UNIVERSIDADE DE BRASÍLIA
FACULDADE DE AGRONOMIA E MEDICINA VETERINÁRIA
PROGRAMA DE PÓS–GRADUAÇÃO EM AGRONOMIA

ATIVIDADE ENZIMÁTICA E FRACIONAMENTO DA MATÉRIA ORGÂNICA DO SOLO: FERRAMENTAS PARA APRIMORAMENTO DO MANEJO DO SOLO EM SISTEMAS DE PRODUÇÃO DE HORTALIÇAS

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TESE DE DOUTORADO EM AGRONOMIA

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TESE DE DOUTORADO SUBMETIDA AO PROGRAMA DE PÓS-GRADUAÇÃO EM AGRONOMIA, COMO PARTE DOS REQUISITOS NECESSÁRIOS À OBTENÇÃO DO GRAU DE DOUTOR EM AGRONOMIA

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Resumo

Os sistemas de produção de hortaliças (SPH) são caracterizados por forte dependência de insumos externos, intensidade no preparo de solo, baixa adoção de práticas mantenedoras do carbono orgânico do solo (COS) e de sua atividade biológica, o que pode prejudicar a qualidade do solo (QS). É fundamental que os estudos realizados até o momento, que envolvem atributos químicos, físicos e biológicos do solo em agroecossistemas sejam transformados em ferramentas para avaliação da QS em agroecossistemas olerícolas. O estudo teve como objetivo desenvolver um modelo de avaliação de QS prático e confiável para olericultura em solos tropicais integrando a Avaliação Abrangente da Saúde do Solo (CASH) com o modelo de quatro quadrantes (4QM). Objetivou-se também avaliar o efeito dos SPH orgânicos e convencionais e suas práticas de manejo nas frações lábeis e estáveis do COS e a relação destas frações com indicadores biológicos de QS. O nível de adoção das boas práticas de manejo do solo (BPMS) foi avaliado atribuindo pontuação que variou de 1 a 10. Foram coletadas 90 amostras de solo na profundidade de 0-10 cm (48 de sistemas orgânicos e 42 de convencionais) oriundas de 53 áreas de produção comercial de hortaliças no Distrito Federal, Brasil, em que se determinaram: atividades de arilsulfatase (ARIL) e β-glicosidase (GLI), carbono orgânico do solo (COS), carbono total (CT), carbono orgânico particulado (COP), carbono oxidável em permanganato de potássio (POX-C), carbono orgânico associado aos minerais (MOC), ácidos fúlvicos e húmicos (AF e AH), humina (HU), frações oxidáveis de C em diferentes concentrações de H_2SO_4 (F1, F2, F3 e F4). A adoção de BPMS foi maior em sistemas orgânicos em relação aos convencionais, resultando em aumento de 27 e 86% no conteúdo de COS e atividade da ARIL ($P < 0,05$), respectivamente, determinando melhor QS nos sistemas orgânicos. Entre as duas enzimas avaliadas, a ARIL diferenciou os campos orgânicos e convencionais com mais precisão do que a GLI, confirmando seu potencial para avaliação da QS em sistemas de produção de hortaliças. A textura do solo não influenciou as avaliações de QS neste conjunto de dados, permitindo que as 90 áreas fossem avaliadas em conjunto, independentemente de suas distribuições de tamanho de partícula. A integração de CASH e 4QM, juntamente com medições de ARIL, GLI e COS, tornou possível avaliar a QS nos SPH orgânicos e convencionais, apesar da complexidade e dinâmica destes agroecossistemas. As frações lábeis e estáveis do COS foram maiores nos sistemas orgânicos do que nos convencionais ($P < 0,05$), exceto F3. ARIL correlacionou-se com CT, COS e todas as frações lábeis e estáveis, exceto F3, com destaque para COP, POX-C, F1, F2 e HU. Os sistemas orgânicos tiveram maiores teores de frações lábeis, mas também estabilizaram o carbono, o que pode evitar sua perda em longo prazo. Além da ARIL, as frações COP, POX-C, AH, HU, F1 e F2 mostraram-se indicadores capazes de diferenciar sistemas orgânicos e convencionais.

Palavras-chave: Qualidade do solo, enzimas do solo, matéria orgânica do solo, frações da matéria orgânica do solo, agricultura orgânica.

Abstract

The vegetables production systems (VPS) are characterized by strong dependence on external inputs, intense soil preparation, and low adoption of practices that maintain soil organic carbon (SOC) and its biological activity, which can harm soil quality (SQ). It is crucial that studies conducted involving chemical, physical, and biological soil attributes in agroecosystems are turned into tools for evaluating SQ in VPS. This research aimed to develop a practical and reliable SQ assessment model for VPS in tropical soils, integrating the Comprehensive Assessment of Soil Health (CASH) with the Four Quadrant Model (4QM). It also aimed to evaluate the effects of organic and conventional VPS and their management practices on the labile and stable SOC fractions, and the relationship of these fractions with biological SQ indicators. The level of adoption of the best management practices (BMP) was assessed by assigning scores ranging from 1 to 10. Ninety soil samples were collected at 0-10 cm depth (48 from organic systems and 42 from conventional systems) from 53 commercial vegetable production areas in the Federal District, Brazil. It was determined: activities of arylsulfatase (ARYL) and β-glucosidase (GLU), SOC, total carbon (TC), particulate organic carbon (POC), potassium permanganate oxidizable carbon (POX-C), mineral-associated organic carbon (MOC), fulvic and humic acids (FA and HA), humin (HU), and oxidizable C fractions in different concentrations of H_2SO_4 (F1, F2, F3 and F4). The adoption of BMP was higher in organic systems compared to conventional ones, resulting in increases of 27% and 86% in SOC content and ARYL activity ($P < 0.05$), respectively, indicating better SQ in organic systems. Among the two enzymes evaluated, ARYL distinguished organic and conventional fields more accurately than GLU, confirming its potential for SQ assessment in VPS. Soil texture did not influence SQ assessments in this dataset, allowing the 90 areas to be evaluated together regardless of particle size distribution. The integration of CASH and 4QM, along with measurements of ARYL, GLU and SOC, enabled the evaluation of SQ in organic and conventional VPS, despite the complexity and dynamics of these agroecosystems. Labile and stable SOC fractions were higher in organic systems than in conventional ones ($P < 0.05$), except for F3. ARYL correlated with TC, SOC, and all labile and stable fractions, except F3, with emphasis on POC, POX-C, F1, F2, and HU. The organic systems had higher contents of labile fractions, but also stabilized carbon, which can prevent its loss in the long term. In addition to ARYL, POC, POX-C, HA, HU, F1 and F2 fractions were indicators capable of differentiating organic and conventional systems.

Keywords: Soil quality, soil enzymes, soil organic matter, soil organic matter fractions, organic farming.

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LISTA DE ABREVIATURAS

AEM - Atividade enzimática específica média

AF - Ácidos fúlvicos

AH - Ácidos húmicos

ARIL – Arilsulfatase

ARYL – Arysulfatase

BMP – Best management practices

BPMS – Boas práticas de manejo do solo

C – Carbono

CASH – Comprehensive assessment of soil health (Abordagem abrangente da saúde do solo)

COM – Carbono orgânico associado aos minerais

COP – Carbono orgânico particulado

COS – Carbono orgânico do solo

COT – Carbono orgânico total

CTC – Capacidade de troca de cátions

DNC – Distribuição normal cumulativa

DF – Distrito Federal

GLI - β-glicosidase

GLU – β-glucosidase

H – Hidrogênio

Ha - Hectare

HU – Humina

IQS – índice de qualidade do solo

MIQS – Módulo de Interpretação da Qualidade do Solo

MO – Matéria orgânica

MOS – Matéria orgânica do solo

N – Nitrogênio

PC – Preparo convencional do solo

PD – Plantio direto

PR – Preparo reduzido do solo

QS – Qualidade do solo

Q1, Q2, Q3, Q4 – Quadrantes 1, 2, 3 e 4, respectivamente

SS – Saúde do solo

RRA – Rendimento relativo acumulado

SPH – Sistemas de produção de hortaliças

VBP - Valor bruto da produção

VPS – Vegetable production systems

Sumário

1. Introdução

A agricultura do século XXI tem desafios fortemente conectados com os objetivos do desenvolvimento sustentável (ODS) estabelecidos pela Organização das Nações Unidas (ONU), um deles acabar com a fome e promover uma agricultura sustentável. Estes e outros objetivos demandarão investimentos em educação, pesquisa, extensão rural e políticas públicas. Questões como abastecimento da população mundial com alimentos saudáveis, diminuição de perdas pós-colheita e desperdícios, desenvolvimento de agroecossistemas sustentáveis, conservação dos recursos naturais, redução da vulnerabilidade dos sistemas produtivos às mudanças climáticas, sequestro de carbono (C) e o progresso das comunidades rurais estão na lista de desafios (Altieri et al., 2015; Shen et al., 2024).

A degradação do solo tem sido amplamente relatada, inclusive no cultivo de hortaliças. Esses processos decorrem da intensidade no cultivo com altos aportes de nitrogênio, frequente preparo do solo, cultivos com ciclos muito curtos e pouca adoção de rotações de cultura, causando o declínio da matéria orgânica do solo (MOS) em quantidade e qualidade, deterioração de sua estrutura e perda de biodiversidade, ou seja, redução da qualidade do solo (QS) (Valarini et al., 2011; Willekens et al., 2014; Lima et al., 2018). Como os recursos terrestres globais são limitados, eles precisam ser gerenciados de forma sustentável, afinal segurança alimentar e a proteção da biodiversidade começam pelo solo (Lal, 2016; FAO, 2022). O manejo sustentável dos agroecossistemas pressupõe uma continuidade espacial e temporal da produção, ciclagem de nutrientes, manutenção e restabelecimento de cadeias tróficas, plantas bem adaptadas e solos saudáveis (Feiden, 2005; Teixeira et al., 2018).

O interesse pelos temas “Qualidade” e “Saúde” do solo é crescente nos últimos anos. Doran e Parkin (1994) salientaram a importância de um solo saudável, não somente para a produção de alimentos, fibras e energia, mas também para o funcionamento global dos ecossistemas, incluindo armazenamento e filtragem de água, sequestro de C, ambiente adequado para a manutenção da biota do solo, responsáveis por parte dos ciclos biogeoquímicos. Desta forma, o termo saúde do solo (SS) deve ser usado em sentido amplo, para indicar sua capacidade de funcionar como um sistema vital, sustentar a produtividade biológica, promover qualidade ambiental e manter a saúde das plantas e animais (Doran e Zeiss, 2000). Enquanto a QS está relacionada às funções do solo ou ao que ele proporciona, a SS apresenta o solo como um recurso vivo, finito, dinâmico e com amplas funções ecossistêmicas (Lal, 2016). É possível inferir que, no limite, um solo com alta qualidade poderá ser classificado como solo saudável. A partir desse conceito, Doran e Parkin (1994) propuseram indicadores físicos, químicos e biológicos relacionados às diversas funções do solo. A partir dos estudos clássicos da década de 1990 (Dick e Tabatabai, 1993; Doran e Parkin, 1994; Trasar-Cepeda et al., 1998; Bandick e Dick, 1999), diversos estudos têm sido realizados com o objetivo de aperfeiçoar métodos para a avaliação da QS. Faz-se um destaque para os estudos realizados em regiões tropicais e subtropicais do Brasil (Balota et al., 2004; Lopes et al., 2013; Duval et al. 2018; Mendes et al., 2021; Chaer et al., 2023).

A MOS é um componente chave normalmente considerado para compreensão da QS e juntamente com os organismos vivos do solo são responsáveis por funções ecológicas e serviços ecossistêmicos fundamentais ao equilíbrio dos agroecossistemas (Chabbi et al., 2022). Assim, boas práticas de manejo do solo, como o plantio direto, adubação verde, adequadas rotações de cultura, devem preservar a qualidade ambiental, manter adequados estoques de C, propiciar a manutenção da biota existente ou seu incremento e a maior diversidade (Carneiro et al., 2004; Niemi et al., 2008; Lange et al., 2023). As consequências poderão ser a ativação dos mecanismos ecológicos relacionados à fertilidade, supressão de doenças, condições adequadas ao desenvolvimento radicular e melhor funcionamento fisiológico das plantas cultivadas, influenciando a produtividade das culturas e a sustentabilidade dos agroecossistemas (Lal, 2016; Mendes et al., 2019a).

Se a MOS e os componentes biológicos são fundamentais para o solo, deve-se investigar quais manejos são mais adequados para a sua conservação e dinamização. Para isso, a pesquisa agrícola vem desenvolvendo métodos, que envolvem análises laboratoriais e avaliações em campo, algumas com participação dos agricultores, contemplando aspectos químicos, físicos e biológicos (Plaza-Bonilla et al., 2014; Duval et al., 2018; Bongiorno et al., 2019; Mendes et al., 2019a; Hargreaves et al., 2019; Bíla et al., 2020; Valani et al., 2020; Comin et al., 2024; Carneiro et al., 2024). A MOS está entre os indicadores mais estudados para avaliar QS, pois regula grande parte das funções essenciais do solo, como ciclagem de nutrientes, formação de agregados, retenção de água, provisão de alimento e habitat para a biodiversidade (Haynes, 2005; Bünemann et al., 2018), correlacionando-se com a produtividade de culturas (Johnston et al., 2009; Lopes et al., 2013; Mi et al., 2019; Mendes et al., 2019b). Neste contexto, as frações da MOS têm se mostrado ainda mais sensíveis do que a matéria orgânica (MO) total para detecção de diferenças entre manejos, que melhoram ou pioram a QS (Figueiredo et al., 2010; Duval et al., 2018; Santos et al., 2024). As enzimas do solo também são componentes das frações lábeis da MO (Tirol-Padre e Ladha, 2004) e possuem elevado potencial como indicadoras de QS graças à sua sensibilidade, simplicidade e baixo custo para determinação (Stott et al., 2010, Mendes et al., 2021).

O lançamento da tecnologia de bioanálise de solo (BioAS) em julho de 2020 posicionou o Brasil na vanguarda mundial de monitoramento da saúde do solo em áreas de produção agrícola. Resultado de 20 anos de pesquisa, a BioAS baseia-se na análise de duas enzimas do solo, a β-glicosidase (GLI) e a arilsulfatase (ARIL), integrando-as às análises químicas tradicionais de rotina (pH, H+Al, P, K, Ca, Mg e MOS). O desenvolvimento de sistemas de interpretação para estes dois bioindicadores, específicos para áreas sob cultivos anuais, permitiram que finalmente os agricultores pudessem monitorar a saúde de seus solos, sabendo exatamente se os mesmos estão numa condição saudável, em adoecimento, doente, ou em recuperação (Mendes et al., 2019a, 2021, 2024). Embora o lançamento ao nível comercial da BioAS seja o mais novo aliado para a sustentabilidade agrícola, a pesquisa precisa avançar para ampliar sua inserção em outros setores da agricultura, como por exemplo, as áreas de produção de hortaliças. Este representa um segmento com grande importância econômica e social no Brasil, considerando o valor bruto da produção agropecuária (VBP) gerado, sua importante, complexa e dinâmica cadeia produtiva, bem como a geração de postos de trabalho pela elevada demanda de mão de obra (CNA, 2017; CNA, 2024).

Tendo em vista a diversidade de manejos de solos nos cultivos de hortaliças, é necessário que se investigue quais são mais adequados para manutenção e dinâmica da biota do solo e conservação de uma fertilidade sistêmica duradoura nestes agroecossistemas. Nesta abordagem sistêmica, quanto mais complexo o sistema de produção, com mais espécies cultivadas, menos preparo do solo, integrado com criações, mais serão intensificadas as relações e funções do solo, tornando-o mais fértil, com vida abundante, boa porosidade, nutrientes e água disponíveis (Anghinoni e Vezzani, 2021).

Assim, no capítulo 1 da presente tese de doutorado objetivou-se expandir o uso da BioAS para áreas sob cultivo de hortaliças ampliando o monitoramento da saúde do solo dos sistemas agrícolas do Distrito Federal (DF). O capítulo 2 foi planejado considerando a necessidade de diagnosticar o efeito dos diversos manejos de solo em cultivos comerciais de hortaliças nas frações da MOS, e de compreender sua relação com a atividade enzimática, bem como seu potencial como indicadores de QS para estes agroecossistemas.

2. Revisão de literatura

2.1. Produção de hortaliças no DF e no Brasil

A cadeia produtiva de hortaliças no Brasil contribui de forma relevante para o VBP (CNA, 2024). Em 2023 foi projetado um VBP brasileiro de R$ 1,24 trilhão, tendo a soja (*Glycine max*) na primeira colocação alcançando R$ 367 bilhões, enquanto o somatório das cadeias produtivas do tomate, batata e cebola alcançou R$ 30 bilhões, valor superior ao de outras importantes cadeias produtivas como a do feijão, trigo, e não contabilizando o VBP de outras olerícolas como cenoura, morango, pimentão, alho (CNA, 2024).

No DF, a importância das hortaliças é relativamente maior do que no contexto brasileiro devido a alguns fatores: estrutura fundiária, com predominância de pequenas propriedades; robusto mercado consumidor com elevada renda *per capita* da população; proximidade do campo às cidades; infraestrutura de transporte e energia compatíveis com a demanda tecnológica; significativo mercado representado pela Região integrada de desenvolvimento do DF e Entorno, contemplando municípios populosos; linhas de crédito apropriadas e acessíveis (Emater-DF, 2024b). O VBP das hortaliças no DF alcançou R$ 1,9 bilhão em 2023, enquanto os cultivos de grãos (soja, milho, trigo, outras) alcançaram R$ 1,5 bilhão em 2023 (Emater-DF, 2024a). Em 2023, foram cultivados cerca de 8.900 hectares de hortaliças no DF, que produziram cerca de 261 mil toneladas de alimentos, tendo como cultivos principais: tomate, alface, morango, pimentão, couve, brócolis, chuchu, alho, repolho, cebola. Os montantes de recursos financeiros circulantes na produção olerícola fazem movimentar significativamente as economias regionais, além de representar grande importância social pelo potencial de geração de postos de trabalho (Resende Filho et al., 2019). Neste segmento, há grande demanda de mão de obra para plantio, cultivo, colheita e pós-colheita, representando de 17 a 52% do custo total para as principais culturas (CNA, 2017). Segundo informações da Emater-DF (2024b), o segmento da olericultura gera de 3 a 5 empregos diretos por hectare, dependendo da espécie cultivada.

A produção orgânica ocupa crescente espaço neste cenário, perfazendo em 2023 6,5% do VBP e 5,2% de área plantada em relação ao total do DF (Emater-DF, 2024a). São áreas certificadas pelo Instituto Biodinâmico de Desenvolvimento Rural (IBD), Ecocert Brasil, Organismo Participativo de Avaliação da Conformidade (OPAC)

Cerrado, OPAC AGE ou credenciadas como orgânicas pelo Ministério da Agricultura, Pecuária e Abastecimento por meio de um Organismo de Controle Social (OCS).

2.2. Produção orgânica, práticas agroecológicas e a busca de sustentabilidade

Para Gaitán-Cremaschi et al. (2019), os sistemas alimentares dominantes se configuram a partir do paradigma produtivista, pela produção de grandes quantidades de alimentos padronizados e de baixo custo. Embora sejam sistemas predominantes em todo o mundo, grande parte dos estudos conclui pela necessidade de uma transição para sistemas com amplos princípios de produção sustentável e desenvolvimento rural. Segundo Srivastava et al. (2016), há forte tendência e necessidade de utilização dos conceitos e práticas biológicas no manejo fitossanitário, fertilidade do solo, promoção de crescimento vegetal, resistência à seca, contribuindo com a produtividade e sustentabilidade da agricultura. Neste contexto, a agroecologia ganha força por sua abordagem técnica, sistêmica e transformadora com vistas à conciliação da produção de alimentos com a preservação do bom funcionamento dos ecossistemas (Palomo-Campesino et al., 2018). Neste processo, a adoção de práticas agroecológicas com aumento da biodiversidade é importante para manter rendimentos satisfatórios das culturas e a fertilidade do solo (Teixeira et al., 2021).

A produção orgânica avança em todo o mundo, sendo impulsionada pela atenção crescente de consumidores quanto aos impactos ambientais, saúde e ética na produção e consumo (Lima et al., 2020). No Brasil, são cerca de 26 mil produtores rurais (MAPA, 2024), com um aumento considerável na área agrícola sob cultivo orgânico, estimada em 1,14 milhão de hectares, representando um mercado de US$ 879 milhões (Willer e Lernoud, 2019).

Há um conjunto de princípios e práticas que deve pautar o planejamento produtivo da produção orgânica. A lei 10.831 de 23 de dezembro de 2003, que dispõe sobre a agricultura orgânica, em seu artigo 1°, indica que o incremento da atividade biológica do solo, a promoção de seu uso saudável e a manutenção ou incremento de sua fertilidade em longo prazo são finalidades de um sistema orgânico de produção. No âmbito desta lei, o conceito de sistema orgânico de produção agropecuária e industrial abrange as denominações de ecológico, biodinâmico, natural, regenerativo, biológico, agroecológico e permacultura. Palomo-Campesino et al. (2018) elencaram diversas práticas comumente utilizadas na produção orgânica ou em processos de transição agroecológica, as quais têm maior ou menor grau de utilização dependendo do tamanho das áreas cultivadas (Liebert et al., 2022), das vivências, aspectos sociais, particularidades ecológicas: utilização de composto orgânico, consórcio de cultivos, introdução ou manutenção de espécies vegetais para atração de insetos benéficos, preparo de solo reduzido ou plantio direto, rotação de culturas planejada e eficaz, cultivos de cobertura do solo e adubos verdes, agroflorestas, bordaduras ou cercas vivas planejadas em volta dos cultivos, conservação de matas de galeria, integração da produção vegetal e animal, técnicas naturais e biológicas para controle de pragas, pousio, diversificação de cultivos.

Por princípio, a produção orgânica precisa se valer, em grande medida, das práticas agroecológicas para atingir seus objetivos econômicos, sociais e ambientais, bem como suprir serviços ecossistêmicos (Palomo-Campesino et al., 2018, 2022). No presente estudo, diversas outras práticas foram observadas nas propriedades com produção orgânica como a utilização de biofertilizantes, uso de rochas naturais moídas, compostos orgânicos especiais tais como o Bokashi, uma mistura de farelos vegetais com ou sem adubos orgânicos de origem animal. Na prática, a produção orgânica tende a caminhar para um diferencial, uma melhoria do manejo do solo em comparação às propriedades convencionais, embora se observe que estas últimas, de forma ainda incipiente, vêm adotando práticas que melhoram a QS e a sustentabilidade dos agroecossistemas (Palomo-Campesino et al., 2021; Liebert et al., 2022; Rhioui et al., 2023).

