LIP	PROT	CF	TTA	TSS	pH	AA
			%			Meq L^{-1}	°Brix		mg 100 g^{-1}
	Fertilizer (F)								
CMP	89.28	8.82	3.54	2.77	15.02	0.64	4.34a	6.93b	17.11
PCMP	89.77	8.78	3.13	2.82	16.25	0.61	3.20b	7.26a	20.12
GOF	90.09	8.67	2.27	2.66	15.31	0.67	3.59b	7.18a	15.87
%	Rate (R)								
0	89.96	8.54	3.13	2.66	15.60	0.61b	3.76 b	7.26a	16.95
50	89.71	8.87	3.28	2.78	15.07	0.65b	3.30b	6.99c	15.94
75	89.05	8.52	3.29	2.80	16.25	0.58b	3.50b	7.10b	18.88
100	90.13	9.06	3.55	2.75	15.19	0.72a	4.28a	7.16a	19.03
F-test for F	0.93 ^{ns}	0.16 ^{ns}	7.15 ^{ns}	0.83 ^{ns}	2.08 ^{ns}	1.18 ^{ns}	13.54 *	27.81 **	4.27 ^{ns}
F-test for R	1.82 ^{ns}	2.49 ^{ns}	2.71 ^{ns}	0.70 ^{ns}	1.08 ^{ns}	4.40 *	4.76 *	9.26 **	0.37 ^{ns}
F-test for F x R	0.72 ^{ns}	4.83 ^{ns}	0.84 ^{ns}	2.05 ^{ns}	1.62 ^{ns}	7.71 **	8.74 **	6.81 **	7.17 ^{ns}
CV% for F	1.15	7.63	8.14	11.25	9.98	14.38	14.66	1.59	20.68
CV% for R	1.30	5.66	9.62	7.84	9.90	13.91	15.69	1.56	18.04

* = Significant ($p < 0.01$); ** = Significant ($p < 0.05$); ns = Not significant. Means followed by the same lowercase letter in the column compare attributes within each season, while uppercase letters in the columns compare attributes between seasons, which do not differ according to the Scott–Knott test ($p < 0.05$). CV% = Coefficient of variation; MOI = Moisture; ASH = Ash; LIP = Lipids; PROT = Proteins; CF = Crude fiber; TSS = Total soluble solids; TTA = Total titratable acidity; pH = Hydrogen potential (pH); and AA = Ascorbic acid.

According to Mcdonald et al. [58], vegetables are not natural sources of LIP. Lipids are highly energetic molecules found in plant and animal tissues that act in the organism as electron carriers, substance transporters in enzymatic reactions, components of biological membranes, and as energy reserves. However, this behavior was not observed in this study for broccoli, which showed high LIP contents.

Ornellas [29] reported that broccoli and cauliflower contain between 1.0% and 3.0% protein (PROT), a range also observed in the present study for broccoli. The author further emphasized that these morphologically similar species exhibit nutritional variation depending on the plant part analyzed.

The TSS content in plants refers to the amount of soluble substances present in the sap and can be indirectly affected by the availability of P. In this study, the highest TSS content (4.34°Brix) was obtained in the CMP treatment, probably due to the higher availability of phosphorus in the soil, since this fertilizer has greater solubility and releases nutrients more quickly compared to GOF and PCMP, as also observed by Torres et al. [10]. According to Santos et al. [6], the soluble sugars in fruits and vegetables in combined forms are responsible for sweetness, flavor, and color, which may vary depending on climatic conditions, cultivar, soil characteristics, and the amount of water added during sample processing.

According to Rinaldi et al. [59], TSS levels range from 2 to 5°Brix for brassicas, with their study on minimally processed cabbage reporting levels ranging from 3.67 to 4.25°Brix. This was also observed by Ferreira et al. [28], who obtained a TSS content of 5.56°Brix for white cabbage, and for broccoli, it also fell within this range, ranging from 3.20 to 4.34°Brix.