Áreas com produção orgânica ou com alto grau de adoção de práticas agroecológicas e diminuição de insumos sintéticos chamam a atenção pela manutenção da fertilidade do solo e potencial produtivo das culturas (Resende Filho et al., 2019; Teixeira et al., 2021). Nestas áreas, o manejo com práticas agroecológicas, por períodos maiores que 5 anos, pode contribuir para o aumento da fertilidade e maior disponibilização de nutrientes nos solos, a exemplo do fósforo, podendo determinar menores níveis de suficiência de nutrientes (Haneklaus et al., 2005; Stockdale et al., 2006; Bhat et al., 2017). O efeito positivo do manejo agroecológico na QS tem como base o aumento da biodiversidade nos agroecossistemas como um todo, que contribuirá para a sustentabilidade dos mesmos (Teixeira et al., 2021). Desta forma, é possível considerar a possibilidade de que algumas destas áreas de produção orgânica, com adoção mais frequente de práticas agroecológicas, sejam consideradas referências de manejos mais sustentáveis do solo, tanto do ponto de vista ambiental, como também pela manutenção da capacidade produtiva e funções ecossistêmicas do solo em longo prazo e melhoria dos indicadores de QS (Fess and Benedito, 2018; Norris e Congreves, 2018; Xu et al., 2020).

2.3. Atividade enzimática e qualidade dos solos em olericultura

Nos últimos 30 anos, houve expressivos avanços científicos na aplicação dos indicadores biológicos, que permitiram a elaboração de índices e modelos de avaliação da QS (Dick e Tabatabai, 1993; Balota et al., 2004; Kaschuk et al., 2010; Veum et al., 2014; Mendes et al., 2019a; Maurya et al., 2020; Mendes et al., 2021; Chaer et al., 2023).

A atividade da ARIL e GLI tem sido relatada como excelente indicador biológico da QS, pois possui alta sensibilidade às mudanças de manejo do solo, simplicidade e baixo custo para determinação, além de grande capacidade de predição de tendências de melhoria ou redução na QS (Stott et al., 2010; Pritchett et al., 2011; Dick e Burns, 2011; Bhat et al., 2017; Boafo et al., 2019; Mendes et al., 2021). ARIL é uma esterase, catalisadora da hidrólise de ésteres sulfatos, que libera sulfato no solo, elemento essencial para plantas e microrganismos (Klose et al., 2011). GLI é uma exocelulase participante da decomposição da celulose, especificamente na conversão de celobiose em duas moléculas de glicose, uma fonte essencial de energia para microrganismos do solo (Deng e Popova, 2015).

Esta atividade é promovida por enzimas oriundas de microrganismos, plantas, animais e das enzimas abiônticas, que são aquelas que se acumulam ao longo do tempo nos solos protegidas em complexos com argilas e frações da MOS (Wallenstein e Burns, 2011). Este acúmulo de enzimas abiônticas no solo traz uma consequência importante, pois reflete o manejo que vem sendo realizado ao longo do tempo. A existência de ARIL e GLI de origem abiôntica é o motivo pelo qual a atividade dessas enzimas é, em alguns casos, desacoplada dos teores de carbono da biomassa microbiana (Mendes et al., 2019a), assim como ocorre um desacoplamento entre atividade dessas enzimas e o aumento da MOS em estágios iniciais (Mendes et al., 2019a; Chaer et al., 2023). No caso da MOS, essa desconexão possivelmente ocorra devido à dificuldade de detecção de algumas dinâmicas da MO (armazenamento, estabilização, agregação, porosidade), comparada a atividade dessas enzimas, que são muito sensíveis, mostram diferenças em curto período e são de simples determinação (Bandick e Dick, 1999; Dick e Burns, 2011). A atividade dessas enzimas é indicadora de que o manejo do solo está favorecendo o acúmulo ou decréscimo de MOS (Mendes et al., 2019 a).

Nos estudos realizados por Lopes et al. (2013) e Mendes et al. (2019b), as atividades da ARIL e GLI se correlacionaram com o COS e com o rendimento de grãos. Esses estudos contribuíram com a intensa busca de parâmetros e índices de QS, que foram sendo desenvolvidos a partir da constatação de que essas enzimas se correlacionavam com outros atributos microbiológicos do solo (Klose et al., 1999; Chaer e Tótola, 2007, Lopes et al., 2013; Mendes et al., 2019 b). Desta forma, as recentes descobertas sobre a dinâmica de enzimas no solo de Cerrado, o desenvolvimento de indicadores de QS, sua aplicação nos agroecossistemas de grãos (Lopes et al., 2013) e o advento da tecnologia BioAS (Mendes et al. 2019a) possibilitam também a busca de parâmetros de QS para agroecossistemas olerícolas. Isto possibilitará diferenciar manejos que degradam ou melhoram a QS nestas áreas, sendo este um dos aspectos inéditos deste projeto.

Mendes et al. (2021) propuseram uma forma de avaliar a QS integrando a atividade destas enzimas em um índice de qualidade do solo (IQS) denominado FERTBIO. Este índice contempla um IQS biológico relacionado à ciclagem de nutrientes com a determinação da atividade da ARIL e GLI e um IQS químico relacionado ao armazenamento e suprimento de nutrientes, determinando-se capacidade de troca de cátions (CTC), MOS e nutrientes do solo.

Há vários fatores, que podem influenciar a atividade das enzimas, tais como textura, agregação, manejo do solo, disponibilidade e qualidade do substrato, entre outros (Balota et al., 2004; Burns et al., 2013; Mendes et al., 2019a).

Quanto à textura, em solos cultivados, pode não ocorrer correlação entre atividade da ARIL e GLI com os teores de argila do solo (Gianfreda et al., 2005) ou pode haver correlação negativa (Bonanomi et al., 2011). Isto poderia ser explicado pela alta afinidade das moléculas proteicas pelas superfícies de argila com redução da atividade catalítica, podendo restringir a acessibilidade ao substrato, obstruir locais ativos e causar mudanças conformacionais das enzimas (Gianfreda e Ruggiero, 2006; Burns et al., 2013). Por outro lado, a atividade potencial pode ser mantida em alto nível devido à estabilização das enzimas na superfície das argilas (Allison e Jastrow, 2006). O trabalho de Passinato et al. (2021) mostrou variações de comportamento da relação entre a atividade destas enzimas e a textura do solo. Neste estudo, solos da região Centro-Oeste e Nordeste do Brasil não apresentaram correlação entre teores de argila e atividade da GLI, enquanto na região sul essa correlação foi significativa.

Áreas com menores distúrbios ou sistemas com práticas sustentáveis, mais favoráveis à QS, tendem a apresentar maiores atividades enzimáticas (Lopes et al., 2013), e propiciam a predominância de populações fúngicas, significando possivelmente uma integridade funcional do solo com seus serviços ecossistêmicos (Acosta-Martínez et al., 2008; Brennan e Acosta-Martinez, 2019). Piutti et al. (2015) salientaram que a maior parte da atividade da ARIL no solo pode estar mais relacionada às populações fúngicas do que bacterianas.

A produção orgânica tende a caminhar para um diferencial de QS em comparação com as propriedades convencionais. Niemi et al. (2008) observaram maiores atividades da ARIL e GLI em sistemas orgânicos cultivados com rotações de culturas, adubos verdes e composto orgânico em comparação com sistemas convencionais com limitada rotação de culturas e fertilizantes sintéticos, semelhante ao observado por Lagomarsino et al. (2009) em relação à GLI. Maharjan et al. (2017), em seu estudo sobre o impacto de atividades agrícolas sobre a atividade microbiana no solo, concluíram que atividade da ARIL e GLI foi maior em sistemas orgânicos do que em convencionais e que os atributos microbianos devem ser considerados em avaliações e modelos de risco ambiental como indicadores de perturbação do ecossistema causada por práticas de uso e gestão do solo. Entretanto, mesmo entre os sistemas orgânicos, há diferenças de QS e necessidade de se buscar formas de manejo mais conservacionistas, com opções de preparo reduzido do solo, plantio direto de hortaliças, introdução frequente de cultivos de cobertura do solo nas rotações de cultura, que contribuem para a melhoria da QS (Brennan e Acosta-Martinez, 2017; Ferreira et al., 2018; Lima et al., 2018). Em sistemas orgânicos, a QS pode ser mais influenciada pela diversificação das rotações de cultura e adequadas adições de materiais orgânicos do que pela redução do preparo do solo (Pearsons et al., 2023), embora todas essas práticas sejam mais saudáveis para o solo em qualquer sistema produtivo.

Quanto ao preparo de solos nas áreas cultivadas, Kunito et al. (2022) observaram que a razão ARIL/GLI foi significativamente maior em áreas de floresta em comparação às áreas cultivadas, condição atribuída à maior perturbação do sistema solo e menores teores de matéria orgânica dos agroecossistemas. A GLI é indicativa de processos biológicos oxidativos, aumentando temporariamente em sistemas de preparo convencional do solo e em períodos seguintes à incorporação de restos de culturas (Bergstrom et al., 1998; Notaro et al., 2018), situações que ocorrem constantemente nas áreas olerícolas. A GLI pode ter sua atividade fortemente influenciada pelo modo de preparo de solo, qualidade e quantidade de resíduos vegetais e não ser influenciada pela qualidade ou quantidade de adubos orgânicos incorporados ao solo (Pritchett et al., 2011). Em estudo realizado por Mendes et al. (2019 a), as rotações que envolveram duas espécies de *Urochloa* em sistema de PD induziram elevadas atividades da ARIL e GLI, em comparação às áreas com preparos convencionais do solo e se destacaram por proporcionar melhorias significativas na QS.

As quantidades e qualidade das adubações orgânicas são muito estudadas quanto à sua influência na QS, que em geral é positiva (Hepperly et al., 2009; Sissoko & Kpomblekou-A, 2010). O manejo de culturas com composto orgânico, uso frequente de culturas de cobertura resulta em maiores níveis de atividade enzimática (Brennan e Acosta-Martinez, 2019). Bandick e Dick (1999), comparando parcelas com adubações orgânicas e minerais, não observaram diferença significativa na atividade da GLI em parcelas adubadas com nitrogênio (N) mineral em relação às parcelas fertilizadas com adubos orgânicos. Neste mesmo estudo, a ARIL foi significativamente maior nos tratamentos com adubos orgânicos, semelhante ao estudo de Chang et al. (2007). Estudos de Tejada e Benítez (2011) e Igalavithana et al. (2017), com 3 a 10 anos de contínua aplicação de fertilizantes orgânicos, respectivamente, mostraram aumento da atividade da ARIL e GLI nas áreas com adubação orgânica comparadas às áreas com adubação mineral. Segundo os autores, a ciclagem de nutrientes pode ser mais intensa em solos submetidos aos manejos com fertilizantes naturais, pelo maior estímulo da atividade microbiana, além do insumo poder conter enzimas intra e extracelulares. Adubações orgânicas constantes podem ter efeito em curto prazo graças a biodegradação dos materiais orgânicos adicionados, que geram substratos potenciais para atividade enzimática (Bastida et al., 2008; Bonanomi et al., 2014). Em longo prazo, pode haver aumento da atividade das enzimas, que vão sendo adsorvidas por substâncias húmicas, bem como aumento e diversificação das populações de fungos e bactérias (Bastida et al., 2008).

A produtividade das culturas em solos onde boas práticas de manejo foram adotadas (rotação de culturas, plantas de cobertura, adubação verde, plantio direto, adubações orgânicas e minerais equilibradas) pode ser um bom indicador de sustentabilidade agrícola, pois reflete níveis adequados de MOS, agregação, infiltração, pH, nutrientes, atividade biológica (Oldfield et al., 2022). No entanto, essa estratégia viabiliza-se com menor dificuldade para cultivos específicos como soja, milho e quando há possibilidade de acompanhamento de um gradiente contínuo de produtividades com o objetivo de desenvolver e interpretar indicadores individuais de QS. Mas, devido à diversidade das culturas olerícolas, interpretar indicadores de QS com base nas produtividades pode ser muito difícil. Desta forma, novas estratégias de utilização de indicadores para avaliar estes sistemas produtivos devem ser desenvolvidas.

Na busca de abordagens que pudessem atender aos requisitos de diversidade e complexidade dos sistemas olerícolas, o modelo de Avaliação Abrangente da Saúde do Solo (CASH) (Moebius-Clune et al., 2016) juntamente com o modelo de quatro quadrantes (4QM) proposto por Chaer et al. (2023) apresentam-se como promissoras estratégias. Estas abordagens focam nos resultados líquidos apresentados pelos indicadores (COS, ARIL e GLI) de acordo com as práticas de manejo adotadas, viabilizando analisar o conjunto de manejos trabalhados, sem necessidade de acompanhamento de produtividades. Mas, é importante salientar que áreas com boas práticas de manejo de solo (plantio direto, manutenção de cobertura viva ou morta do solo, rotação de culturas com maior diversificação incluindo leguminosas) e com altas produtividades podem apresentar elevadas atividades de ARIL e GLI (Lopes et al., 2013; Passinato et al., 2021). Boas produtividades vêm de solos saudáveis, com boa fertilidade natural, equilibrados quimicamente, bem estruturados, biologicamente ativos e biodiversos, solos supressivos (Mendes et al., 2019a; Anghinoni e Vezzani, 2021).

Além das melhores produtividades, o aumento da atividade destas enzimas em solos bem manejados e produtivos tem relação com processos importantes no agroecossistema: degradação de inseticidas no solo como bifentrina e permetrina (Portilho et al., 2014); aumento da concentração de flavonoides e proteínas na soja (Anghinoni et al., 2021) e aumento da biodiversidade do solo, incluindo gêneros de microrganismos benéficos tais como *Bacillus, Penicillium, Trichoderma, Pseudomonas, Bradyrhizobium and Rhizobium* (Passinato et al., 2021). Neher et al., (2017) relataram que as enzimas GLI e quitinase podem ser ótimas indicadoras de supressividade à *Rhizoctonia solani* e que o composto orgânico maturado ou vermicomposto aumentam a atividade dessas enzimas e promovem a supressão a esse fitopatógeno. Assim, a atividade da ARIL e GLI tem relação com a saúde do solo em seu sentido amplo como nos conceitos propostos por Doran e Parkin (1994), Doran e Zeiss (2000), Lal (2016) e Anghnoni e Vezzani (2021).

Com a abordagem 4QM é possível verificar diferentes padrões indicativos do manejo e QS em uma determinada área, independente do conhecimento do histórico de manejo anterior (Chaer et al., 2023). Neste modelo de avaliação da QS, se o solo está: i) no quadrante 1 (Q1) com alta AEM e alto COS, significa estabilidade com solo sadio e alta QS; ii) no quadrante 2 (Q2) com baixa AEM e alto COS, significa que está em transição, perdendo qualidade e com tendência de perda de C; iii) no quadrante 3 (Q3) com baixa AEM e baixo COS, representa estabilidade com solo doente e baixa QS; iv) no quadrante 4 (Q4) com alta AEM e baixo COS, representa transição, ganhando qualidade, com tendência de ganho de C. Nos quadrantes Q2 e Q4, que se referem aos momentos de transição, a atividade enzimática média se reduz ou cresce antes do COS, respectivamente. É por este motivo que a diminuição ou aumento da atividade enzimática, ao longo do tempo, pode ser um indicativo de que o sistema está favorecendo a perda ou acúmulo de MOS, respectivamente (Mendes et al., 2019a).

A abordagem CASH consiste no desenvolvimento de curvas de pontuação entre 0 e 100 para os parâmetros de SS, estimando sua função de distribuição normal cumulativa (DNC) usando a média e os desvios padrão de um grupo de amostras de solo. As curvas de pontuação baseadas no DNC podem ser muito úteis para estabelecer valores de referência para indicadores de SS em situações em que os dados de produtividade dos cultivos não estejam disponíveis (Moebius-Clune et al., 2016).

2.4. Frações da matéria orgânica e qualidade do solo em olericultura

Um dos desafios para o cultivo de hortaliças é a necessidade de preservação da QS, a qual pode sofrer declínios devido à intensidade de preparo do solo e ausência de práticas benéficas ao solo (Valarini et al., 2011; Lima et al., 2018), com reflexos diretos na atividade biológica e COS. A MOS pode ser considerada como um reservatório de C em diferentes estados de proteção contra a decomposição, a depender de sua composição, das condições ambientais predominantes, manejos, composição mineralógica do solo, atividade microbiana e das enzimas do solo.

As substâncias húmicas são compostos relativamente estáveis, considerados reservatórios de C e de intrínseca recalcitrância natural (Grinhut et al., 2007) e contém ácidos húmicos (AH), ácidos fúlvicos (AF) e humina (HU). Sendo frações mais estáveis da MOS, podem representar 80% ou mais da MOS total (Guimarães et al., 2013; Souza et al., 2016). Em relação aos ácidos fúlvicos, os ácidos húmicos possuem maior peso molecular, maior grau de polimerização, menor biodegradabilidade e maior conteúdo de C, N e Hidrogênio (H), além de gerarem maior CTC (Canellas et al., 2003; Cunha et al., 2005). A relação entre essas frações pode ser utilizada como indicadora da qualidade da MOS e pode ajudar a diferenciar sistemas que adotam boas práticas de manejo do solo (BPMS) daqueles menos adotantes. Se os valores de AH são maiores que os de AF, isso dá indicação de boa QS, ou seja, solos com bons índices de humificação, maior CTC. Relações menores do que 1 podem indicar evolução limitada da matéria orgânica devido a razões edáficas, de manejo ou aportes recentes de matéria orgânica (Cunha et al., 2005).

Embora a busca por sistemas sustentáveis de produção tenha como uma de suas principais estratégias a preservação da MOS, seu teor total é considerado menos sensível do que suas frações para detectar mudanças no manejo e avaliar a QS. A MOS pode ter boa performance como indicador de QS nas comparações entre manejos quando as diferenças ficam acima de 0,5% (Hargreaves et al., 2019), o que limitaria a detecção de mudanças ou tendências da QS quando as diferenças de valores fossem mais estreitas. As frações lábeis da MOS têm sido citadas como alternativas adequadas para o acompanhamento das alterações provocadas por práticas de manejo (Souza et al., 2016; Bongiorno et al., 2019; Kunde et al., 2020), mudanças estas, às vezes difíceis de identificar por medição do carbono orgânico total (COT) (Haynes, 2005). Hargreaves et al. (2019) detectaram grande sensibilidade, repetibilidade e consistência do carbono lábil, oxidável em $KMnO_4$, corroborado por Plaza-Bonilla et al., (2014) e Bongiorno et al. (2019).

Outra fração muito sensível e utilizada em estudos como parâmetro para detectar mudanças adotadas nas práticas agrícolas de manejo do solo é o carbono orgânico particulado (COP) (Duval et al., 2013; Bongiorno et al., 2019; Jiao et al., 2020). Figueiredo et al. (2010) estudaram o efeito do plantio direto (PD), preparo convencional (PC) e reduzido (PR) do solo nas frações lábeis e estáveis da MOS tendo o cerrado nativo e a pastagem como referências. Os autores observaram os maiores teores de COP no cerrado e pastagem e que esta fração foi superior no PD em relação ao PC e PR. Além disso, o COP foi a fração mais sensível na diferenciação entre os manejos. Souza et al. (2016) também observaram elevada sensibilidade das frações lábeis de carbono e maiores teores de COP em PD em relação ao PC. Além da sensibilidade, esta fração pode se correlacionar com a produtividade de culturas como soja e milho (Woomer et al., 2000; Sharma et al., 2017).

BPMS, comuns em processos de transição agroecológica ou em áreas de produção orgânica como as citadas por Teixeira et al. (2018) e Palomo-Campesino et al. (2021), tendem a favorecer o aumento das frações lábeis e estáveis da MOS. Por exemplo, a utilização de composto orgânico ao invés de estercos puros, adubação verde e práticas que aportem resíduos vegetais ao solo aumentam a produtividade das culturas, o crescimento radicular, a CTC, disponibilidade de nutrientes e melhoram as características da matéria orgânica humificada, aumentando o estoque de C em frações mais estáveis (Canellas et al., 2005; Adeli et al., 2017; Kumar et al., 2018; Meza et al., 2022; Ouyang et al., 2022; Matos et al. 2023). Este aumento provocado pela adoção das BPMS tende a aproximar os teores das frações lábeis e estáveis aos de áreas nativas (Li et al., 2018). Em longo prazo, adubações orgânicas constantes podem aumentar significativamente o COP quando comparada a parcelas que só recebem adubações minerais nitrogenadas, melhorando os atributos físicos e químicos do solo e em consequência, sua fertilidade (Hoover et al., 2019). Além disso, diferenças também podem ser observadas nas frações de C do solo quando o sistema recebe correções adequadas de adubos fosfatados (Ratke et al., 2021; Souza et al., 2016).

Vários estudos têm demonstrado grandes benefícios para a QS pelo uso de adubação verde e culturas de cobertura com diferentes famílias botânicas, bem como sua inclusão nas rotações de culturas. Souza et al. (2019) trabalhando com feijão de porco (*Canavalia ensiformes*) demonstraram a capacidade desse adubo verde em aumentar COS e as frações AH, AF, HU consistentemente até 20 cm de profundidade. É possível que isto ocorra devido à elevada quantidade de compostos ricos em C oriundo desta leguminosa e à capacidade de biossíntese de compostos húmicos pela riqueza da biota alcançada em solos assim manejados. Corroborando tais observações, frações mais estáveis de C, como o carbono orgânico associado aos minerais (COM), mas também frações mais lábeis como o COP intra-microagregado foram aumentadas pelo uso de leguminosas como adubos verdes (Yao et al., 2019). Cunha et al. (2016) observaram que uma mistura contendo 25% leguminosas e 75% de não leguminosas (adubos verdes) consorciadas ao cultivo de manga (*Mangifera indica*) minimizou perdas de C da MOS e aumentou o teor de substâncias húmicas.

Outro aspecto interessante observado nos estudos de Cunha et al. (2016) e Souza et al. (2016) foi a capacidade diferenciada das plantas de cobertura do solo em promover mudanças na composição das substâncias húmicas. Tal conclusão foi corroborada por Coelho et al. (2013), que observaram que o calopogônio (*Calopogonium mucunoides*) promoveu maiores teores de AF com baixo teor de C e maior de oxigênio, ou seja, com menor estabilidade estrutural e mais fácil mineralização. Por outro lado, o estilosantes (*Stylozanthes guyanensis*) e a mucuna preta (*Stizolobium aterrimum*) favoreceram a formação de AF com maior estabilidade estrutural, que possibilitam maior cobertura do solo. Ainda sobre as culturas de cobertura e rotação de culturas, o gênero *Urochloa* tem despertado interesse por sua possibilidade de rotação com cultivos de grãos e seu potencial como melhorador das propriedades físicas, químicas e biológicas do solo. A rotação Soja/Braquiária (*Glycine max*/*Urochloa ruziziensis*) pode ser responsável por aumentos no estoque de C em todo o perfil do solo, bem como aumento da fração COP, diferenciando-se de outras rotações (Rossi et al., 2012). Estes autores também confirmaram a eficácia do COP para evidenciar diferenças de manejo do solo. Ferreira et al. (2018), utilizando diversificado esquema de rotação de culturas contendo gramíneas, leguminosas e brassicaceas em sistema de PD de hortaliças, observaram aumento substancial do COP nestes sistemas.

Muitos estudos são dedicados à tentativa de compreender a dinâmica das frações lábeis e estáveis da MOS a partir dos sistemas de preparo de solo para plantio de grãos e mais recentemente para o cultivo de hortaliças. É de se esperar que haja decréscimo progressivo no conteúdo das frações humificadas a partir da substituição de florestas por cultivos (Spaccini et al., 2006), que pode ser devido à oxidação biológica da MOS, previamente protegida nos agregados do solo, que passam a ser destruídas pelo uso de implementos (Canellas et al., 2005). Os AH, mais do que os AF e HU, podem ser afetados pelo excessivo preparo do solo, afetando consideravelmente suas propriedades. Isto pode ocorrer devido à grande participação dos AH na maioria das reações que ocorrem no solo, na agregação e estabilidade de agregados (Canellas et al. 2005).

Apesar da relativa estabilidade das frações húmicas da MOS, é possível promover mudanças nos teores de AH, AF e HU ao longo do perfil do solo por meio de manejos e correções adequadas. A formação de AH e HU, por exemplo, é favorecida em sistemas com menor perturbação do solo, maior aporte de resíduos vegetais, adubos orgânicos e adubação verde, o que nem sempre ocorre com AF (Canellas et al., 2005; Souza et al., 2014; Melo et al., 2016; Mi et al., 2019). A maior polimerização de compostos húmicos em sistemas menos perturbados e diversificados e a maior porosidade dos solos nessas áreas, facilitam a translocação de AF para camadas abaixo de 10 cm de profundidade (Loss et al., 2010). Souza et al. (2016), concluíram que adubações fosfáticas constantes e o uso do milheto como planta de cobertura no PD, após 11 anos, promoveram significativo aumento dos teores de substâncias húmicas na camada de 0 a 5 cm do solo em comparação ao PC, estratificando o perfil do solo em relação às substâncias húmicas. Pode-se inferir que o aporte de resíduos orgânicos, que alimenta o processo de humificação, promova melhoria dos atributos do solo e garanta ao agricultor a manutenção da fertilidade do sistema produtivo.

Sistemas de PD em hortaliças ou de preparo reduzido têm sido recomendados e estimulados em vários estudos, inclusive com o desenvolvimento de métodos para avaliar a QS nestes sistemas (Comin et al., 2020). São práticas que fortalecem a estrutura do solo e podem induzir ao acúmulo de grande parte do C na forma de COM, bem como aumentar os estoques de COP oclusos em agregados estáveis (Lima et al., 2016). No estudo de Rosset et al. (2016), as frações mais lábeis de C e seu estoque nas frações humificadas, principalmente HU, aumentaram após 22 anos de implantação do PD, resultado da menor perturbação do solo e do maior aporte de resíduos em superfície. Melo et al. (2016) também concluíram que o PD de repolho (*Brassica oleracea*, var. capitata) proporcionou aumento do estoque de C no solo, bem como de COP, substâncias húmicas e C associado aos minerais.

Outras práticas agroecológicas podem influenciar no acúmulo e dinâmica do C no solo. Os estudos de Yadav et al. (2021) revelaram que o estabelecimento de SAF em terras degradadas aumentou a quantidade de C, suas frações lábeis e estáveis e teve um efeito considerável na QS em comparação aos solos sob terras em monocultivo podendo viabilizar cultivo simultâneo de árvores multiuso, horticultura e outros usos, semelhante ao observado por Matos et al. (2023) e Melkani et al. (2024) em estudos com sistemas agroflorestais.

Finalmente, é importante salientar que correlações importantes podem ser encontradas entre frações lábeis da MOS e atividade enzimática da ARIL e GLI, provavelmente devido à formação de complexos húmus-enzima ou argila-enzima e à maior atividade de microrganismos induzida pelas frações mais lábeis de C (Kalambukattu et al., 2013). A maior quantidade de resíduos provenientes de composto orgânico, adubos verdes, rotações de cultura, cobertura do solo tendem a aumentar as frações lábeis da MOS, garantindo nutrientes e energia para os microrganismos (Lal, 2016), aumentando a biomassa microbiana do solo e a atividade da ARIL e GLI (Hok et al., 2018).

3. Objetivos

3.1. Objetivo geral

Estabelecer parâmetros biológicos e identificar indicadores da MOS, que permitam avaliar a qualidade dos solos em agroecossistemas olerícolas do cerrado brasileiro.

3.2. Objetivos específicos

a. Estabelecer modelos para interpretação dos resultados de atividade das enzimas ARIL, GLI, dos teores de COS visando a avaliação da QS em áreas sob produção orgânica e convencional de hortaliças;
b. Avaliar sistemas orgânicos e convencionais de produção de hortaliças em áreas de produção comercial quanto à adoção de BPMS e relações entre frações da MOS e indicadores biológicos de QS;
c. Identificar frações lábeis e estáveis da MOS, que possam diferenciar e expressar a QS em diferentes sistemas de produção de hortaliças;

4. Hipóteses

a. Combinando a abordagem CASH e 4QM será possível desenvolver uma ferramenta de avaliação da saúde do solo simples, prática e robusta para sistemas de produção de hortaliças em solos tropicais;
b. A adoção de BPMS em sistemas orgânicos melhora a QS ao aumentar a atividade biológica e as frações lábeis e estáveis da MOS.
c. As frações da MOS são potenciais indicadoras dos impactos das práticas adotadas na produção de hortaliças;

5. Referências bibliográficas

Acosta-Martínez, V., Acosta-Mercado, D., Sotomayor-Ramírez, D., Cruz-Rodríguez, L., 2008. Microbial communities and enzymatic activities under different management in semiarid soils. Appl. Soil Ecol. 38, 249–260. https://doi.org/10.1016/ j.apsoil. 2007.10.012

Adeli, A., Read, J., Feng, G., McGrew, R., Jenkins, J., 2017. Organic Amendments and Nutrient Leaching in Soil Columns. Agron. J. 109, 1294–1302. https://doi.org/ 10.2134/agronj2016.11.0634

Allison, S.D., Jastrow, J.D., 2006. Activities of extracellular enzymes in physically isolated fractions of restored grassland soils. Soil Biology and Biochemistry 38, 3245–3256. https://doi.org/10.1016/j.soilbio.2006.04.011

Altieri, M.A., Nicholls, C.I., Henao, A., Lana, M.A., 2015. Agroecology and the design of climate change-resilient farming systems. Agron. Sustain. Dev. 35, 869–890. https://doi.org/10.1007/s13593-015-0285-2

Anghinoni, G.; Anghinoni, F.B.G.; Tormena, C.A.; Braccini, A.L.; Mendes, I.C.; Zancanaro, L.; Lal, R., 2021. Conservation agriculture strengthen of Brazilian grain production and food security. Land Use Policy 108. https://doi.org/10.1016/j.landusepol.2021.105591

Anghinoni, I.; Vezzani, F.M., 2021. Fertilidade Sistêmica do Solo como produto da auto-organização do sistema resultante do manejo. Rev. Bras. Cienc. Solo 45:e0210090. https://doi.org/10.36783/18069657rbcs20210090

Balota, E.L., Kanashiro, M., Colozzi Filho, A., Andrade, D.S., Dick, R.P., 2004. Soil enzyme activities under long-term tillage and crop rotation systems in subtropical agro-ecosystems. Braz. J. Microbiol. 35, 300–306. https://doi.org/10.1590/S1517-83822004000300006

Bandick, A.K.; Dick, R.P., 1999. Field management effects on soil enzyme activities. Soil Biol. Biochem. 31, 1471–1479. doi: 10.1016/S0038-0717(99)00051-6

Bastida, F., Kandeler, E., Hernández, T., García, C., 2008. Long-term Effect of Municipal Solid Waste Amendment on Microbial Abundance and Humus-associated Enzyme Activities Under Semiarid Conditions. Microb. Ecol. 55, 651–661. https:// doi.org/10.1007/s00248-007-9308-0

Bergstrom, D.W., Monreal, C.M., King, D.J., 1998. Sensitivity of Soil Enzyme Activities to Conservation Practices. Soil Sci. Soc. Am. J. 62, 1286–1295. https://doi.org/10.2136/sssaj1998.03615995006200050020x

Bhat, N.A., Riar, A., Ramesh, A., Iqbal, S., Sharma, M.P., Sharma, S.K., Bhullar, G.S., 2017. Soil Biological Activity Contributing to Phosphorus Availability in Vertisols under Long-Term Organic and Conventional Agricultural Management. Front. Plant Sci. 8, 1523. https://doi.org/10.3389/fpls.2017.01523

Bíla, P.; Sarapatka, B.; Horňák, O.; Novotná, J.; Brtnický, M., 2020. Which quality indicators reflect the most sensitive changes in the soil properties of the surface horizons affected by the erosion processes? Soil Water Res. 15, 116-124. http://dx.doi.org/ 10.17221/71/2019-swr

Boafo, D. K.; Kraisornpornson, B.; Panphon, S.; Owusu, B.E.; Amaniampong, P.N., 2020. Effect of organic soil amendments on soil quality in oil palm production. Appl. Soil Ecol. 147, 1-20 http://dx.doi.org/10.1016/j.apsoil.2019.09.008

Bonanomi, G., D'Ascoli, R., Antignani, V., Capodilupo, M., Cozzolino, L., Marzaioli, R., Puopolo, G., Rutigliano, F.A., Scelza, R., Scotti, R., Rao, M.A., Zoina, A., 2011. Assessing soil quality under intensive cultivation and tree orchards in Southern Italy. Appl. Soil Ecol. 47, 184–194. https://doi.org/10.1016/j.apsoil.2010.12.007

Bonanomi, G., D'Ascoli, R., Scotti, R., Gaglione, S.A., Caceres, M.G., Sultana, S., Scelza, R., Rao, M.A., Zoina, A., 2014. Soil quality recovery and crop yield enhancement by combined application of compost and wood to vegetables grown under plastic tunnels. Agric. Ecosyst. Environ. 192, 1–7. https://doi.org/ 10.1016/ j. agee.2014.03.029

Bongiorno, G.; Bünemann, E.K.; Oguejiofor, C.U.; Meier, J.; Gort, G.; Comans, R.; Mäder, P.; Brussaard, L.; Goede, R., 2019. Sensitivity of labile carbon fractions to tillage and organic matter management and their potential as comprehensive soil quality indicators across pedoclimatic conditions in Europe. Ecol. Indic. 99, 38-50. http://dx.doi.org/10.1016/j.ecolind.2018.12.008

Brennan, E.B., Acosta-Martinez, V., 2017. Cover cropping frequency is the main driver of soil microbial changes during six years of organic vegetable production. Soil Biol. Biochem. 109, 188–204. https://doi.org/10.1016/j.soilbio.2017.01.014

Brennan, E.B., Acosta-Martinez, V., 2019. Cover Crops and Compost Influence Soil Enzymes during Six Years of Tillage-Intensive, Organic Vegetable Production. Soil Sci. Soc. Am. J. 83, 624–637. https://doi.org/10.2136/sssaj2017.12.0412

Bünemann, E.K.; Bongiorno, G.; Baic, Z.; Creamer, R.E; Deyn, G.; Goede, R.; Fleskensd, L.; Geissend, V.; Kuyper, T.W.; Mädera, P.; Pulleman, M.; Sukkelf, W.; Groenigenb, J.W.V.; Brussaard, L. (2018) Soil quality – A critical review. Soil Biol. Biochem. 120, 105-125. https://doi.org/10.1016/j.soilbio.2018.01.030

Burns, R.G., DeForest, J.L., Marxsen, J., Sinsabaugh, R.L., Stromberger, M.E., Wallenstein, M.D., Weintraub, M.N., Zoppini, A., 2013. Soil enzymes in a changing environment: Current knowledge and future directions. Soil Biol. Biochem. 58, 216–234. https://doi.org/10.1016/j.soilbio.2012.11.009

Canellas, L.P.; Velloso, A.C.X.; Marciano, C.R.; Ramalho, J.F.G.P.; Rumjanek, V.M.; Rezende, C.E.; Santos, G.A., 2003. Propriedades químicas de um Cambissolo cultivado com cana-de-açúcar, com preservação do palhiço e adição de vinhaça por longo tempo. Rev. Bras. Ciênc. Solo 27, 935–944. https://doi.org/10.1590/S0100-06832003000500018

Canellas, L.P.; Busato, J.G.; Caume, D.J. O uso e manejo da matéria orgânica humificada sob a perspectiva da Agroecologia. In: Canellas, L.P. e Santos, G.A. (ed.) Humosfera: tratado preliminar sobre a química das substâncias húmicas. Campos dos Goytacazes: L. P. Canellas, G.A. Santos, 2005. p.244-267. Disponível em: https://www.gov.br/agricultura/pt-br/assuntos/insumos-agropecuarios/insumos-agricolas/fertilizantes/publicacoes-fertilizantes/humosfera.pdf. Acesso em: 07 out. 2024

Carneiro, R.G., Mendes, I. de C., Lovato, P.E., Carvalho, A.M. de, Vivaldi, L.J., 2004. Indicadores biológicos associados ao ciclo do fósforo em solos de Cerrado sob plantio direto e plantio convencional. Pesq. agropec. bras. 39, 661–669. https://doi.org/10.1590/S0100-204X2004000700007

Carneiro, R.G., Figueiredo, C.C.D., Malaquias, J.V., Mendes, I.C., 2024. A soil health assessment tool for vegetable cropping systems in tropical soils based on beta-glucosidase, arylsulfatase, and soil organic carbon. Appl. Soil Ecol. 198, 105394. https://doi.org/10.1016/j.apsoil.2024.105394

Chabbi, A., Rumpel, C., Hagedorn, F., Schrumpf, M., Baveye, P.C., 2022. Editorial: Carbon Storage in Agricultural and Forest Soils. Front. Environ. Sci. 10. https://doi.org/10.3389/fenvs.2022.848572

Chaer, G.M., Tótola, M.R., 2007. Impacto do manejo de resíduos orgânicos durante a reforma de plantios de eucalipto sobre indicadores de qualidade do solo. Rev. Bras. Ciênc. Solo 31, 1381–1396. https://doi.org/10.1590/s0100-06832007000600016

Chaer, G.M., Mendes, I.C., Dantas, O.D., Malaquias, J.V., Dos Reis Junior, F.B., Oliveira, M.I.L., 2023. Evaluating C trends in clayey Cerrado Oxisols using a four-quadrant model based on specific arylsulfatase and β-glucosidase activities. Appl. Soil Ecol. 183, 104742. https://doi.org/10.1016/j.apsoil.2022.104742

Chang, E.-H., Chung, R.-S., Tsai, Y.-H., 2007. Effect of different application rates of organic fertilizer on soil enzyme activity and microbial population. Soil Sci. Plant Nutr. 53, 132–140. https://doi.org/10.1111/j.1747-0765.2007.00122.x

Coelho, M.S.; Mendonça, E.S.; Lima, P.C.; Guimarães, G.P.; Cardoso, I.M., 2013 Qualidade da matéria orgânica de solos sob cultivo de café consorciado com adubos verdes. Rev. Bras. Ciênc. solo 37, 1576-1586.

Comin, J.J.; Fayad, J.A.; Kurtz, C.; Mafra, A.L.; Curmi, P. (2020) Guia prático de avaliação participativa da qualidade do solo em Sistema de Plantio Direto de Hortaliças (SPDH). 2. ed.; UFSC: Florianópolis, Brasil; 20 p.

CNA - Confederação da Agricultura e Pecuária do Brasil, 2017. Mapeamento e qualificação da cadeia produtiva das hortaliças do Brasil. Brasília: CNA 2017. 79p. Disponível em: https://www.cnabrasil.org.br/assets/arquivos/bibliotecas/livro_final3_mapeamento_e_quantificacao_da_cadeia_de_hortalicas_08.pdf. Acesso em: 16 set. 2024.

CNA - Confederação da Agricultura e Pecuária do Brasil, 2024**.** VBP da agropecuária deve cair 2,6% em 2023**.** Brasília: CNA. Disponível em: https:// www. cnabrasil. org.br/publicacoes/vbp-da-agropecuaria-deve-cair-2-6-em-2023. Acesso em: 16 set. 2024.

Cunha T.J.F.; Canella, L.P.; Santos, G.A.; Ribeiro, L.P. Fracionamento da matéria orgânica humificada em solos brasileiros. In: Canellas, L.P.; Santos, G.A. Humosfera: tratado preliminar sobre a química das substâncias húmicas. Campos dos Goytacazes: L. P. Canellas, G.A. Santos, 2005. p.54-80. Disponível em: https://www.gov.br/agricultura/pt-br/assuntos/insumos-agropecuarios/insumos-agricolas/fertilizantes/publicacoes-fertilizantes/humosfera.pdf. Acesso em: 07 out. 2024.

Cunha, T.J.F; Giongo, V.; Salviano, A.M.; Marques, F.A.; Canellas, L.P. (2016) Humified fraction of organic matter due to plant mixture cultivation. Rev. Caatinga 29, 3. https://doi.org/10.1590/1983-21252016v29n307rc

Deng, S., Popova, I., 2015. Carbohydrate Hydrolases, in: Dick, R.P. (Ed.), SSSA Book Series. American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, Madison, WI, USA, pp. 185–209. https://doi.org/10.2136/sssabookser9.c9

Dick, W.A.; Tabatabai, M.A. Significance and potential uses of soil enzymes. In: Metting Junior., F.B. (ed). Soil microbial ecology applications in agricultural and environmental management. New York: M. Dekker, 1993, p.95-127

Dick R.P.; Burns R.G. A brief history of soil enzyme research. In: Dick R.P. (ed). Methods of soil enzymology. Madison: Soil Sci. Soc. Am. 2011. p. 1-19

Doran, J. W.; Parkin, T. B. Defining and assessing soil quality. In: Doran J. W; Coleman, D.C.; Bezdicek, D.F.; Stewart, B.A., Eds. Defining soil quality for a sustainable environment. Madison: Soil Sci. Soc. Am. J., 1994, p. 3-21. http://dx.doi.org/10.2136/sssaspecpub35.c1

Doran, J.W.; Zeiss, M.R. (2000) Soil Health and sustainability: management th biotic component of soil quality. Appl. Soil Ecol. 15, 3-11

Duval, M.E.; Galantini, J.A.; Iglesias, J.O.; Canelo, S.; Martinez, J.M.; Wall, L., 2013. Analysis of organic fractions as indicators of soil quality under natural and cultivated systems. Soil Till. Res., 131,11-19. http://dx.doi.org/10.1016/ j.still.2013.03.001.

Duval, M.E.; Galantini, J.A.; Martínez, J.M.; Limbozzi, F., 2018. Labile soil organic carbon for assessing soil quality: influence of management practices and edaphic conditions. Catena 171, 316-326. http://dx.doi.org/10.1016/ j.catena. 2018.07.023

Emater-DF. Valor bruto de produção agropecuária. Brasília: Emater-DF, 2024a, 15p. Disponível em: https://emater.df.gov.br/informacoes-agropecuarias-do-distrito-federal/. Acesso em: 16 set. 2024.

Emater-DF. Programa de olericultura. Brasília: Emater-DF, 2024b. Disponível em https://www.emater.df.gov.br/programa-de-olericultura/. Acesso em 03 Dez. 2024.

FAO, 2022. Healthy soils for a healthy people and planet: FAO calls for reversal of soil degradation [WWW Document]. Newsroom. URL https://www.fao.org/ newsroom/detail/agriculture-soils-degradation-FAO-GFFA-2022/ acesso em: 13 set. 2024.

Feiden. A. Agroecologia: Introdução e conceitos. In Aquino, A.M.; Assis, R.L. (org.). Agroecologia: Princípios e técnicas para uma agricultura orgânica sustentável. Brasília-DF: Embrapa Informação tecnológica, 2005, p. 49-70.

Ferreira, L.B., Loss, A., Giumbelli, L.D., Ventura, B.S., Souza, M., Mafra, Á.L., Kurtz, C., Comin, J.J., Brunetto, G., 2018. Organic carbon and nitrogen contents and their fractions in soils with onion crops in different management systems. Soil Res. 56, 846. https://doi.org/10.1071/SR18167

Fess, T., Benedito, V., 2018. Organic versus Conventional Cropping Sustainability: A Comparative System Analysis. Sustainability 10, 272. https://doi.org/10.3390/ su10010272

Figueiredo, C.C.D., Resck, D.V.S., Carneiro, M.A.C., 2010. Labile and stable fractions of soil organic matter under management systems and native cerrado. Rev. Bras. Ciênc. Solo 34, 907–916. https://doi.org/10.1590/S0100-06832010000300032

Gaitán-Cremaschi, D., Klerkx, L., Duncan, J., Trienekens, J.H., Huenchuleo, C., Dogliotti, S., Contesse, M.E., Rossing, W.A.H., 2019. Characterizing diversity of food systems in view of sustainability transitions. A review. Agron. Sustain. Dev. 39, 1. https://doi.org/10.1007/s13593-018-0550-2

Gianfreda, L., Antonietta Rao, M., Piotrowska, A., Palumbo, G., Colombo, C., 2005. Soil enzyme activities as affected by anthropogenic alterations: intensive agricultural practices and organic pollution. Sci. Total Environ. 341, 265–279. https://doi.org/10.1016/j.scitotenv.2004.10.005

Gianfreda, L., Ruggiero, P., 2006. Enzyme Activities in Soil, in: Nannipieri, P., Smalla, K. (Eds.), Nucleic Acids and Proteins in Soil, Soil Biology. Springer Berlin Heidelberg, pp. 257–311. https://doi.org/10.1007/3-540-29449-X_12

Grinhut, T.; Hadar, Y.; Chen, Y., 2007. Degradation and transformation of humic substances by saprotrophic fungi: processes and mechanisms. Fungal Biol. Rev. 21, 179-189. DOI:10.1016/j.fbr.2007.09.003

Guimarães, D.V., Gonzaga, M.I.S., Da Silva, T.O., Da Silva, T.L., Da Silva Dias, N., Matias, M.I.S., 2013. Soil organic matter pools and carbon fractions in soil under different land uses. Soil Till. Res. 126, 177–182. https://doi.org/10.1016/j.still.2012.07.010.

Haneklaus, S., Schnug, E., Paulsen, H.M., Hagel, I., 2005. Soil Analysis for Organic Farming. Commun. Soil Sci. Plant Anal. 36, 65–79. https://doi.org/10.1081/CSS-200042968

Hargreaves, S.K.; Dejong, P.; Laing, K.; Mcquail, T.; Van Eerd, L.L., 2019. Management sensitivity, repeatability, and consistency of interpretation of soil health indicators on organic farms in southwestern Ontario. Can. J. Soil Sci. 99, 508-519. http://dx.doi.org/10.1139/cjss-2019-0062

Haynes, R. J., 2005. Labile organic matter fractions as central components of the quality of agricultural soils: an overview. Adv. Agron. 85, 221 - 268.