The pH value of CMP fertilizer (6.93) was significantly lower than that of GOF (7.18) and PCMP (7.26) fertilizers, which had similar values. However, it is known that in very acidic soils (pH below 5.5) or very alkaline soils (pH above 7.5), P can become less available to plants, being fixed or forming insoluble compounds [48], which shows that, even though the CMP value is lower than the others, all are within the range considered normal for the crop [27].

The TTA refers to the amount of acids present in the vegetable and is an important measure for characterizing the quality of broccoli, especially in relation to its freshness and processing. Fernandes et al. [60] point out that, as the harvest period approaches, ATT levels decrease in the plant, a condition not observed in this study.

Regarding the rates, the highest values for TTA (0.72 Meq L^{-1}), TSS (4.28°Brix), and pH (7.16) always occurred at the highest rate evaluated (100%), except for pH, which did not differ from the zero rate (Table 5). This pattern was expected, as at this rate, the plants exhibited the best nutritional status (Table 4).

A significant interaction was observed between fertilizer type and application rate for total titratable acidity (TTA), total soluble solids (TSS), and pH. Regression analysis of the interaction effects revealed a polynomial fit for total titratable acidity (TTA) (Figure 5A), total soluble solids (TSS) (Figure 5B), and pH (Figure 5C). As the fertilizer application rate increased, the values of these parameters decreased to minimums of 0.59 Meq L^{-1}, 3.2°Brix, and pH 7.03 at rates of 32%, 50%, and 52%, respectively, after which they began to increase again with higher application rates.