Hepperly, P., Lotter, D., Ulsh, C.Z., Seidel, R., Reider, C., 2009. Compost, manure and synthetic fertilizer influences crop yields, soil properties, nitrate leaching and crop nutrient content. Compost Sci. Util. 17, 117–126. https://doi.org/10.1080/1065657X.2009.10702410

Hoover, N.L.; Lawb, J.Y.; Longa, L.A.M.; Kanwarc, R.S.; Soupird, M.L., 2019. Long-term impact of poultry manure on crop yield, soil and water quality, and crop revenue. J. Environ. Manage**.** 252, 1-11. https://doi.org/10.1016/ j.jenvman.2019.109582

Igalavithana, A., Lee, S., Niazi, N., Lee, Y.-H., Kim, K., Park, J.-H., Moon, D., Ok, Y., 2017. Assessment of Soil Health in Urban Agriculture: Soil Enzymes and Microbial Properties. Sustainability 9, 310. https://doi.org/10.3390/su9020310

Jiao, S.; Li J.; Li Y.; Xu Z.; Kong, B.; Li, Y.; Shen, Y. Variation of soil organic carbon and physical properties in relation to land uses in the Yellow River Delta, China. Sci. Rep**.** 10 (1), 20317. http://dx.doi.org/10.1038/s41598-020-77303-8

Johnston, A.E., Poulton, P.R., Coleman, K., 2009. Chapter 1 Soil Organic Matter, in: Advances in Agronomy. Elsevier, pp. 1–57. https://doi.org/10.1016/S0065-2113(08)00801-8

Kalambukattu, J.G., Singh, R.D., Patra, A.K., Arunkumar, K., Pote, J., 2013. Land use practices in the Central Himalayan region affect soil enzyme activities and their relationship with carbon pools. Acta Agr. Scand. B-S P 63, 403–408. https://doi.org/10.1080/09064710.2013.789124

Kaschuk, G.; Alberton, O.; Hungria, M. (2010) Three decades of soil microbial biomass studies in Brazilian ecosystems: lessons learned about soil quality and indications for improving sustainability. Soil Biol. Biochem. 42, 1-13. http://dx.doi.org/10.1016/j.soilbio.2009.08.020

Klose, S., Moore, J.M., Tabatabai, M.A., 1999. Arylsulfatase activity of microbial biomass in soils as affected by cropping systems. Biol. Fertil. Soils 29, 46–54. https://doi.org/10.1007/s003740050523

Klose, S.; Bilen, S.; Tabatabai, M.A.; Dick, W.A., 2011. Sulfur cycle enzymes. In: Dick, R. P. (Ed.), Methods of soil enzymology, 1st1. Soil Sci. Soc. Am., Madison, WI, USA, pp. 125–156

Kumar, S., Meena, R.S., Lal, R., Yadav, G.S, Mitran, T. Meena, B.L., Dotaniya, M.L., El-Sabagh A., 2018. Role of Legumes in Soil Carbon Sequestration. In: Meena, R., Das, A., Yadav, G., Lal, R. (eds) Legumes for Soil Health and Sustainable Management. Springer, Singapore. https://doi.org/10.1007/978-981-13-0253-4_4

Kunde, R.J.; Lima, A.C.R.; Silva, J.L.S.; Valgas, R.A.; Kohler, T.W.; Pillon, C.N., 2020. Qualidade física, química e biológica de um Neossolo Litólico sob integração lavoura-pecuária no Bioma Pampa. Res. Soc. Dev., 9(10), 1-20. http://dx.doi.org/10.33448/rsd-v9i10.9015

Kunito, T., Kurita, H., Kumori, M., Sakaguchi, K., Nishizawa, S., Fujita, K., Moro, H., Sawada, K., Miyabara, Y., Toda, H., Nagaoka, K., Ishikawa, Y., 2022. Microbial synthesis of arylsulfatase depends on the soluble and adsorbed sulfate concentration in soils. Eur. J. Soil Biol 111, 103418. https://doi.org/10.1016/j.ejsobi.2022.103418

Lagomarsino, A., Moscatelli, M.C., Tizio, A.D., Mancinelli, R., Grego, S., Marinari, S., 2009. Soil biochemical indicators as a tool to assess the short-term impact of agricultural management on changes in organic C in a Mediterranean environment. Ecol. Indic. 9, 518–527. https://doi.org/10.1016/j.ecolind.2008.07.003

Lal, R., 2016. Soil health and carbon management. Food Energy Secur. 5, 212–222. https://doi.org/10.1002/fes3.96

Lange, M., Eisenhauer, N., Chen, H., Gleixner, G., 2023. Increased soil carbon storage through plant diversity strengthens with time and extends into the subsoil. Glob. Change Biol. 29, 2627–2639. https://doi.org/10.1111/gcb.16641

Li, J., Wen, Y., Li, X., Li, Y., Yang, X., Lin, Z., Song, Z., Cooper, J.M., Zhao, B., 2018. Soil labile organic carbon fractions and soil organic carbon stocks as affected by long-term organic and mineral fertilization regimes in the North China Plain. Soil Till Res. 175, 281–290. https://doi.org/10.1016/j.still.2017.08.008

Liebert, J., Benner, R., Bezner Kerr, R., Björkman, T., De Master, K.T., Gennet, S., Gómez, M.I., Hart, A.K., Kremen, C., Power, A.G., Ryan, M.R., 2022. Farm size affects the use of agroecological practices on organic farms in the United States. Nat. Plants 8, 897–905. https://doi.org/10.1038/s41477-022-01191-1

Lima, C.E.P.; Fontenelle, M.R.; Madeira, N.R.; Silva, J.; Guedes, I.M.R.; Silva, L.R.B.; Soares, D.C., 2016. Compartimentos de carbono orgânico em Latossolo cultivado com hortaliças sob diferentes manejos. Pesq. Agrop. Bras. 51, 378-387. doi: 10.1590/S0100-204X2016000400011

Lima, C.E.P.; Guedes, I.M.R., Silva, J., Alcântara, F.A., Madeira, N.R., Carvalho, A.D.F., Fontenelle, M.R., 2018. Effects of Five Years Adoption of No-Tillage Systems for Vegetables Crops in Soil Organic Matter Contents. Agric. Sci. 09, 117–128. https://doi.org/10.4236/as.2018.91009

Lima, S.K., Galiza, M., Valadares, A., Alves, F., 2020. Produção e consumo de produtos orgânicos no mundo e no Brasil. Texto para discussão/ Instituto de Pesquisa Econômica Aplicada. 2538.

Lopes, A.A.C., Sousa, D.M.G., Chaer, G.M., Reis Junior, F.B., Goedert, W.J., Mendes, I.C., 2013. Interpretation of microbial soil indicators as a function of crop yield and organic carbon. Soil Sci. Soc. Am. J. 77, 461–472. https://doi.org/10.2136/sssaj2012.0191

Loss, A.; Pereira, M.G.; Schultz, N.; Anjos, L.H.C.D.; Silva, E.M.R.D., 2010. Quantificação do carbono das substâncias húmicas em diferentes sistemas de uso do solo e épocas de avaliação. Bragantia 69, 913–922. https://doi.org/10.1590/S0006-87052010000400018

Maharjan, M.; Sanaullah, M.; Razavi, B.S.; Kuzyakov, Y., 2017. Effect of land use and management practices on microbial biomass and enzyme activities in subtropical top- and sub-soils. Appl. Soil Ecol. 113, 22–28. https://doi.org/10.1016/ j.apsoil. 2017.01.008

MAPA - Ministério da Agricultura, Pecuária e Abastecimento, 2024. Cadastro Nacional de Produtores Orgânicos [WWW Document]. Ministério da Agricultura e Pecuária. URL https://www.gov.br/agricultura/pt-br/assuntos/sustentabilidade/organicos/cadastro-nacional-produtores-organicos (accessed 10.05.24).

Matos, P.S., Pinto, L.A. S.R., Lima, S.S., Alves, T. C., Cerri, E.P., Pereira, M.G., Zonta, E., 2023. Soil organic carbon fractions in agroforestry system in Brazil: seasonality and short-term dynamic assessment. Rev. Bras. Ciênc. Solo 47. https://doi.org/10.36783/18069657rbcs20220095

Maurya, S., Abraham, J.S., Somasundaram, S., Toteja, R., Gupta, R., Makhija, S., 2020. Indicators for assessment of soil quality: a mini-review. Environ Monit Assess 192, 604. https://doi.org/10.1007/s10661-020-08556-z

Melkani, S., Singh, V., Bhadha, J.H., 2024. Quantifying the impact of different agroforestry systems on soil carbon fractions lability and long-term carbon sequestration in Central Himalayas. Soil Use Manag. 40, e13012. https://doi.org/10.1111/sum.13012

Melo, G.B.; Pereira, M.G.; Perin, A; Guareschi, R.F.; Soares, P.F.C., 2016. Estoques e frações da matéria orgânica do solo sob os sistemas plantio direto e convencional de repolho. Pesq. Agrop. Bras. 51, 1511-1519. doi: 10.1590/S0100-204X2016000900050

Mendes, I.C., Sousa, D.M.G., Reis Junior, F.B., Lopes, A.A.C., Souza, L.M., Chaer, G.M., 2019a. Bioanálise de solo: aspectos teóricos e práticos. Topicos Ci. Solo 10, 1–64.

Mendes, I.D.C., Souza, L.M.D., Sousa, D.M.G.D., Lopes, A.A.D.C., Reis Junior, F.B.D., Lacerda, M.P.C., Malaquias, J.V., 2019b. Critical limits for microbial indicators in tropical Oxisols at post-harvest: The FERTBIO soil sample concept. Appl. Soil Ecol. 139, 85–93. https://doi.org/10.1016/j.apsoil.2019.02.025

Mendes, I.C., Sousa, D.M.G., Dantas, O.D., Lopes, A.A.C., Reis Junior, F.B., Oliveira, M.I, Chaer, G.M., 2021. Soil quality and grain yield: A win–win combination in clayey tropical oxisols. Geoderma 388, 114880. https://doi.org/10.1016/j.geoderma.2020.114880

Mendes, I.C., Chaer, G.M., Reis Junior, F.B., Dantas, O.D., Malaquias, J.V., Oliveira, M.I. L., Nogueira, M.A., Hungria, M., 2024. Soil Bioanalysis (SoilBio): A Sensitive, Calibrated, and Simple Assessment of Soil Health for Brazil. In: Mendes, I.C.; Cherubin, M.R. (Ed.). Soil Health and Sustainable Agriculture in Brazil. 01ed. Soil Sci. Soc. Am., 01. Madison, WI, pp. 292–326.

Meza, K., Vanek, S.J., Sueldo, Y., Olivera, E., Ccanto, R., Scurrah, M., Fonte, S.J., 2022. Grass–Legume Mixtures Show Potential to Increase Above- and Belowground Biomass Production for Andean Forage-Based Fallows. Agronomy 12, 142. https://doi.org/10.3390/agronomy12010142

Mi, W., Sun, Y., Gao, Q., Liu, M., Wu, L., 2019. Changes in humus carbon fractions in paddy soil given different organic amendments and mineral fertilizers. Soil and Till. Res. 195, 104421. https://doi.org/10.1016/j.still.2019.104421

Moebius-Clune, B.N.; Moebius-Clune, D.J.; Gugino, B.K.; Idowu, O.J.; Schindelbeck, R.R.; Ristow, A.J.; Van Es, H.M.; Thies, J.E.; Shayler, H.A.; Mcbride, M.B.; Kurtz, K.S.M; Wolfe, D.W.; Abawi, G.S., 2016. Comprehensive assessment of soil health-The cornell framework, edition 3.2, Cornell University, Geneva, NY. 134p.

Neher, D.A.; Fang, L.; Weicht, T.R., 2017. Ecoenzymes as Indicators of Compost to Suppress Rhizoctonia Solani. Compost Sci. Util. 25(4), 251-261. http://dx.doi.org/10.1080/ 1065657x.2017.1300548

Niemi, R.M, Vepsäläinen, M., Wallenius, K., Erkomaa, K., Kukkonen, S., Palojärvi, A., Vestberg, M., 2008. Conventional versus organic cropping and peat amendment: Impacts on soil microbiota and their activities. Eur. J. Soil Biol. 44, 419–428. https://doi.org/10.1016/j.ejsobi.2008.06.001

Norris, C.E; Congreves, K.A., 2018. Alternative Management Practices Improve Soil Health Indices in Intensive Vegetable Cropping Systems: A Review. Front. Environ. Sci. 6, 1-18. https://doi.org/10.3389/fenvs.2018.00050

Notaro, K.A., Medeiros, E.V.D., Duda, G.P., Moreira, K.A., Barros, J.A.D., Santos, U.J.D., Lima, J.R.D.S., Moraes, W.D.S., 2018. Enzymatic activity, microbial biomass, and organic carbon of Entisols from Brazilian tropical dry forest and annual and perennial crops. Chil. j. agric. res. 78, 68–77. https://doi.org/10.4067/S0718-58392018000100068

Oldfield, E.E.; Bradford, M.A.; Augarten, A.J.; Cooley, E.T.; Radatz, A.M.; Radatz, T., Ruark, M.D., 2022. Positive associations of soil organic matter and crop yields across a regional network of working farms. Soil Sci. Soc. Am. J. 86, 384–397. https://doi.org/10.1002/saj2.20349

Ouyang, Y.; Reeve, J.R.; Norton, J.M., 2022. The quality of organic amendments affects soil microbiome and nitrogen-cycling bacteria in an organic farming system. Front. Soil Sci. 2. https://doi.org/10.3389/fsoil.2022.869136

Palomo-Campesino, S., González, J., García-Llorente, M., 2018. Exploring the Connections between Agroecological Practices and Ecosystem Services: A Systematic Literature Review. Sustainability 10, 4339. https://doi.org/10.3390/su10124339

Palomo-Campesino, S., García-Llorente, M., González, J.A., 2021. Characterizing agroecological and conventional farmers: uncovering their motivations, practices, and perspectives toward agriculture. Agroecol. Sust. Food Syst. 45, 1399–1428. https://doi.org/10.1080/21683565.2021.1933671

Palomo-Campesino, S., García-Llorente, M., Hevia, V., Boeraeve, F., Dendoncker, N., González, J.A., 2022. Do agroecological practices enhance the supply of ecosystem services? A comparison between agroecological and conventional horticultural farms. Ecosyst. Serv. 57, 101474. https://doi.org/10.1016/j.ecoser. 2022.101474

Passinato, J.H., Amado, T.J.C., Kassam, A., Acosta, J.A.A., Amaral, L.D.P., 2021. Soil Health Check-Up of Conservation Agriculture Farming Systems in Brazil. Agronomy 11, 2410. https://doi.org/10.3390/agronomy11122410

Pearsons, K.A., Omondi, E.C., Zinati, G., Smith, A., Rui, Y., 2023. A tale of two systems: Does reducing tillage affect soil health differently in long-term, side-by-side conventional and organic agricultural systems? Soil Till. Res. 226, 105562. https://doi.org/10.1016/j.still.2022.105562

Piutti, S., Slezack-Deschaumes, S., Niknahad-Gharmakher, H., Vong, P.-C., Recous, S., Benizri, E., 2015. Relationships between the density and activity of microbial communities possessing arylsulfatase activity and soil sulfate dynamics during the decomposition of plant residues in soil. Eur. J. Soil Biol. 70, 88–96. https://doi.org/10.1016/j.ejsobi.2015.07.007

Plaza-Bonilla, D.; Álvaro-Fuentes, J.; Cantero-Martínez, C., 2014. Identifying soil organic carbon fractions sensitive to agricultural management practices. Soil Till. Res. 139, 19-22. http://dx.doi.org/10.1016/j.still.2014.01.006.

Portilho, I.I.R.; Scorza Júnior, R.P.; Salton, J.C.; Mendes, I.C.; Mercante, F.M. Persistence of insecticides and microbiological attributes in a soil under different management systems. Ciênc. Rural 45(1), 22-28. https://doi.org/10.1590/0103-8478cr20131328.

Pritchett, K., Kennedy, A.C., Cogger, C.G., 2011. Management Effects on Soil Quality in Organic Vegetable Systems in Western Washington. Soil Sci. Soc Am. J. 75, 605–615. https://doi.org/10.2136/sssaj2009.0294

Ratke, R.F.; Bertechini, M.C.; Figueiredo C.C.; Arauco, A.M.S.; Dias, B.O.; Oliveira, J.C., 2022. Soil Organic Matter Fractions and Enzymes Activities under No-tillage System: effects of organomineral and mineral fertilizer with humic substances. Commun. soil sci. plant anal. 52(2), 1-10. doi:10.1080/00103624.2021.1993886

Reatto, A; Martins, E.S.; Farias, M.F.R. Silva, A.V., Carvalho Júnior, O. A. Mapa pedológico digital - SIG atualizado do Distrito Federal escala 1:100.000 e uma síntese do texto explicativo. Planaltina: Embrapa Cerrados, 2004. 31p. (Documentos).

Resende Filho, M.A., Andow, D.A., Carneiro, R.G., Lorena, D.R., Sujii, E.R., Alves, R.T., 2019. Economic and productivity incentives to produce organically in Brazil: Evidence from strawberry production in the Federal District. Renew. Agric. Food Syst. 34, 155–168. https://doi.org/10.1017/S1742170517000412

Rhioui, W., Al Figuigui, J., Lahlali, R., Laasli, S.-E., Boutagayout, A., El Jarroudi, M., Belmalha, S., 2023. Towards Sustainable Vegetable Farming: Exploring Agroecological Alternatives to Chemical Products in the Fez-Meknes Region of Morocco. Sustainability 15, 7412. https://doi.org/10.3390/su15097412

Rossi, C.Q; Pereira, M.G.; Giácomo, S.G.; Betta, M.; Polidoro, J.C., 2012. Frações lábeis da matéria orgânica em sistema de cultivo com palha de braquiária e sorgo. Rev. Ciênc. Agron. 43, 38-46.

Santos, J.A. dos, Santos, A. de D. dos, Costa, C.R., Araujo, A.S. de, Leite, G.G., Coser, T.R., Figueiredo, C.C. de, 2024. Fractions of Organic Matter and Soil Carbon Balance in Different Phases of an Agroforestry System in the Cerrado: A Ten-Year Field Assessment. Soil Syst. 8, 44. https://doi.org/10.3390/soilsystems8020044

Sharma, K.L., Srinivasarao, Ch., Chandrika, D.S., Lal, M., Indoria, A.K., Thakur, P.B., Srinivas, K., Reddy, K.S., Usha Rani, K., 2017. Effect of Graded Levels of Surface Crop Residue Application Under Minimum Tillage on Carbon Pools and Carbon Lability Index in Sorghum (Sorghum bicolor (L.) Moench)-Cowpea (Vigna unguiculata) System in Rainfed Alfisols. Commun. Soil Sci. Plant Anal. 48, 2506–2513. https://doi.org/10.1080/00103624.2017.1416125

Shen, J., Zhu, Q., Hou, Y., Cong, W.-F., Xu, W., Xu, J., An, Z., Jiao, X., Zhang, K., Yu, T., Ma, L., Oenema, O., Davies, W.J., Zhang, F., 2024. Agriculture green development in China: insights and advances. Front. Agr. Sci. Eng. 11, 5–19. https://doi.org/10.15302/J-FASE-2024535

Sissoko, A., Kpomblekou-A, K., 2010. Carbon decomposition in broiler litter-amended soils. Soil Biol. Biochem. 42, 543–550. https://doi.org/10.1016/j.soilbio.2009.10.007

Souza, R.F. de, Figueiredo, C.C. de, Madeira, N.R., Alcântara, F.A. de, 2014. Effect of management systems and cover crops on organic matter dynamics of soil under vegetables. Rev. Bras. Ciênc. Solo 38, 923–933. https://doi.org/10.1590/S0100-06832014000300024

Souza, G.P.D., Figueiredo, C.C.D., Sousa, D.M.G.D., 2016. Soil organic matter as affected by management systems, phosphate fertilization, and cover crops. Pesq. agropec. bras. 51, 1668–1676. https://doi.org/10.1590/s0100-204x2016000900067

Souza, B.J.; Carmo, D.L.; Santos, R.H.S.; Oliveira, T.S.; Fernandes, R.B.A., 2019. Residual Contribution of Green Manure to Humic Fractions and Soil Fertility. J. Soil Sci. Plant Nutr. 19, 878–886. https://doi.org/10.1007/s42729-019-00086-z

Spaccini, R., Mbagwu, J.S.C., Conte, P., Piccolo, A., 2006. Changes of humic substances characteristics from forested to cultivated soils in Ethiopia. Geoderma 132, 9–19. https://doi.org/10.1016/j.geoderma.2005.04.015

Srivastava, P., Singh, R., Tripathi, S., Raghubanshi, A.S., 2016. An urgent need for sustainable thinking in agriculture – An Indian scenario. Ecol. Indic. 67, 611–622. https://doi.org/10.1016/j.ecolind.2016.03.015

Stockdale, E.A., Shepherd, M.A., Fortune, S., Cuttle, S.P., 2006. Soil fertility in organic farming systems - fundamentally different? Soil Use and Manag. 18, 301–308. https://doi.org/10.1111/j.1475-2743.2002.tb00272.x

Stott, D.E.; Andrews, S.S.; Liebig, M.A.; Wienhold, B. J.; Karlen, D. L., 2010. Evaluation of β-Glucosidase Activity as a Soil Quality Indicator for the Soil Management Assessment Framework. Soil Sci. Soc. Am. J. 74, 107-119. http://dx.doi.org/10.2136/ sssaj2009.0029

Teixeira, H.M., Van Den Berg, L., Cardoso, I.M., Vermue, A.J., Bianchi, F.J.J.A., Peña-Claros, M., Tittonell, P., 2018. Understanding Farm Diversity to Promote Agroecological Transitions. Sustainability 10, 4337. https://doi.org/ 10.3390 /su10124337

Teixeira, H.M., Bianchi, F.J.J.A., Cardoso, I.M., Tittonell, P., Peña-Claros, M., 2021. Impact of agroecological management on plant diversity and soil-based ecosystem services in pasture and coffee systems in the Atlantic forest of Brazil. Agric. Ecosyst. Environ. 305, 107171. https://doi.org/10.1016/j.agee.2020.107171

Tejada, M., Benítez, C., 2011. Organic amendment based on vermicompost and compost: differences on soil properties and maize yield. Waste Manag. Res. 29, 1185–1196. https://doi.org/10.1177/0734242X10383622

Tirol-Padre, A., Ladha, J.K., 2004. Assessing the Reliability of Permanganate-Oxidizable Carbon as an Index of Soil Labile Carbon. Soil Sci. Soc Am. J. 68, 969–978. https://doi.org/10.2136/sssaj2004.9690

Trasar-Cepeda, C.; Leiro´s, C.; · Gil-Sotres, F.; Seoane, S., 1998. Towards a biochemical quality index for soils: An expression relating several biological and biochemical Properties. Biol. Fertil. Soils 26, 100–106.

Valani, G.P., Vezzani, F.M., Cavalieri-Polizeli, K.M.V., 2020. Soil quality: Evaluation of on-farm assessments in relation to analytical index. Soil Till. Res. 198, 104565. https://doi.org/10.1016/j.still.2019.104565

Valarini, P.J., Oliveira, F.R., Schilickmann, S.D.F., Poppi, R.J., 2011. Qualidade do solo em sistemas de produção de hortaliças orgânico e convencional. Hortic. Bras. 29, 485–491. https://doi.org/10.1590/S0102-05362011000400007

Veum, K.S.; Goyne, K.W.; Kremer, R.J.; Miles, R.J.; Sudduth, K.A., 2014. Biological indicators of soil quality and soil organic matter characteristics in an agricultural management continuum. Biogeochemistry 117, 81-99. http://dx.doi.org/10.1007/s10533-013-9868-7

Wallenstein M.D.; Burns R.G. Ecology of extracellular enzyme activities and organic matter degradation in soil: a complex community-driven process. In: Dick R.P. (ed). Methods of soil enzymology. Madison: Soil Sci. Soc. Am. 2011. p. 35-56.

Willekens, K., Vandecasteele, B., Buchan, D., De Neve, S., 2014. Soil quality is positively affected by reduced tillage and compost in an intensive vegetable cropping system. Appl. Soil Ecol. 82, 61–71. https://doi.org/10.1016/j.apsoil.2014.05.009

Willer, H.; Lernoud, J. The World of Organic Agriculture: Statistics and Emerging Trends 2017; FiBL-IFOAM Report; Research Institute of Organic Agriculture (FiBL), International Federation of Organic Agriculture Movements (IFOAM): Frick, Switzerland, 2017.

Woomer, P.L.; Palm, C.A.; Alegre, J.; Castilla, C.; Cordeiro, D.G.; Hairaah, K.; Kotto-Same, J.; Moukam, A.; Riese, A.; Rodrigues, V.; Van Noordwijk, M., 2000. Slash and burn effects on carbonstocks in the humid tropics. In: Lal, R., Kimble, J.M., Stewart, B.A. (Eds.). Global Climate Change and Tropical Ecosystems. Boca Raton: CRC Press, 2000, p. 99–115.

Xu, Q., Hu, K., Zhang, H., Han, H., Li, J., 2020. Organic Vegetable Cultivation Reduces Resource and Environmental Costs While Increasing Farmers' Income in the North China Plain. Agronomy 10, 361. https://doi.org/10.3390/agronomy10030361

Yadav, G.S., Kandpal, B.K., Das, A., Babu, S., Mohapatra, K.P., Devi, A.G., Devi, H.L., Chandra, P., Singh, R., Barman, K.K., 2021. Impact of 28 year old agroforestry systems on soil carbon dynamics in Eastern Himalayas. J. Environ. Manage. 283, 111978. https://doi.org/10.1016/j.jenvman.2021.111978

Yao, Z., Xu, Q., Chen, Y., Liu, N., Huang, L., Zhao, Y., Zhang, D., Li, Y., Zhang, S., Cao, W., Zhai, B., Wang, Z., Adl, S., Gao, Y., 2019. Enhanced Stabilization of Soil Organic Carbon by Growing Leguminous Green Manure on the Loess Plateau of China. Soil Sci. Soc. Am. J. 83, 1722–1732. https://doi.org/10.2136/sssaj2019.03.0089

CHAPTER I

A SOIL HEALTH ASSESSMENT TOOL FOR VEGETABLE CROPPING SYSTEMS IN TROPICAL SOILS BASED ON BETA-GLUCOSIDASE, ARYLSULFATASE, AND SOIL ORGANIC CARBON

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6.1. Abstract

Vegetable production is characterized by a strong dependence on external inputs and intense tillage, which can harm soil health (SH) by reducing organic matter levels, soil biota diversity, and overall ecosystem functions. Tools to assess SH affected by organic and conventional vegetable production systems are crucial and still scarce. This study aimed to develop a practical and reliable SH assessment tool for vegetable production systems in tropical soils by integrating Cornell's Comprehensive Assessment of Soil Health (CASH) with the four-quadrant model (4QM). Furthermore, the study evaluated the relationship between management practices and SH status. Arylsulfatase (ARYL) and β-glucosidase (GLU) activities, and soil organic carbon (SOC) were analyzed in 90 soil samples (0 to 10 cm depth) collected from 53 organic and conventional vegetable farms in the Federal District, Brazil. The adoption of practices aimed at improving or maintaining SH was significantly greater on organic farms than on conventionally managed farms, resulting in a SOC content and ARYL activity 27% and 86% higher in organic farms than in conventional systems, respectively ($P < 0.05$). ARYL proved to be more accurate in separating organic and conventional fields than GLU, highlighting its potential for SH evaluation in vegetable production systems. The integration of CASH and the 4QM, along with ARYL, GLU, and SOC measurements, effectively addressed the complexity of both organic and conventional vegetable production systems. This combined approach facilitated differentiation between systems based on varying levels of adoption of best management practices (BMPs). Further research is needed to assess the performance of this approach across different soil types and regions where vegetables are cultivated.

Keywords: Soil quality, soil enzymes, soil organic matter, organic agriculture

6.2. Introduction

Vegetable cropping systems are characterized by intensive practices that frequently disturb the soil, such as tillage, fertilizer and herbicide application, plastic mulch usage, and weed management through cultivation, hilling, and harvesting. These practices contribute significantly to a decrease in soil organic matter (SOM), thereby leading to soil degradation and nutrient losses, ultimately impacting overall soil health (SH) (Norris and Congreves, 2018). Extensive research conducted across different regions, including Brazil (Figuerêdo et al., 2020; Mauri et al., 2024), China (Kalkhajeh et al., 2021), and the USA (Amsili et al., 2021), has consistently demonstrated that vegetable cropping systems often exhibit lower levels of SH than other cropping systems.

Studies evaluating SH in organic and conventionally managed vegetable farming systems in Brazil are lacking. Few studies have addressed the activities of the soil enzymes arylsulfatase (ARYL) and beta-glucosidase (GLU) in these areas. The interest in ARYL and GLU stems from their successful utilization since 2020 in extensive SH assessments across Brazil, particularly in areas dedicated to annual row crops (Mendes et al., 2018, 2019a, 2021, 2024).

ARYL is an enzyme of the esterase class that catalyzes the hydrolysis of ester sulfates, releasing sulfate anions essential for plants and microorganisms (Klose et al., 2011). GLU is an exocellulase responsible for the decomposition of organic matter in the soil, acting specifically to break down cellulose and convert cellobiose into two molecules of glucose, an essential source of energy for soil microorganisms (Deng & Popova, 2011). Given their importance in biogeochemical cycles and their sensitivity as indicators of soil management changes, analyses of enzyme activity, particularly that of ARYL and GLU, have been widely studied and used to monitor and support soil management decisions (Mendes et al., 2024).

To enable ARYL and GLU use in routine SH assessments in Brazil, interpretative frameworks for the individual values of these two soil enzymes were developed. These frameworks establish reference levels (low, medium, adequate, and high) according to soil textural classes (Lopes et al., 2013; Mendes et al., 2019b; 2024), which allows independent interpretation and establish limits for standardized scoring functions, aiding soil quality index (SQI) calculations (e.g., Karlen & Stott, 1994; Hussain et al., 1999; Mendes et al., 2021a). The first interpretative framework was based on the principles of soil nutrient calibration (Lopes et al., 2013). In that study, using linear regression models, ARYL and GLU were interpreted as a function of long-term cumulative yields of maize, soybean, and SOC.

Calibrating biological indicators as a function of crop yield is advantageous because it is related to economic outcomes and considers farmer satisfaction (Mendes et al., 2021b). Moreover, crop yield in long-term, well-managed soils can be considered a good field indicator for evaluating the sustainability of agricultural systems because it is the result of several soil indicators (e.g., organic matter, soil pH, nutrient supply, biological activity, mechanical resistance to penetration, topsoil depth, infiltration, aggregation, etc.) (Oldfield et al., 2022). In fact, specific crop yield situations (ranging from low to high) have proven useful in developing guidelines for interpreting individual SH indicators (Lopes et al., 2013; Mendes et al., 2019b; 2023). However, considering the intrinsic characteristics of vegetable cropping systems, with the great diversity of herbaceous plants, including edible roots, stems, leaves, flower buds, fruits, and seeds, it is difficult to interpret SH indicators in these cropping systems in relation to plant yield. Consequently, in these systems, strategies for interpreting and scoring SH indicators must not rely on plant yield, and new alternatives must be identified.

Various approaches have been suggested for interpreting SH/soil quality (SQ) indicators. The Comprehensive Assessment of Soil Health (CASH), proposed by Cornell University (Moebius-Clune et al., 2016), was originally developed to interpret SH measurements by adapting the work of Andrews et al. (2004), which also led to the development of the Soil Monitoring Assessment Framework (SMAF) (Stott et al., 2010) and Soil Health Assessment Protocol and Evaluation (SHAPE) (Nunes et al., 2021). It consists of the development of scoring curves (that assign scores between 0 and 100) for SH parameters by estimating their cumulative normal distribution (CND) function using the mean and standard deviations of a large group of soil samples (Moebius-Clune et al., 2016). It uses separate scoring functions for different soil texture groupings to account for their strong influence on some indicators. The scoring curves based on the CND can be very helpful for establishing reference values for SH indicators in situations where plant yield data are unavailable.

The four-quadrant model (4QM) approach introduced by Chaer et al. (2023) allows the separation of larger groups of soil samples with unknown history into four categories: healthy soils (quadrant 1), soils undergoing biological degradation (quadrant 2), unhealthy soils (quadrant 3), and soils undergoing regenerative processes (quadrant 4). The 4QM relies on the SOC relationship with average ARYL and GLU activities per unit of SOC (average specific enzyme activity, ASEA). By combining ARYL and GLU, ASEA eliminates strong covariances with SOM and accounts for differences in SOC contents. To calibrate the model, relationships were established between SOC and ASEA (0 to 10 cm soil samples) and the relative cumulative grain yield of soybean and corn in long-term field experiments. The threshold values for the SOC and ASEA were arbitrarily defined as the equivalent of 50% of the maximum cumulative corn and soybean yields. These thresholds were used to divide the ASEA vs. SOC scatter plot into four quadrants.

With increasing global awareness of the importance of vegetable consumption for human health, there is growing interest in assessing the SH status of intensively managed vegetable production systems. However, as already mentioned, in contrast to cereal crops, the intrinsic characteristics of vegetable production systems make it difficult to calibrate SH indicators in relation to crop yield, as proposed by Lopes et al. (2013).

In the present study, we hypothesized that by combining the CASH approach (Moebius-Clune et al., 2016) and the 4QM (Chaer et al., 2023), it would be possible to develop a simple, practical, and robust SH assessment tool for vegetable production systems in tropical soils. This study also aimed to evaluate the impact of the two production systems on SH indicators and establish a relationship between the management practices adopted in organic and conventional systems and SH status.

6.3. Materials and methods

6.3.1. Study areas

The study was carried out in 2022 on rural properties in the Federal District (DF), which is located between the parallels of 15°30' and 16°03' south latitude and 47°20' and 48°10' west longitude, in the central-west region of Brazil. According to the Köppen classification, the regional climate is Cwa type (Alvares et al., 2013), with 1500 mm of average annual rainfall and two well-defined seasons: dry, from May to September, and rainy, from October to April. The average annual maximum and minimum temperatures are 26.4°C and 15.9°C, respectively.

A total of 90 sampling site located at 53 commercial farms, in general ranging from 1 to 20 hectares in different localities were selected for this study with the support of the Technical Assistance and Rural Extension Company of the Federal District (Emater-DF), a government rural development agency (Fig. 1). The selected field sites included 48 representative organic and 42 conventional production systems and their variations, with different implementation times and content of SOM. Soil samples were collected from different botanical families, with Solanaceae, Asteraceae and Brassicaceae predominantly and ranging from harvest to the end of the crop cycle. The same area was often cultivated 2-3 times a year.

There were 18 sites with an establishment time between 0 and 5 years, 22 between 6 and 11 years and 50 with more than 12 years.

The properties associated with organic production were certified by the Biodynamic Institute for Rural Development (IBD), Ecocert Brasil (an audit certification system), OPAC Cerrado (a participatory organic conformity assessment system) or registered as organic by the Ministry of Agriculture, Livestock and Supply through a Social Control Organization of family farmers (SCO). A diagnosis of the soil use and management history, as well as the practices adopted, was carried out on each property by means of a questionnaire (details in section 2.4).

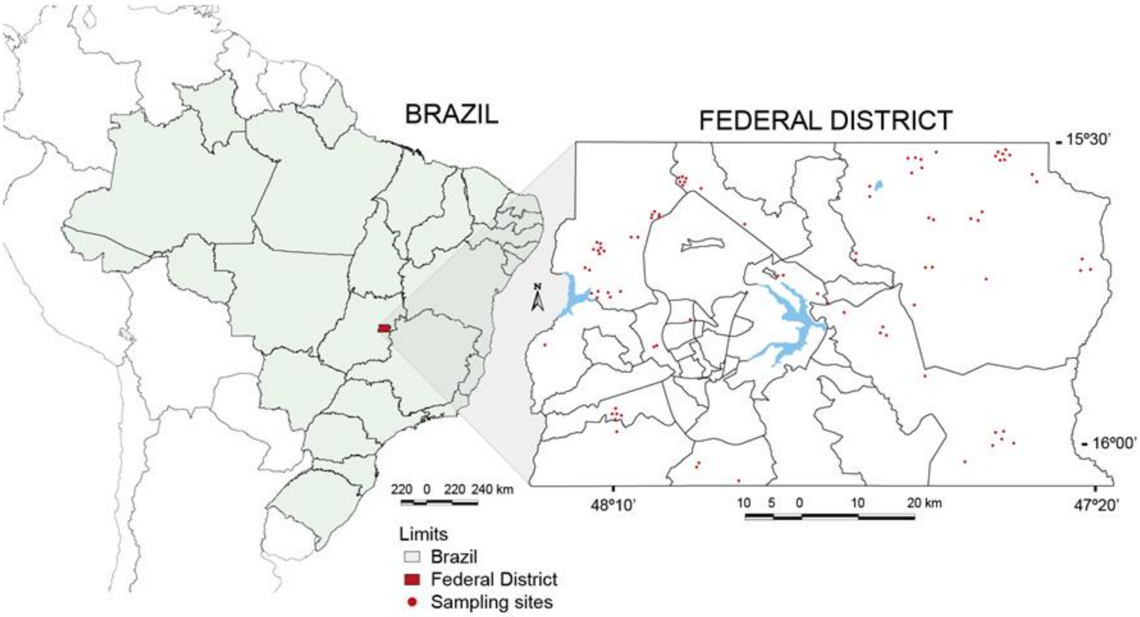


Figure 1. Location of the sampled areas in the Federal District, Brazil.

6.3.2. Soil sampling and analyses

Soil sampling was conducted in June and July 2022. The soil samples were collected from the topsoil layer (0–10 cm depth) with a range of soil textures from 16% to 64% clay content. All samples were collected from soils classified as Oxisols (Rodhic Hapludox) (Soil Survey, 2014) equivalent to Latossolo Vermelho according to the Brazilian Soil Classification System (Santos et al., 2018). At each sampling site, soil samples were a composite mixture of 10 subsamples taken with a soil probe (5 cm diameter).

The soil particle size distribution (texture) was determined from air-dried soil samples using the pipette method. The method uses 10 ml of sodium hydroxide solution (1 mol/L) to disperse soil samples. The samples were then passed through sieving and sedimentation steps to determine the percentages of sand, silt and clay (Teixeira et al., 2017).

The chemical analyses were performed as follows: Ca^{2+} and Mg^{2+} were extracted with 1 N KCl and determined through atomic absorption; P and K^+ were extracted using the Mehlich 1 (H_2SO_4 0.0125 M + HCl 0.05 M) method and determined through flame spectrophotometry (K^+) and the blue-Mo method (P) (Teixeira et al., 2017). The potential acidity ($H+Al^{3+}$) was extracted with sodium acetate buffer at pH=7.0 and determined by volumetric analysis using NaOH in the presence of phenolphthalein as an acid–base indicator. The cation exchange capacity (CEC) was determined as the sum of $H+Al^{3+}$, Ca^{2+}, Mg^{2+} and K^+. The CEC was expressed in $cmol_c$ dm^{-3}. The SOC content was measured using the Walkley and Black method (Nelson & Sommers, 1996) and calculated according to Jackson (1958).

Soil samples for GLU, ARYL and SOC determinations were prepared according to the FERTBIO soil sample concept described in Mendes et al. (2019b). Briefly, soil samples were air-dried at room temperature for at least two weeks, passed through a 2 mm sieve and stored at room temperature until the analyses were performed within a period of one week after air-drying. The activities of the enzymes β-glucosidase and arylsulfatase were determined according to Tabatabai (1994) based on the colorimetric determination of the *p*-nitrophenol released by these enzymes when the soil was incubated with a buffered solution of substrates specific to each enzyme. Two analytical replicates plus a control were used for each sample. Due to the short incubation period (one hour), toluene was omitted from the assays. The values of enzyme activities are expressed in mg p-nitrophenol kg^{-1} h^{-1} (= mg PNP kg^{-1} h^{-1}).

6.3.3. Average specific enzyme activity (ASEA)

To normalize enzyme activities to the size of SOC, each enzyme (GLU and ARYL) was divided by SOC, resulting in specific GLU activity (S-GLU) (equation 1) and specific ARYL activity (S-ARYL) (equation 2) (Trasar-Cepeda et al., 2008 a,b):

$$S - GLU = \frac{GLU}{SOC} \quad (1)$$

$$S - ARYL = \frac{ARYL}{SOC} \quad (2)$$

The average specific enzyme activity (ASEA) was calculated as the average of S-GLU and S-ARYL (equation 3).

$$ASEA = \frac{S-GLU+S-ARYL}{2} \qquad (3)$$

ASEA was expressed in g p-nitrophenol kg^{-1} SOC h^{-1} (=g PNP kg^{-1} SOC h^{-1})

6.3.4. Database on practices adopted by farmers

The soil management practices of the 90 sites were assessed based on the two years prior to sampling. Information was collected through interviews, questionnaires and farmer observations during visits to the sampling areas, with a focus on aspects related to soil management. The duration of continuous intensive cultivation was documented. Additionally, agronomic practices routinely conducted on both organic and conventional farms were assessed, including (i) crop rotation history; (ii) soil tillage methods (types and frequency per crop or year); (iii) application of mineral and organic amendments (types and application rates per year); (iv) history of green manure usage; (v) implementation of cover crops; and (vi) adoption of intercropping or agroforestry practices.

These observations culminated in a comprehensive database aimed at elucidating the extent to which soil BMPs have been adopted within these vegetable production systems.

6.3.5. Soil texture effects

To evaluate the effects of soil texture on the SH indicators (SOC, ARYL and GLU), the 90 soil samples were divided into three datasets: 1) all 90 soil samples, 2) soil samples with 16-35% clay content and 3) soil samples with 35-60% clay content. For each soil texture dataset, linear regression equations were defined to express the relationships between SOC, ARYL and GLU and percent clay content. The correlation and determination coefficients, the regression equations and the significance of the models were obtained using R Project software.

6.3.6. Development of a strategy to evaluate SH by combining CASH and the 4QM

Due to the difficulty in obtaining yield data for the vegetables produced on the 53 farms, the first step was to develop histograms showing the distribution of SOC and ASEA, as proposed by Moebius-Clune et al. (2016).

The mean and standard deviation of the three textural datasets (all samples, 16-35% and 36-60% clay content) were used to calculate the cumulative normal distributions

(CND) for the SOC and ASEA. The CND represents scoring functions, as they provide for each parameter scores on a scale ranging from 0-100 (Moebius-Clune et al., 2016). In this way, based on the CND, it was possible to define scoring values equal to 50 as the critical levels for the SOC and ASEA. The 50% score was proposed by Chaer et al. (2023) and represents the minimal acceptable values of SOC and ASEA to be maintained for both the economic perspective and the functioning of these tropical Oxisols. Values below these limits would be a strong indication of soil agroecosystems compromised from both the economic and SH perspectives.

Similarly, the SOC and ASEA of the soil samples associated with the three soil textural datasets were analyzed using the four quadrants graphical visualization by plotting the ASEA on the x-axis and the SOC on the y-axis (Chaer et al., 2023). The SOC and ASEA thresholds obtained using the CASH approach were used to divide the ASEA vs. SOC scatter plot into four quadrants. Quadrants 1 (high SOC/high ASEA) and 3 (low SOC/low ASEA) represent stable patterns of high- and low-quality soils (healthy and unhealthy soils), respectively. Quadrants 2 (low ASEA/high SOC) and 4 (high ASEA/low SOC) represent transitional patterns or soils undergoing biological degradation (C loss) and regenerative processes (C gain), respectively.

6.3.7. Statistical analysis

For each dataset, normality was tested using the Shapiro–Wilk normality test, and homogeneity of variance (homoscedasticity) was tested using the Breusch–Pagan test. Since these criteria were not met, the nonparametric Wilcoxon (for comparing two independent groups) and Kruskal–Wallis (for more than two independent groups) tests were used.

Box plot representations of descriptive statistics (mean, median, minimum, maximum, first and third quartile values) were used to characterize the ARYL, GLU and SOC in the organic and conventional farms. Box plots were also used to describe SOC and ASEA for each quadrant of the 4QM in the three soil texture groups.

For the database on practices adopted by farmers in the different vegetable production systems, the frequencies of the adoption of BMPs between organic and conventional systems were compared using the Z test ($P<0.05$) due to the large sample size ($n>30$).

To assess whether there was an influence of soil texture on the classification of soil samples in the four quadrants obtained after the combination of the CASH and 4QM approaches, for each of the three textural datasets (all samples, 16-35% clay content, and 36-60% clay content), different quadrant boundaries were established. Using boxplot representation and the Kruskal–Wallis test at the 5% significance level, the ASEA and SOC values in each of the four quadrants of the three soil textural groups were compared. Another investigation to assess whether there was an influence of soil texture on the classification of soil samples in the four quadrants, was performed using Cohen's kappa coefficient, a statistical metric that quantifies the agreement between categorical evaluations, considering the agreement that could occur at random. The 3 textural datasets were submitted to this agreement test. This test allowed to evaluate if the number of samples that changed their position in the 4Q graphical display, due to the different quadrant boundaries associated to soil texture, was significant or not.