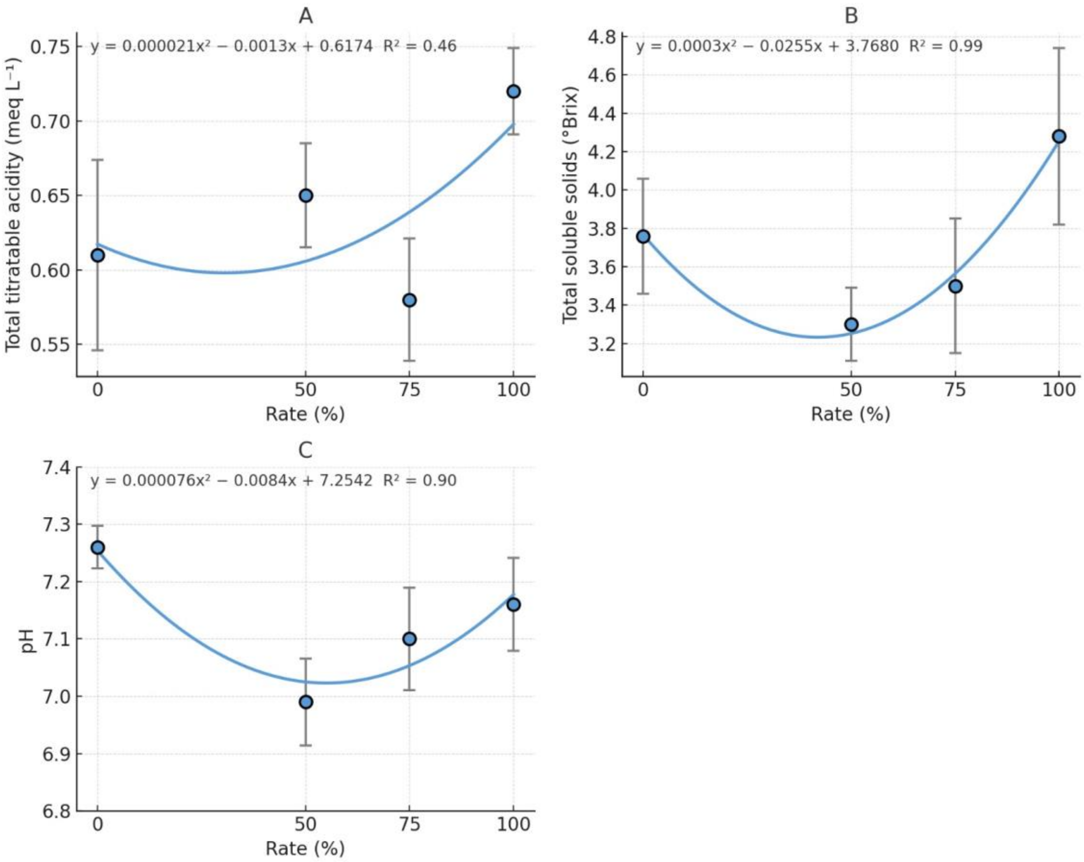

Figure 5. Polynomial regression analysis of the interaction effects on total titratable acidity (TTA) (**A**), total soluble solids (TSS) (**B**), and pH (**C**) in broccoli harvested from the experimental area in Uberaba, MG, 2024.

According to Torres et al. [10], the physicochemical quality of brassicas is directly influenced by climatic factors, the variety and mineral nutrition of the plant, as well as the residues from the cover crops of predecessor plants, which also affect these same bromatological attributes. Fernandes et al. [60] emphasized that citric acid content and overall acidity tend to decrease during the maturation process, increasing pH in certain crops.

4. Conclusions

Granulated organomineral fertilizer (GOF) provided the best agronomic performance (HFM, HDM and YLD) for broccoli and the greatest residual effect in the soil compared to polymerized monoammonium phosphate (PCMP) and conventional monoammonium phosphate (CMP).

The moisture, ash, protein, lipid, total titratable acid and ascorbic acid contents were not significantly ($p < 0.05$) affected by the fertilizers used; on the other hand, total soluble solids and pH showed the highest and lowest values, respectively, with CMP.

The best agronomic performance, the highest phosphorus content in the soil and plant, and the best physicochemical quality of broccoli occurred at a dose of 100% (400 kg ha^{-1} of P_2O_5) of the recommendation for the crop, with the three fertilizers evaluated.

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Data Availability Statement: The original data presented in the study will be openly available at https://https://repositorio.ufu.br as soon as the doctoral thesis is defended in the Postgraduate Program in Agronomy.

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CONCLUSÕES GERAIS

No primeiro ciclo, o brócolis apresentou melhor desempenho agronômico para o NF (24), MFC (1,05 kg planta^{-1}), MSC (0,27 kg planta^{-1}) e PROD (18,81 Mg ha^{-1}) onde foi aplicado o Fosfato monoamônico polimerizado (MAPPol), que foi, respectivamente, 5%, 25%, 8% e 23% superior ao fertilizante organomineral granulado (ORG) e 20%, 25%, 14% e 34% superior ao Fosfato monoamônico convencional (MAPConv).

No segundo ciclo, o melhor desempenho agronômico para o NF (23), MFC (1,85 kg planta^{-1}), MSC (0,26 kg planta^{-1}) e PROD (33,01 Mg ha^{-1}) ocorreu onde foi aplicado o Org, que foi superior 4%, 15%, 8% e 5% quando comparado ao MAPConv e em 2, 24, 4 e 14% quando comparado ao MAPPol, respectivamente.

No terceiro ciclo, o brócolis apresentou o melhor desempenho agronômico para a MFC (0,91 kg planta^{-1}), a MSC (0,29 kg planta^{-1}) e a PROD (22,82 Mg ha^{-1}), onde foi aplicado o Org, que foi superior em 4%, 5%, 10% e 6% quando comparado ao MAPPol e em 24%, 10% e 10% quando comparado ao MAPConv, respectivamente

O melhor desempenho agronômico, o maior teor de fosforo no solo e na planta e a melhor qualidade físico-química do brócolis ocorreram na dose de 100% (400 kg ha^{-1} de P_2O_5) da recomendação para a cultura, nos três fertilizantes avaliados.

Os teores de umidade, cinzas, proteínas, lipídios, ácidos totais tituláveis e ácido ascórbico não foram afetados significativamente pelos fertilizantes utilizados, por outro lado, os sólidos solúveis totais e o pH apresentaram os maiores e os menores valores no MAPConv, respectivamente.

O ORG foi o que proporcionou o melhor desempenho agronômico do brócolis e o maior efeito residual no solo no segundo e terceiro ciclos em comparação com o MAPPol e ao MAPConv.