All the statistical procedures were performed using R project software (R Core Team, 2019).

6.4. Results and Discussion

6.4.1. Management practices adopted on organic and conventional farms

As expected, the interviews and field observations showed that adopting practices with the potential to improve or maintain SH was significantly greater on the organic farms than conventionally managed farms (Table 1). Similar results were reported by Fess & Benedito (2018) and Palomo-Campesino et al. (2021). In the organically managed farms, there was greater use of no-till/minimum tillage, organic composting, Bokashi-type compost, biofertilizers, crop rotation, green manure, living or dead soil cover, and vegetable gardens in the agroforestry systems and consortia.

Table 1. Frequencies of soil management practices observed in the organic and conventional vegetable production systems where samples were taken for soil health assessment.

Practices	Organic System		Conventional System		P value *
	n/N	%	n/N	%	
No-till or Minimum tillage	8/48	17	2/42	5	< 0.01
Subsoiler	14/48	29	12/42	29	1.00
Tillage (1 to 4 times/crop)	40/48	83	36/42	86	0.75
Tillage (5 to 6 times/crop)	0/48	0	4/42	10	0.06
Organic amendments [1]	27/48	56	32/42	76	< 0.01
Compost (all types)	40/48	83	11/42	26	< 0.01
Bokashi compost [2]	15/48	31	2/42	5	< 0.01
Biofertilizers	24/48	50	11/42	26	< 0.01
Crop rotation	43/48	90	24/42	50	< 0.01
Green manure	25/48	52	7/42	17	< 0.01
Cover crop	22/48	46	4/42	10	< 0.01
Agroforestry systems [3]	5/48	10	0/42	0	0.06
Intercropping	20/48	42	5/42	12	< 0.01

[1]noncomposted; [2]specifically Bokashi compost; [3]vegetables grown in agroforestry systems; n= number of samples in which the practice was adopted; N= total number of organic or conventional samples. * P value according to the Z test at 5% significance.

Interestingly, although mechanical tillage practices for soil preparation were similar between organic and conventional farms, organically managed sites had higher rates of natural soil cover and less soil disturbance due to greater use of minimum or no-tillage systems. It is important to note that, in both vegetable production systems (organic and conventional), the use of mechanical soil preparation is widely adopted by producers for raising beds, incorporating fertilizers, and weed control (Chen et al., 2017), which can be detrimental to SH, as observed by Valarini et al. (2011). Conservation practices have been widely researched and promoted to produce vegetables with greater adoption of agroecological practices, improving SH, and enhancing the economic performance of farms (Price & Norsworthy, 2013; Lima et al., 2017; Palomo-Campesino et al., 2022; Comin et al., 2024).

The supply of organic amendments, without a defined frequency, was present in both production systems (organic and conventional). Non-composted organic fertilizers were used on 56% and 76% of the organic and conventional farms, respectively. In the organic production farms, these non-composted organic amendments consisted mainly of castor bean cake and bone meal. In conventional farms, chicken litter, cattle manure, horse manure (matured or not), castor bean cake, and bone meal were common. The amount of organic amendments applied varied from 2 to 20 tonnes per hectare, depending on the crop sequence, availability of financial resources, and suppliers. The quality of the organic amendments used varied among the producers. In the group of organic producers, 83% used some organic compost compared to 26% in conventional farms. Organic compost from cattle or poultry manure, straw, and Bokashi compost (a mixture of wheat bran, microorganisms, and molasses, which may contain chicken litter) were mainly used on organic farms, while urban organic waste compost was used exclusively in the conventional areas studied. The use of organic amendments (e.g., manure and compost) has been shown to increase the activity of enzymes such as GLU and chitinase and to promote the suppression of soil-borne diseases in cultivated plants (Neher et al., 2017). Additionally, it has proven effective in improving crop quality, yield, and greenhouse gas (GHG) mitigation potential (Martínez-Sabater et al., 2022). Several studies have shown that Bokashi, a more elaborate type of organic amendment, is beneficial for plant productivity, microbial activity and biomass, soil fertility, and the physical-hydric properties of substrates and agricultural soils (Gómez-Velasco et al., 2014; Lasmini et al., 2018; Reyna-Ramírez et al., 2018; Kruker et al., 2023). In the present study, Bokashi was used by 31% of the organic producers compared to 5% of the conventional producers. The use of composts in organic farms is more frequent due to their requirement for certification and to improve the quality of the organic input (Moeskops et al., 2010; White et al., 2020). A total of 50% and 26% of organic and conventional areas, respectively, use biofertilizers, which are substances containing living microorganisms with beneficial properties aimed at plant growth promotion and suppression of phytopathogens (Xiong et al., 2017; Zhao et al., 2024). Similar to Bokashi, biofertilizers can increase microbial biomass carbon (MBC), soil enzyme activity (Dinesh et al., 2010; Ou-zine et al., 2022), and crop yields (Lima et al., 2018; Barzee et al., 2019; Thingujam et al., 2020; Pérez et al., 2023).

In terms of mineral fertilizers, the organic systems used thermophosphates, KMag (langbeinite), K_2SO_4, and various rock powders. In conventional systems, several formulas containing conventional N-P-K sources are used. Fertirrigation is also common with intensive use of mineral fertilizers such as potassium nitrate, calcium nitrate, monoammonium phosphate, monopotassium phosphate, and magnesium sulfate.

Green manure, crop rotation, vegetable gardens cultivated in agroforestry systems and natural soil cover were used in 52%, 90%, 10%, and 46% of the organic farms, respectively. On the conventional farms, these percentages were 17%, 50%, 0%, and 10%, respectively. Crop management using organic compost, especially the frequent use of cover crops, also results in greater levels of MBC and enzyme activity (Brennan and Acosta-Martinez, 2019). The list of BMPs widely adopted on organically managed farms also included planned crop rotations and intercropping (Niemi et al., 2008; Fernández et al., 2022). Taken together, these practices can positively affect SH.

6.4.2. Soil texture effects on ARYL, GLU, and SOC

The study encompassed 90 fields with soil samples divided into two groups based on clay content: i) sandy loam, 16-35% clay content, with 30 samples, and ii) clayey texture, 36-64% clay content, with 60 samples. Despite these differences, minimal soil texture effects were observed for ARYL, GLU, and SOC, as shown in Fig. S1 and S2 in the supplementary material.

Soil texture, defined by the granulometric fraction, influences soil function and generally reflects greater carbon retention through organo-mineral associations (Von Lützow et al., 2006; Razafimbelo et al., 2013). Contrary to previous findings associating higher clay concentrations with increased enzyme activity (Vinhal-Freitas et al., 2017) and SOC content (Amsili et al., 2021), at 0-10 cm and 0-15 cm depth, respectively, the present dataset, comprising soil samples from vegetable production systems, showed no significant effects of soil texture on ARYL, GLU, or SOC (Figs. S1 and S2). This result might be attributed to the greater intensity of soil preparation and carbon and nutrient inputs in vegetable production areas compared to those studied by Vinhal-Freitas et al. (2017) in Brazil, which included soils under native vegetation, pasture, and sugarcane. The absence of positive relationships between GLU and ARYL and clay content was also observed in some fields evaluated by Gianfreda et al. (2005) and Passinato et al. (2021) at 5-15 cm and 0-10 cm depth, respectively. Conversely, Bonanomi et al. (2011) reported a negative correlation between ARYL and GLU activities and soil clay content in southern Italy at 0-20 cm depth, attributed to the high affinity of protein molecules for clay surfaces leading to reduced catalytic activity.

In a comprehensive study using a dataset of 1,750 soil samples from New York State, Amsili et al. (2021) found that chemical, physical, and biological indicators were influenced by both soil texture and cropping system and that the magnitude of the effects of soil texture on these parameters differed depending on the parameter evaluated. In the present study, regionally specific results suggest that in vegetable cropping systems, the effects on ARYL, GLU, and SOC associated with differences in carbon and nutrient inputs and soil disturbance by tillage are more pronounced than those associated with soil texture. This finding underscores the need for further research to understand better the effects of soil texture (an inherent and unchangeable property) and cropping system (an anthropogenic effect) on different SH parameters.

Given the limited influence of soil texture observed in our dataset, we were able to analyze the 90 samples together, regardless of their particle size distribution.

6.4.3. Chemical and Biological Soil Properties in Organic and Conventional Vegetable Production Systems

Compared to grain-producing areas within the same region (Sousa and Lobato, 2004), both organic and conventional areas in the present study showed very high levels of soil nutrients and base saturation despite marked differences in fertilizer input quantity and type (organic and mineral) and soil management practices (see Table 2). Wide ranges of P and K values indicate significant variability in these chemical properties between the two production systems. These results can be explained by factors such as underdeveloped root systems in certain cultivars, high P and K requirements, inadequate soil management practices, and substantial nutrient inputs from both chemical and organic fertilizers due to excessive fertilizer use, often exceeding plant needs (Chan et al., 2007; Chen et al., 2017; Wang et al., 2019). Due to this difference, it is now possible to understand the need for a different and specific approach to assessing SQ in vegetable agroecosystems in relation to grains crops production systems.

Table 2. Average ± Standard Deviation of soil chemical properties (0 to 10 cm depth) in 48 organically and 42 conventionally managed vegetable production systems.

System*	P	K	Ca	Mg	Al	H+Al	CEC	V	pH
	mg dm^{-3}		$cmol_c$ dm^{-3}					(%)	(H_2O)
Organic	281±288	315.±224	6.7±1.4	2.8±0.9	0.0	0.6±0.7	10.8±2.2	94±7	7.1±0.3
Conventional	361±290	259±192	6.0±1.4	1.9±0.6	0.0	2.5±1.4	11.1±2.1	78±12	6.5±0.4

ARYL and SOC were significantly greater on organic farms than on conventional farms (*P <0.0001*), whereas GLU was not affected by the vegetable production system (Fig. 2). The study encompassed a wide range of commercial farms differing in the degree of adoption of practices favorable to SH, resulting in a wide range of enzyme activities and SOC levels. For instance, the percent change in ARYL from the lowest to highest observed values (18 to 519 mg p-nitrophenol kg^{-1} soil h^{-1}) was equivalent to 2883%. This relative change was equivalent to 477% for GLU (60 to 286 mg p-nitrophenol kg^{-1} soil h^{-1}) and 540% for SOC (10 to 54 g kg^{-1}). The greater variation in ARYL values observed in the present study reflected its ability to differentiate areas under organic and conventional management compared to SOC and GLU. ARYL, a soil enzyme highly sensitive to changes in soil management, has a great ability to predict trends in SH improvement or reduction (Bandick & Dick, 1999; Balota et al., 2004; Lopes et al., 2013; Mendes et al., 2019a; 2021a; Chaer et al., 2023).

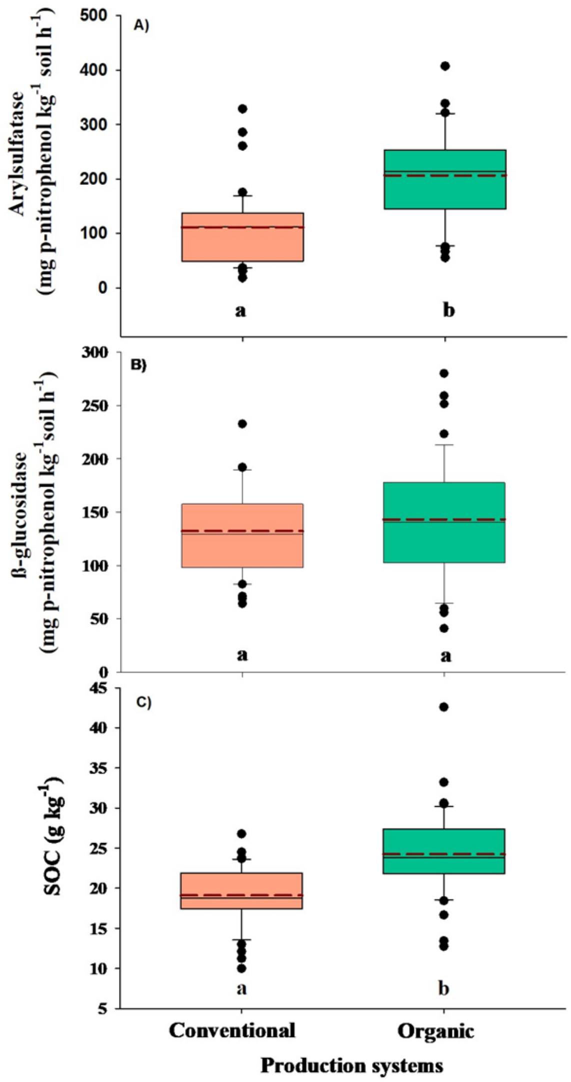


Figure 2. Box plots of Arysulfatase (A), β-glucosidase (B) and soil organic carbon, SOC (C) from commercial vegetable-producing farms under organic and conventional management in the Federal District, Brazil. Box plots identified with similar letters do not differ according to the Wilcoxon test at 5% significance.

The significantly increased levels of ARYL and SOC on organically managed properties can be attributed to the higher frequency and intensity of compost, animal manure, and green manure use compared to conventionally managed farms (Hepperly et al., 2009; Sissoko & Kpomblekou-A, 2010). General agroecosystem management practices, including crop rotation, legume introduction, soil cover, consortia, and reduced tillage, also contribute to this effect (Ugarte et al., 2014; Sánchez-Navarro et al., 2020; Cerecetto et al., 2021). Conversely, on conventional farms, high-intensity vegetable cultivation, frequent tillage, short-lived crops, limited crop rotations, and reduced use of cover crops, green manure, and compost contribute to declining ARYL and SOC levels, negatively impacting SH (Willekens et al., 2014; Bonanomi et al., 2011).

The lack of significant difference between GLU activity levels at organically and conventionally managed vegetable farms might reflect the intensive use of organic amendments, such as poultry waste and cattle manure, on the conventional farms evaluated (Table 1). It is likely that the addition of high amounts of these exogenous organic carbon sources, which act as GLU substrates, increased its activity in conventional fields, resulting in activity levels similar to those obtained at organic sites. Moeskops et al. (2012) reported increased enzyme activities in response to the application of different organic amendments (cattle slurry, farmyard manure, and garden waste compost), particularly the activity of enzymes involved in the decomposition of lignocellulose, such as GLU and β-glucosaminidase.

For vegetable cropping systems, ARYL may more accurately differentiate organic/conventional fields than GLU due to its association with fungal biomass. Ester sulfates, important ARYL substrates (Balota et al. 2004), are characteristic of fungi but not bacteria (Bandick & Dick, 1999; Piutti et al., 2015). In more conservationist systems with greater adoption of sustainable soil management practices, such as organic production systems, fungal populations, and diversity are relatively increased (Scotton et al., 2020; Passinato et al., 2021; Singh et al., 2023). Thus, higher levels of ARYL activity in organic fields may reflect higher fungal biomass production and turnover compared to conventional fields.

A wealth of literature indicates that long-term organic farming significantly increases SOC over conventional systems under different crop/cropping systems (Marriott & Wander, 2006; Leifeld et al., 2009; Campanelli & Canali, 2012; Gajda et al., 2016; Maharjan et al., 2017; Sheoran et al., 2019). In the present study, the average SOC level on organic farms (21.2 g kg^{-1}) at the 0-10 cm depth was 30% greater than that on conventional farms and 20% greater than the critical limit considered adequate (17.5 g kg^{-1}) for tropical clayey Oxisols under grain crops (Mendes et al., 2019b). Further monitoring studies are necessary to verify the impact of SOC increase in organic systems in terms of C sequestration and greenhouse gas emission mitigation in tropical regions. By acting synergistically and in association with the length of time the production systems have been in place, these practices improve overall SH (Crystal-Ornellas et al., 2021; Mauri et al., 2024), as evidenced by increased SOC and ARYL levels in the organically managed farms in the present study.

6.4.4. SH assessments in vegetable cropping systems combining CASH and the 4QM

The SH assessment tool combining CASH and the 4QM applied to the 90 samples will be presented.

Based on the CASH approach, the first step toward the standardization of SOC and ASEA data and deriving interpretive scores is the construction of individual histograms (Fig. S3), and cumulative normal distribution (CND) functions using mean and standard deviation values for SOC and ASEA (Fig. 3). The CND provides scores on a scale ranging from 0 to 100. The thresholds for SOC (22.9 g kg^{-1} soil) and ASEA (6.9) were equivalent to a score of 50, arbitrarily defined as the minimally acceptable values of SOC and ASEA for both economic and soil functioning perspectives in these tropical soils (Chaer et al., 2023). These threshold values defined the four quadrants in the ASEA vs.SOC scatterplot.

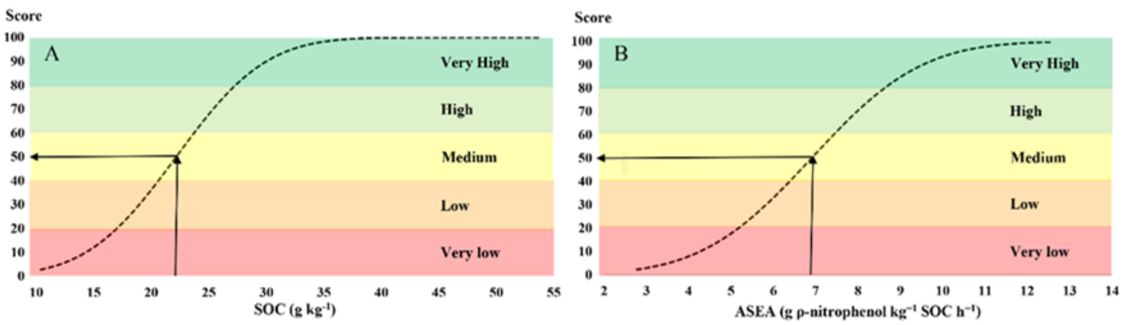


Figure 3. Cumulative normal distribution (CND) for scoring soil organic carbon (SOC) (A) and average specific enzyme activity (ASEA) (B) in soils from commercial farms under vegetable production.

The distribution of the data points (90 samples) in the 4Q graph is shown in Fig. 4. As observed by Chaer et al. (2023), based on the ASEA vs. SOC scatter plot, it was possible to separate the 90 soil samples from vegetable production systems into four quadrants. Quadrants 1 (high SOC/high ASEA) and 3 (low SOC/low ASEA) represented stable patterns of healthy and unhealthy soils, respectively. Quadrants 2 (low ASEA/high SOC) and 4 (high ASEA/low SOC) represented transitional patterns or soils undergoing biological degradation (getting sick) and regenerative processes, respectively. A summary of the distribution of points in each quadrant is presented in Table 3.

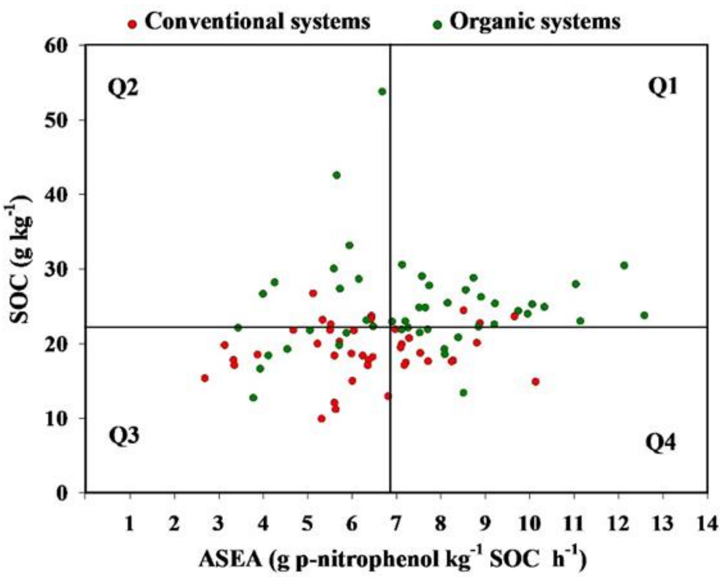


Figure 4. Scatter plot between soil organic carbon (SOC) and average specific enzyme activity (ASEA) from 90 soil samples (0 to 10 cm) from vegetable commercial farms in the Federal District. The soil texture dataset ranges from 16% to 64% clay content.

Table 3. Distribution of the 90 soil samples from organic and conventional vegetable-producing farms in the four quadrants: Q1, Q2, Q3 and Q4.

Quadrant	Number of soil samples		
	Organic farms	Conventional farms	Total
Q1 –Healthy	22	3	25
Q2- Getting sick	10	6	16
Q3- Unhealthy	8	21	29
Q4- Recovering	8	12	20
Total	48	42	90

Since the field sites selected for the present study represented a gradient in terms of the adoption of SH management practices such as cash crop diversity, cover crop use, soil disturbance, and the application of organic amendments, it was not surprising that the 90 soil samples were distributed into the four quadrants. In Q1 (high SOC/high ASEA), equivalent to a healthy soil condition, organic sites predominated, with 22 sites as opposed to only 3 under conventional management. On the other hand, in Q3 (low SOC/low ASEA), which is equivalent to unhealthy soil conditions, conventional sites predominated (21) with only 8 organic sites.

In the transitional quadrant Q2 (high SOC/low ASEA), which represents soils undergoing biological degradation, the numbers of organic and conventional sites were 10 and 6, respectively. The opposite was observed in transitional quadrant Q4 (low SOC/high ASEA), representing soils undergoing regeneration, where the numbers of organic and conventional sites were 8 and 12, respectively.

The distributional properties of the four groups representing commercial vegetable farms are presented in Fig. 5. The box plot distributions of the SOC values from the soil samples in Q1 and Q2 were similar. Furthermore, a similar distribution of SOC values was observed for the soil samples in Q3 and Q4 (Fig. 5A). On average, the SOC values in Q1 and Q2 ranged between 22.3 and 53.8 g kg^{-1}, whereas the SOC values in Q3 and Q4 ranged between 10.0 and 22.2 g kg^{-1} (Fig. 5A). The mean SOC in the soil samples in Q1 and Q2 was 27.1 g kg^{-1}, which was significantly greater (almost 1.5 times) than the mean SOC in the soil samples in Q3 and Q4 (18.5 g kg^{-1}). For the ASEA, the values in Q1 and Q4 were greater than those in Q2 and Q3 (Fig. 5B). The mean ASEAs for Q1, Q2, Q3, and Q4 were 9.1, 5.8, 5.0, and 7.8, respectively.

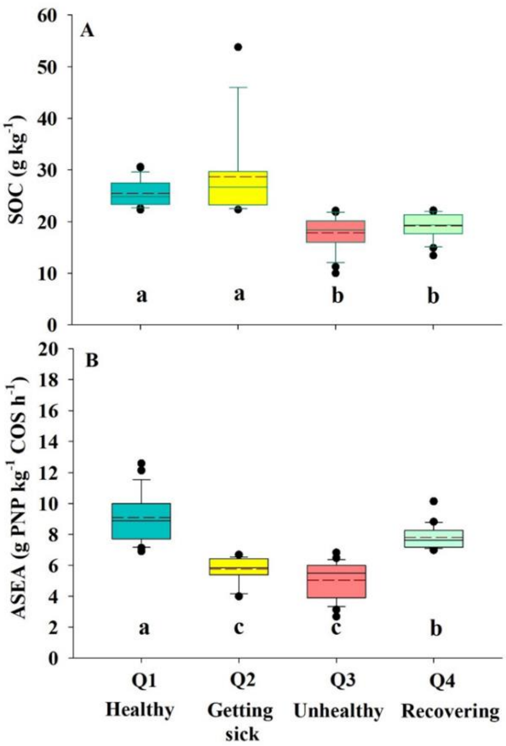


Figure 5. Box plots of soil organic carbon (SOC) (A) and average specific enzyme activity (ASEA) (B) data from 90 sites under commercial vegetable production systems of the Federal District region, Brazil. Soil quality classifications (healthy, getting sick, unhealthy and recovering) are based on data matching into the four-quadrant model. Box plots identified with similar letters do not differ according to the Kruskal–Wallis test ($P < 0.05$).

Different quadrant boundaries were established for the other two soil textural groups (16-35% and 36-60% clay content) to confirm the absence of soil texture effects on the present dataset. Through the use of box plots and the Kruskal–Wallis test at the 5% significance level, the ASEA and SOC values in each of the four quadrants of the three soil textural groups (all 90 samples; 16–35% and 36–60% clay content) were compared (Fig. S4). The analysis revealed no significant differences. In addition, Cohen's Kappa coefficient showed results that varied from "substantial agreement" to "almost perfect agreement," indicating that the number of samples that changed position in the graphical representation of the 4Q due to the different quadrant boundaries associated with soil texture, was not significant (data not shown). All these results confirmed the absence of significant soil textural effects on these samples from vegetable cropping systems, as discussed in section 3.2.

Combining the CASH and 4QM approaches for assessing SH in vegetable cropping systems has proven highly promising. The 90 field sites were successfully categorized based on the history of management practices adopted at each site. Notably, the distribution of soil samples from organic and conventional systems across the four quadrants enabled the identification of areas with the best soil management practices, as plotted in Q1, supported by both field observations and the results of semi-structured interviews. Conversely, field sites with greater adoption of practices unfavorable to SH were positioned in Q3. For instance, 100%, 84%, 84%, 64%, 48%, 28% of the samples classified in Q1 used crop rotation, compost, green manures or fallow with grasses or corn, intercropping or agroforestry systems, biofertilizers, soil predominantly covered with plant residues or with living mulch, respectively. While in quadrant Q3, this same sequence of observed practices was 48%, 21%, 34%, 3%, 31%, 0%. It is important to note that despite the predominance of soil samples from organic farms in Q1 (46% of total samples from organically managed sites), samples from these areas were also present in Q2 (21%) and Q3 (17%). Similarly, despite the prevalence of soil samples from conventional farms in Q3 (50% of total samples from these sites), samples from these areas were also found in Q1 (7%) and Q4 (29%).

These results showed that conventional and organic systems can cause soil degradation due to the management practices adopted at each site, such as mechanized and intensive tillage, lower adoption of cover crops, lack of soil cover, and adequate crop rotations (Valarini et al., 2011). The reasons for the presence of organic sites in Q2 and Q3 were the short conversion time to organic management, the length of agroecological management adoption, or the discontinuation of certain practices beneficial to the soil due to problems related to operational management or possibly for economic reasons on the farm. On the other hand, as shown in Table 3, 7% and 29% of the soil samples from conventionally managed sites were plotted in Q1 (healthy soils) and Q4 (soils under regeneration), respectively. These results demonstrate that under certain circumstances, that is, with adopting BMPs, particular crop types, and growing conditions, conventional systems can match organic systems in terms of SH. For example, one of the conventional farms with two samples classified as Q1 constantly used biofertilizers, bokashi-type compost, annual subsoiling, crop rotation, green manuring, and less intense soil preparation. The third sample came from a farm where biofertilizers were used weekly. In addition, crop rotation, less intense tillage, reduced use of synthetic mineral fertilization, and thin alternating layers of straw and manure distributed directly on the soil were common practices. In this way, it was possible to state that the classification of the samples in this study into 4 quadrants was consistent with field observations and the recent history reported by farmers, as observed by Chaer et al. (2023) in their dataset for model validation.

Notably, 43 of the 54 areas distributed in quadrants 1 and 3 have been under consistent use and similar management practices for over 5 years, with 25 areas exceeding 20 years. This suggests that even in vegetable crop areas, which typically undergo more intensive and dynamic management than grain-producing areas, there is a tendency for stabilization into certain patterns, namely, healthy (Quadrant 1) or diseased (Quadrant 3) soils. Conversely, among the 18 samples with less than 5 years of management, 11 were distributed across quadrants 2 and 4. This indicates that the persistent adoption of practices detrimental to SH or BMPs can, within a shorter timeframe, result in either a getting sick (Q2) or recovering (Q4) soil condition, respectively.

In Brazil, organic producers still lack significant investment in research and technical assistance (Andow et al., 2017; Vilpoux et al., 2021). Nevertheless, as demonstrated in the present study, well-managed organic production systems not only have the capacity to provide high-quality food products but also contribute to improving SH, a crucial factor in reversing trends of soil degradation. The increasing adoption of practices such as compost use, bokashi, biofertilizers, crop rotation, cover crops, and minimal soil disturbance in well-managed conventional production systems has also led to improvements in SH. This study revealed that compared with conventional systems, organic systems exhibited better results in terms of SH, supporting findings from previous studies (Bonanomi et al., 2011; Fess & Benedito, 2018; Palomo-Campesino et al., 2022; Liebert, 2022).

Assessments of SH based on ASEA and SOC, utilizing a combination of the CASH and 4QM approaches, revealed discernible trends of both deterioration and improvement in SH under both conventional and organic management systems. These findings highlight the extent to which healthy soil management practices are embraced in both systems. Examples include using high-quality organic amendments, green manuring, reduced tillage intensity, appropriate crop rotations, and composting. Indeed, there is a window of opportunity for the adoption of agroecological practices by both organic and conventional producers, thereby enhancing the sustainability of their respective systems (Palomo-Campesino et al., 2021).

Achieving a balance between promoting productivity and minimizing environmental impact is essential. In this way, public policies play a crucial role in shaping the practices and outcomes of both organic and conventional vegetable production systems, particularly in the context of SH (Schmidt et al., 2023). These policies may include financial support for soil conservation measures, research, technical assistance, funding for innovative farming techniques, government purchases of agricultural products from more sustainable systems, promotion of media engagement, and regulations that encourage responsible land management, such as payment for environmental services. Ultimately, comprehensive public policies on SH benefit farmers, the environment, and consumers by ensuring the resilience and productivity of vegetable production systems. In Brazil, law 10.831/2003, which introduced the principles of organic farming, indicates an increase in biological activity and the promotion of SH, as well as the maintenance or increase in fertility in the long term, as the goals of an organic farming system. Currently, several other public policies and their upgrades benefit farmers in general, such as the ABC Plan (Low Carbon Agriculture), the National Policy for Agroecology and Organic Production, and the National Bioinputs Program (Vidal et al., 2021). All of them support conventional, organic, and agroecological transition farmers promoting the use of more sustainable inputs and the adoption of BMPs such as crop rotation, cover crops, minimum or no-tillage, the biological control of pests and diseases, integrated crop-livestock-forest systems, the use of urban organic waste, biochar from sewage sludge, biofertilizers, biological plant growth promoters, and the reduced use of chemicals.

6.5. Conclusions

Adopting practices that could improve or maintain SH was significantly greater on organic farms than on conventionally managed farms, resulting in higher SOC content and ARYL levels.

Among the two enzymes evaluated, ARYL differentiated organic and conventional fields more accurately than GLU, confirming its potential for SH evaluation in vegetable production systems.

Soil texture did not influence the SH assessments in this dataset, allowing the 90 fields to be assessed together, regardless of their particle size distributions.

The proposed combination of CASH and the 4QM approach, coupled with measurements of ARYL, GLU, and SOC, is simple and affordable and has proven capable of addressing the complexity of organic and conventional vegetable production systems. This approach allows the differentiation of these systems based on different levels of adoption of BMPs. With the SH assessment derived from this method, it is possible to provide farmers with recommendations for more sustainable soil management decisions. This, in turn, supports the continuity of economically viable vegetable production in the long term while ensuring the environmentally sound conservation of natural resources and their associated ecosystem services.

6.6. References

Acosta-Martínez, V. Pérez-Guzmán, L., Veum, K.S., Nunes, M.R., Dick, R.P., 2021. Metabolic activity– Enzymes. In: Karlen, D.L., Stott, D.E., Mikha, M.M. (ed.). Soil Health Series: Laboratory Methods for Soil Health Analysis. Madison, WI: John Wiley & Sons, 2, 194–251.

Alvares, C.A., Stape, J.L., Sentelhas, P.C., de Moraes Gonçalves, J.L., Sparovek, G., 2013. Köppen's climate classification map for Brazil. Meteorol. Z. 22, 711–728. http://dx.doi.org/10.1127/0941-2948/2013/0507

Amsili, J.P., Van Es, H.M., Schindelbeck, R.R., 2021. Cropping system and soil texture shape soil health outcomes and scoring functions. Soil Security 4, 100012. https://doi.org/10.1016/j.soisec.2021.100012

Andow, D.A., Resende filho, M.A., Carneiro, R.G., Lorena, D.R., Sujii, E.R., Alves, R.T., 2017. Heterogeneity in intention to adopt organic strawberry production practices among producers in the federal district, Brazil. Ecol. Econ. 140, 177–189. https://doi.org/10.1016/j.ecolecon.2017.04.026

Andrews, S.S., Karlen, D.L., Cambardella, C.A., 2004. The soil management assessment framework. Soil Sci. Soc. Am. J. 68, 1945-1962. http://dx.doi.org/10.2136/ sssaj 2004.1945.

Balota, E.L., Kanashiro, M., Colozzi Filho, A., Andrade, D.S., Dick, R.P., 2004. Soil enzyme activities under long-term tillage and crop rotation systems in subtropical agro-ecosystems. Braz. J. Microbiol. 35, 300–306. https://doi.org/10.1590/S1517-83822004000300006

Bandick, A.K.; Dick, R.P., 1999. Field management effects on soil enzyme activities. Soil Biol. Biochem. 31, 1471–1479. https://doi: 10.1016/S0038-0717(99)00051-6

Barzee, T.J., Edalati, A., El-Mashad, H., Wang, D., Scow, K., Zhang, R., 2019. Digestate Biofertilizers Support Similar or Higher Tomato Yields and Quality Than Mineral Fertilizer in a Subsurface Drip Fertigation System. Front. Sustain. Food Syst. 3, 58. https://doi.org/10.3389/fsufs.2019.00058

Bonanomi, G., D'ascoli, R., Antignani, V., Capodilupo, M., Cozzolino, L., Marzaioli, R., Puopolo, G., Rutigliano, F.A., Scelza, R., Scotti, R., Rao, M.A., Zoina, A., 2011. Assessing soil quality under intensive cultivation and tree orchards in Southern Italy. Appl. Soil Ecol. 47, 184–194. https://doi.org/10.1016// j.apsoil.2010.12.007

Brennan, E.B., Acosta-Martinez, V., 2019. Cover Crops and Compost Influence Soil Enzymes during Six Years of Tillage-Intensive, Organic Vegetable Production. Soil Sci. Soc. Am. J. 83, 624–637. https://doi.org/10.2136/sssaj2017.12.0412

Campanelli, G., Canali, S., 2012. Crop production and environmental effects in conventional and organic vegetable farming systems: the case of a long-term experiment in mediterranean conditions (Central Italy). J. Sustain. Agric. 36, 599–619. https://doi.org/10.1080/10440046.2011.646351

Cerecetto, V., Smalla, K., Nesme, J., Garaycochea, S., Fresia, P., Sorensen, S.J., Babin, D., Leoni, C., 2021. Reduced tillage, cover crops and organic amendments affect soil microbiota and improve soil health in Uruguayan vegetable farming systems. FEMS Microbiol. Ecol. 97(3). https://doi.org/10.1093/femsec/fiab023

Chaer, G.M., Mendes, I.C., Dantas, O.D., Malaquias, J.V., Reis Junior, F.B., Oliveira, M.I.L., 2023. Evaluating C trends in clayey Cerrado Oxisols using a four-quadrant model based on specific arylsulfatase and β-glucosidase activities. Appl. Soil Ecol. 183, 104742. https://doi.org/10.1016/j.apsoil.2022.104742

Chan, K.Y., Dorahy, C.G., Tyler, S., Wells, A.T., Milham, P.P., Barchia, I., 2007. Phosphorus accumulation and other changes in soil properties as a consequence of vegetable production, Sydney region, Aust. J. Soil Res. 45, 139-146. https://doi.org/10.1071/SR06087

Chen, G., Kolb, L., Leslie, A., Hooks, C.R.R., 2017. Using reduced tillage and cover crop residue to manage weeds in organic vegetable production. Weed Technol. 31, 557–573. https://doi.org/10.1017/wet.2017.24

Chen, S., Yan, Z., Chen, Q., 2017. Estimating the potential to reduce potassium surplus in intensive vegetable fields of China. Nutr. Cycl. Agroecosys. 107, 265–277. https://doi.org/10.1007/s10705-017-9835-0

Comin, J.J., Vezzani, F., Souza, M., Kurtz,C., Mafra, A.L., Lovato, P. E., Lourenzi, C. R. , Loss, A., 2024. Soil Health and no-tillage Vegetable production systems-SPDH. In: Mendes, I.C.; Cherubin, M.R. (ed.). Soil health and sustainable agriculture in Brazil. 01ed. Soil Sci. Soc. Am., 01, Madison, WI. pp. 208-237.

Crystal-Ornellas, R., Thapa, R., Tully, K.L., 2021. Soil organic carbon is affected by organic amendments, conservation tillage, and cover cropping in organic farming systems: A meta-analysis. Agric. Ecosyst. Environ. 312, 107356. https://doi.org/10.1016/j.agee.2021.107356

Deng, S., Popova, I., 2011. Carbohydrate hydrolases. In: Dick, R.P. (Ed.), Methods of Soil Enzymology, SSSA Book Ser, 9. SSSA, Madison, WI. https://doi.org/10.2136/sssabookser9.c9, pp. 851–209.

Dinesh, R., Srinivasan, V., Hamza, S., Manjusha, A., 2010. Short-term incorporation of organic manures and biofertilizers influences biochemical and microbial characteristics of soils under an annual crop [Turmeric (Curcuma longa L.)].

Bioresour. Technol. 101, 4697–4702. https://doi.org/10.1016/j.biortech.2010.01.108

Fernández, J.A., Ayastuy, M.E., Belladonna, D.P., Comezaña, M.M., Contreras, J., de Maria Mourão, I., Orden, L., Rodríguez, R.A., 2022. Current trends in organic vegetable crop production: practices and techniques. Horticulturae 8, 893. https://doi.org/10.3390/horticulturae8100893

Fess, T., Benedito, V., 2018. Organic versus conventional cropping sustainability: a comparative system analysis. Sustainability 10, 272. https://doi.org/10.3390/su10010272

Figuerêdo, K.S., Pereira, M.T.J., Nick, C., Silva, I.R., Oliveira, T.S., 2020. Long-term changes in organic matter stocks and quality in an Oxisol under intensive vegetable cultivation. Catena 188, 104442. https://doi.org/10.1016/j.catena.2019.104442

Gajda, A. M., Ewa, A. C., Dexter, A. R., 2016. Effects of long-term use of different farming systems on some physical, chemical and microbiological parameters of soil quality. Int. Agrophys. 30, 165-172. https://doi.org/10.1515/intag-2015-0081

Gianfreda, L., Antonietta R. M., Piotrowska, A., Palumbo, G., Colombo, C., 2005. Soil enzyme activities as affected by anthropogenic alterations: intensive agricultural practices and organic pollution. Sci. Total Environ. 341, 265–279. https://doi.org/10.1016/j.scitotenv.2004.10.005

Gómez-Velasco, D.A., Álvarez-Solís, J.D., Ruiz-Valdiviezo, V.M., Abud-Archila, M., Montes-Molina, J.A., Dendooven, L., Gutiérrez-Miceli, F.A., 2014. Enzymatic activities in soil cultivated with coffee (Coffea arabica L. cv. 'Bourbon') and amended with organic material. Commun. Soil Sci. Plant. Anal. 45, 2529–2538. https://doi.org/10.1080/00103624.2014.932375

Hepperly, P., Lotter, D., Ulsh, C.Z., Seidel, R., Reider, C., 2009. Compost, manure and synthetic fertilizer influences crop yields, soil properties, nitrate leaching and crop nutrient content. Compost Sci. Util. 17, 117–126. https://doi.org/10.1080/1065657X.2009.10702410

Hussain, I., Olson, K.R., Wander, M.M., Karlen, D.L., 1999. Adaptation of soil quality indices and application to three tillage systems in southern Illinois. Soil Till. Res. 50:237–249. https://doi:10.1016/S0167-1987(99)00012-4

Jackson, M.L., 1958. Soil Chemical Analysis. Prentice Hall, Englewood Cliffs, NJ.

Kalkhajeh, Y.K., Huang, B., Hu, W., Ma, C., Gao, H., Thompson, M.L., Hansen, H.C.B., 2021. Environmental soil quality and vegetable safety under current greenhouse vegetable production management in China. Agr. Ecosyst. Environ. 307, 107230. https://doi.org/10.1016/j.agee.2020.107230

Karlen, D.L., Stott, D.E., 1994. A framework for evaluating physical and chemical indicators of soil quality. In: J.W. Doran et al. (ed.). Defining soil quality for a sustainable environment. SSSA Spec. Publ. 35. SSSA and ASA, Madison, WI. pp. 53–72.

Klose, S., Bilen, S., Tabatabai, M.A., Dick, W.A., 2011. Sulfur cycle enzymes. In: Dick, R. P. (Ed.), Methods of soil enzymology, 1st1. Soil Science Society of America, Madison, WI, USA, pp. 125–156.

Kruker, G., Guidi, E.S., Santos, J.M.D.S.D., Mafra, A.L., Almeida, J.A.D., 2023. Quality of Bokashi-Type Biofertilizer Formulations and Its Application in the Production of Vegetables in an Ecological System. Hortic. 9, 1314. https://doi.org/10.3390/horticulturae9121314

Leifeld J., Reiser R. Oberholzer, H. R., 2009. Consequences of conventional versus organic farming on soil carbon: Results from a 27-Year Field Experiment. Agron. J. 101, 204–1218. https://doi.org/10.5958/0974-0228.2016.00014.1

Lasmini, S., Nasir, B., Hayati, N., Edy, N., 2018. Improvement of soil quality using bokashi composting and NPK fertilizer to increase shallot yield on dry land. Aust. J. Crop Sci. 12, 1743–1749. https://doi.org/10.21475/ ajcs.18.12.11.p1435

Liebert, J., Benner, R., Kerr, R.B., Björkman, T., De Master, K.T., Gennet, S., Gómez, M.I., Hart, A.K., Kremen, C., Power, A.G., Ryan, M.R., 2022. Farm size affects the use of agroecological practices on organic farms in the United States. Nat. Plants 8, 897–905. https://doi.org/10.1038/s41477-022-01191-1

Lima, C.E.P., Silva, J., Guedes, I.M.R., Madeira, N.R., Fontenelle, M.R., 2017. Management systems effect on fertility indicators of a Ferralsol with vegetable crops, as determined by different statistical tools. Rev. Bras. Ciênc. Solo 41, e0160468. https://doi.org/10.1590/18069657rbcs20160468

Lima, F.A., Viana, T.V.A., Sousa, G.G., Correia, L.F.M., Azevedo, B.M., 2018. Yield of strawberry crops under different irrigation levels and biofertilizer doses. Rev. Ciênc. Agron. 49, 381–388. https://doi.org/10.5935/1806-6690.20180043

Lopes, A.A.C., Sousa, D.M.G, Chaer, G.M., Reis Junior, F.B., Goedert, W.J., Mendes, I.C., 2013. Interpretation of microbial soil indicators as a function of crop yield and organic carbon. Soil Sci. Soc. Am. J. 77, 461–472. https:// doi.org/10.2136/sssaj2012.0191

Maharjan, M., Sanaullah, M., Razavi, B.S., Kuzyakov, Y., 2017. Effect of land use and management practices on microbial biomass and enzyme activities in subtropical topand sub-soils. Appl. Soil Ecol. 113, 22-28. https://doi.org/ 10.1016/j.apsoil.2017.01.008

Martínez-Sabater, E., Pérez-Murcia, M.D., Andreu-Rodríguez, F.J., Orden, L., Agulló, E., Sáez-Tovar, J., Martínez-Tome, J., Bustamante, M.A., Moral, R., 2022. Enhancing Sustainability in Intensive Dill Cropping: Comparative effects of biobased fertilizers vs. inorganic commodities on greenhouse gas emissions, crop yield, and soil properties. Agronomy 12, 2124. https://doi.org/10.3390/ agronomy12092124

Mauri, L.V.R., Mendonça, E.D.S., Bolzan, L.J., Angeletti, M.D.P., 2024. olericulture no-till system at mountain region: physical and biological attributes of the soil. Appl. Environ. Soil Sci. 2024, 1–11. https://doi.org/10.1155/2024/8682240.

Marriott, E. E., Wander, M. M., 2006. Total and labile soil organic matter in organic and conventional farming systems. Soil Sci. Soc. Am. J. 70, 950–959. https://doi.org/10.2136/sssaj2005.0241

Mendes, I.C., Tormena, C.A., Cherubin, M.R., Karlen, D.L., 2018. Soil health assessment and maintenance in central and south-central Brazil. In: Reicosky, D. (Ed.), Managing Soil Health for Sustainable Agriculture: Monitoring and Management, 1ed.2. Burleigh Dodds Science publishing, 379–415. https://doi.org/ 10.19103/AS.2017.0033.35

Mendes, I.C.; Sousa, D.M.G.; Reis Junior, F.B.; Lopes, A.A.C.; Souza, L.M.; Chaer, G.M. 2019a. Bioanálise de solo: aspectos teóricos e práticos. Tópicos Ci. Solo 10, 1-64.

Mendes, I.C., Souza, L.M., Sousa, D.M.G., Lopes, A.A.C., Reis Junior, F.B., Lacerda, M.P.C., Malaquias, J.V., 2019b. Critical limits for microbial indicators in tropical Oxisols at post-harvest: The FERTBIO soil sample concept. Appl. Soil Ecol. 139, 85–93. https://doi.org/10.1016/j.apsoil.2019.02.025

Mendes, I.C., Sousa, D.M.G., Chaer, G.M., Reis Junior, F.B., Lopes, A.A.C., Dantas, O.D., Souza, L.M., 2021a. Soil bioanalysis: a simple and effective tool to access and interpret soil health. In: Proceedings of the Global Symposium on Soil Biodiversity 256–261. https://doi.org/10.4060/cb7374en

Mendes, I.C., Sousa, D.M.G., Dantas, O.D., Lopes, A.A.C., Reis Junior, F.B., Oliveira, M.I.L., Chaer, G.M., 2021b. Soil quality and grain yield: a win win combination in clayey tropical oxisols. Geoderma 388, 114880. http://dx.doi.org/10.1016/j.geoderma.2020.114880

Mendes, I. C., Chaer, G.M., Reis Junior, F.B. Oliveira, M.I.L., Dantas, O.D., Malaquias, J.V., 2023. Fazendas de referência para a implementação do modelo de quatro quadrantes na avaliação de tendências do carbono do solo pela tecnologia BioAS, Embrapa Cerrados, Planaltina, DF, 41p.

Mendes, I. C., Chaer, G.M., Reis Junior, F.B., Dantas, O.D., Malaquias, J. V., Oliveira, M.I.L., Nogueira, M.A., Hungria, M., 2024. Soil Bioanalysis (SoilBio): A sensitive, calibrated, and simple Assessment of Soil Health for Brazil. In: Mendes, I.C.; Cherubin, M.R. (ed.). Soil health and sustainable agriculture in Brazil. 01ed. Soil Sci. Soc. Am., 01, Madison, WI. pp. 292-326.

Moebius-Clune, B.N., Moebius-Clune, D.J., Gugino, B.K., Idowu, O.J., Schindelbeck, R.R., Ristow, A.J., Van Es, H.M.; Thies, J.E.; Shayler, H.A.; Mcbride, M.B.; Kurtz, K.S.M; Wolfe, D.W.; Abawi, G.S., 2016. Comprehensive assessment of soil health- The cornell framework, edition 3.2, Cornell University, Geneva, NY. 134p.

Moeskops, B., Sukristiyonubowo, Buchan, D., Sleutel, S., Herawaty, L., Husen, E., Saraswati, R., Setyorini, D., Neve, S., 2010. Soil microbial communities and activities under intensive organic and conventional vegetable farming in West Java, Indonesia. Appl. Soil Ecol. 45, 112–120. https://doi.org/10.1016/j.apsoil.2010.03.005

Moeskops, B., Buchan, D., Sukristiyonubowo, Neve, S., Gusseme, B., Widowati, L.R., Setyorini, D., Sleutel, S., 2012. Soil quality indicators for intensive vegetable production systems in Java, Indonesia. Ecol. Indic. 18, 218–226. https://doi.org/10.1016/j.ecolind.2011.11.011

Neher, D.A., Fang, L., Weicht, T.R., 2017. Ecoenzymes as indicators of compost to suppress *Rhizoctonia Solani*. Compost Sci. Util. 25, 251–261. https://doi.org/10.1080/1065657X.2017.1300548

Nelson, D.W., Sommers, L.E., 1996. Total carbon, organic carbon, and organic matter. In: Methods of Soil Analysis: Part 3 Chemical Methods, 5.3, 961–1010. https://doi.org/10.2136/sssabookser5.3.c34

Niemi, R.M., Vepsäläinen, M., Wallenius, K., Erkomaa, K., Kukkonen, S., Palojärvi, A., Vestberg, M., 2008. Conventional versus organic cropping and peat amendment: Impacts on soil microbiota and their activities. Eur. J. Soil Biol. 44, 419–428. https://doi.org/10.1016/j.ejsobi.2008.06.001

Norris, C.E., Congreves, K.A., 2018. Alternative management practices improve soil health indices in intensive vegetable cropping systems: A review. Front. Environ. Sci. 6, 50. https://doi.org/10.3389/fenvs.2018.00050

Nunes, M. R., Veum, K. S., Parker, P. A., Holan, S. H., Karlen, D. L., Amsili, J. P., van Es, H. M., Wills, S. A., Seybold, C. A., & Moorman, T. B., 2021. The soil health assessment protocol and evaluation applied to soil organic carbon. Soil Sci. Soc. Am. J. 85(4), 1196–1213. https://doi.org/10.1002 /saj2.20244

Oldfield, E.E., Bradford, M.A., Augarten, A.J., Cooley, E.T., Radatz, A.M., Radatz, T., Ruark, M.D., 2022. Positive associations of soil organic matter and crop yields across a regional network of working farms. Soil Sci. Soc. Am. J. 86, 384–397. https://doi.org/10.1002/saj2.20349

Ou-Zine, M., El Hilali, R., Haggoud, A., Achbani, E.H., Bouamri, R., 2022. Effects and Relationships of Compost Dose and Organic Additives on Compost Tea Properties, Efficacy Against Fusarium oxysporum and Potential Effect on Endomycorrhization

and Growth of Zea mays L. Waste Biomass Valori. 13, 4431–4445. https://doi.org/10.1007/s12649-022-01795-w
Palomo-Campesino, S., García-Llorente, M., González, J.A., 2021. Characterizing agroecological and conventional farmers: uncovering their motivations, practices, and perspectives toward agriculture. Agroecol. Sustain. Food Syst. 45, 1399–1428. https://doi.org/10.1080/21683565.2021.1933671
Palomo-campesino, S., García-llorente, M., Hevia, V., Boeraeve, F., Dendoncker, N., Gonzáles, J.A., 2022. Do agroecological practices enhance the supply of ecosystem services? A comparison between agroecological and conventional horticultural farms. Ecosyst. Serv. 57, 101474. https://doi.org/10.1016/j.ecoser.2022.101474
Passinato, J.H., Amado, T.J.C., Kassam, A., Acosta, J.A.A., Amaral, L.D.P., 2021. Soil health check-Up of conservation agriculture farming systems in Brazil. Agronomy 11, 2410. https://doi.org/10.3390/agronomy11122410
Pérez, R.O., García, J.C.N., Gallegos-Cedillo, V.M., Ruiz, M.A.D., Hernández, M.S., Nájera, C., Mellado, I.M., Martínez, F.D., 2023. Biofertilizers enriched with PGPB improve soil fertility and the productivity of an intensive tomato crop. Agronomy 13, 2286. https://doi.org/10.3390/ agronomy13092286
Piutti, S., Slezack-Deschaumes, S., Niknahad-Gharmakher, H., Vong, P.-C., Recous, S., Benizri, E., 2015. Relationships between the density and activity of microbial communities possessing arylsulfatase activity and soil sulfate dynamics during the decomposition of plant residues in soil. Eur. J. Soil Biol. 70, 88–96. https://doi.org/10.1016/j.ejsobi.2015.07.007
Price, A.J., Norsworthy, J.K., 2013. Cover crops for weed management in southern reduced-Tillage vegetable cropping systems. Weed Technol. 27, 212–217. https://doi.org/10.1614/WT-D-12-00056.1
Razafimbelo, T., Chevallier, T., Albrecht, A., Chapuis-Lardy, L., Rakotondrasolo, F.N., Michellon, R., Rabeharisoa, L., Bernoux, M., 2013. Texture and organic carbon contents do not impact amount of carbon protected in Malagasy soils. Sci. agric. 70(3), 204–208. https://doi.org/10.1590/S0103-90162013000300009
R Core Team, 2019. R: a Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Austria. https://www.R-project.org/.
Reyna-Ramírez, C.A, Rodríguez-Sánchez, L.M., Vela-Correa, G., Jorge Etchevers-Barrad, J., Fuentes-Ponce, M., 2018. Redesign of the traditional mesoamerican agroecosystem based on participative ecological intensification: Evaluation of the soil and efficiency of the system. Agric. Syst. 165 (2018) 177–186. https://doi.org/10.1016/j.agsy.2018.06.013
Sánchez-navarro, V., Zornoza, R., FAZ, A., Fernández, J. A., 2020. Comparison of soil organic carbon pools, microbial activity and crop yield and quality in two vegetable multiple cropping systems under mediterranean conditions. Sci. Hortic. 261, 109025. https://doi.org /10.1016 /j.scienta.2019.109025
Santos, H.G., Jacomine, P.K.T., Anjos, L.H.C., Oliveira, V.´A., Lumbreras, J.F., Coelho, M.R., Almeida, J.A., Araújo Filho, J.C., Oliveira, J.B., Cunha, T.J.F., 2018. Brazilian soil classification system, 5th ed. Embrapa, Brasília, DF.
Schmidt, N.S., Silva, C.L. da, Santoyo, A.H., 2023. Análise do plano de agricultura de baixo carbono (ABC) no Brasil: resultados e perspectivas. Universidad y Sociedad 15, 279–291.
Scotton, J.C., Homma, S.K., Costa, W.L.F., Pinto, D.F.P., Govone, J.S., Attili-Angelis, D., 2020. Transition management for organic agriculture under citrus cultivation favors fungal diversity in soil. Renew. Agric. Food Syst. 35, 120–127. https://doi.org/10.1017/S1742170518000352

Sheoran, H.S., Phogat, V.K., Dahiya, R., Kakar, R., 2019. Soil organic carbon stocks and carbon dynamics under organic and conventional farming systems in Indo-Gangetic Plains. Indian J. Agric. Sci. 89, 813–820. https://doi.org/10.56093/ijas. v89i5.89663
Singh, I., Hussain, M., Manjunath, G., Chandra, N., Ravikanth, G., 2023. Regenerative agriculture augments bacterial community structure for a healthier soil and agriculture. Front. Agron. 5. https://doi.org/10.3389/fagro.2023.1134514
Sissoko, A., Kpomblekou-A, K., 2010. Carbon decomposition in broiler litter-amended soils. Soil Biol. Biochem. 42, 543–550. https://doi.org/10.1016/j.soilbio. 2009.10.007
Soil Survey Staff, 2014. Keys to Soil Taxonomy, 12 ed. United States Department of Agriculture, Natural Resources Conservation Service, Washington.
Sousa, D.M.G., Lobato, E., 2004. Cerrado: Soil correction and fertilization (In Portuguese), 2nd ed. Embrapa Cerrados, Planaltina. https://www.embrapa. br/busca-de-publicacoes/-/publicacao/555355/cerrado-correcao-do-solo-e-adubacao. (Accessed 4 November 2022).
Stott, D.E., Andrews, S.S., Liebig, M.A., Wienhold, B.J., Karlen, D.L., 2010. Evaluation of β-Glucosidase activity as a soil quality indicator for the soil management assessment framework. Soil Sci. Soc. Am. J. 74, 107-119. http:// dx.doi.org/10.2136/sssaj2009.0029
Tabatabai, M. A., 1994. Soil enzymes. In: WEAVER, R. W., SCOTT, A., BOTTOMLEY, P. J., ed. Methods of soil analysis: microbiological and biochemical properties. Soil Science Society of America: Madison, 778-833.
Teixeira, P.C., Donagemma, G.K., Fontana, A., Teixeira, W.G., 2017. Manual of soil analysis methods (in Portuguese), 3rd ed. Embrapa, Brasília, Brazil. 574p.
Thingujam, U., Bhattacharyya, K., Ray, K., Phonglosa, A., Pari, A., Banerjee, H., Dutta, S., Majumdar, K., 2020. Integrated nutrient management for eggplant: yield and quality models through artificial neural network. *Commun. Soil Sci. Plant Anal.* 51, 70–85. https://doi.org/10.1080/ 00103624.2019.1695824
Trasar-Cepeda, C., Leirós, M.C., Seoane, S., Gil-Sotres, F., 2008a. Biochemical properties of soils under crop rotation. Appl. Soil Ecol. 39, 133–143. https://doi.org/10.1016/j.apsoil.2007.12.003
Trasar-Cepeda, C., Leiros, M.C., Gil-Stores, F., 2008b. Hydrolytic enzyme activities in agricultural and forest soils. Some implications for their use as indicators of soil quality. Soil Biol. Biochem. 40, 2146–2155. https://doi.org/10.1016/j.soilbio .2008.03.015
Ugarte, C.M., Kwon, H., Andrews, S.S., Wander, M.M., 2014. A meta-analysis of soil organic matter response to soil management practices: An approach to evaluate conservation indicators. J. Soil Water Conserv. 69, 422–430. https://doi.org/ 10.2489/jswc.69.5.422
Valarini, P.J., Oliveira, F.R., Schilickmann, S.D.F., Poppi, R.J., 2011. Qualidade do solo em sistemas de produção de hortaliças orgânico e convencional. Hortic. Bras. 29, 485–491. https://doi.org/10.1590/S0102-05362011000400007
Vidal, M.C., Amaral, D.F.S., Nogueira, J.D., Mazzaro, M.A.T., Lira, V.M.C., 2022. Bioinsumos: a Construção de um Programa Nacional pela Sustentabilidade do Agro Brasileiro. Econ. An. L. Rev. 12, 557. https://doi.org/10.31501/ ealr. v12i3.12811
Vilpoux, O.F., Gonzaga, J.F., Pereira, M.W.G., 2021. Agrarian reform in the Brazilian Midwest: Difficulties of modernization via conventional or organic production systems. Land Use Policy 103, 105327. https://doi.org/10.1016/j.landusepol. 2021.105327

Vinhal-Freitas IC, Corrêa GF, Wendling B, Bobul'skác, L., Ferreira, A.S., 2017. Soil textural class plays a major role in evaluating the efects of land use on soil quality indicators Ecol. Indic. 74:182–190. https://doi.org/10.1016/j.ecolind.2016.11.020

Von Lützow, M., K¨ogel-Knabner, I., Ekschmitt, K., Matzner, E., Guggenberger, G., Marschner, B., Flessa, H., 2006. Stabilization of organic matter in temperate soils: mechanisms and their relevance under different soil conditions – a review. Eur. J. Soil Sci. 57 (4), 426–445. https://doi.org/10.1111/j.1365-2389.2006.00809.x

Xiong, W., Guo, S., Jousset, A., Zhao, Q., Wu, H., Li, R., Kowalchuk, G.A., Shen, Q., 2017. Bio-fertilizer application induces soil suppressiveness against Fusarium wilt disease by reshaping the soil microbiome. Soil Biol. Biochem. 114, 238–247. https://doi.org/10.1016/j.soilbio.2017.07.016

Wang, R., Shi, W., Li, Y., 2019. Phosphorus supply and management in vegetable production systems in China. Front. Agr. Sci. Eng. 6, 348. https://doi.org/10.15302/J-FASE-2019277

White, K.E., Brennan, E.B., Cavigelli, M.A., 2020. Soil carbon and nitrogen data during eight years of cover crop and compost treatments in organic vegetable production. Data Brief 33, 106481. https://doi.org/10.1016/j.dib.2020.106481

Willekens, K., Vandecasteele, B., Buchan, D., De Neve, S., 2014. Soil quality is positively affected by reduced tillage and compost in an intensive vegetable cropping system. Appl. Soil Ecol. 82, 61–71. https://doi.org/10.1016/j.apsoil.2014.05.009

Zhao, G., Xiaoling Zhuc, X. Gang Zhenga,G., Meng, G., Dong Z., Baeke, J.H., Jeone, C.O., Yanlai Yaoa, Y., Yuan Hu Xuang, Y.H., Jie Zhang, J., Jia, B., 2024. Development of biofertilizers for sustainable agriculture over four decades (1980–2022). Geogr. Sustain. 5, 19-28. https://doi.org/10.1016/j.geosus.2023.09.006

6.7. Supplementary material – Chapter I

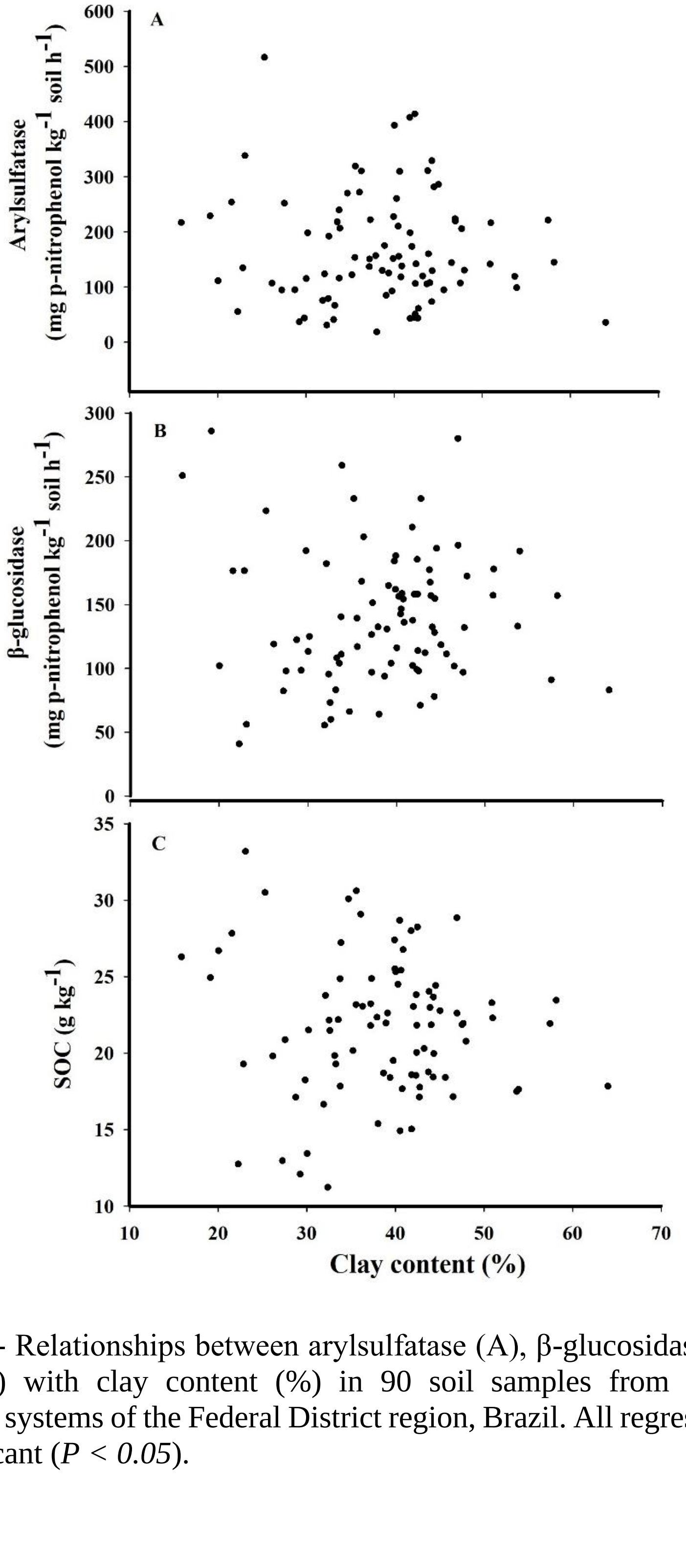


Figure S1 - Relationships between arylsulfatase (A), β-glucosidase (B) and soil organic carbon (C) with clay content (%) in 90 soil samples from commercial vegetable production systems of the Federal District region, Brazil. All regressions parameters were not significant (*$P < 0.05$*).

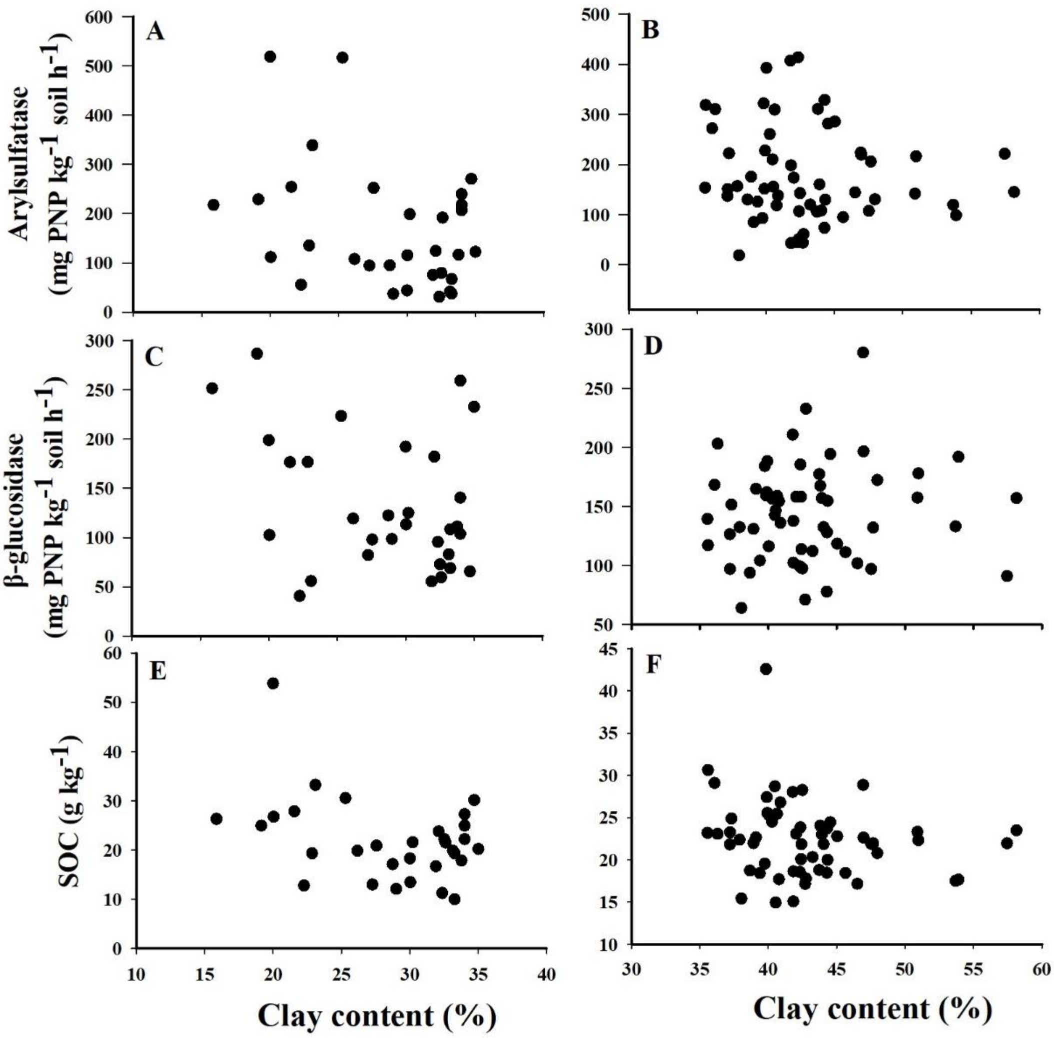


Figure S2. Relationships between arylsulfatase with 16-35% (A) and 36-60% (B) clay content; β-glucosidase with 16-35% (C) and 36-60% (D) clay content; and soil organic carbon (SOC) with 16-35% (E) and 36-60% (F) clay content in soil samples from commercial vegetable production systems of the Federal District region, Brazil. All regressions parameters were not significant ($P < 0.05$).

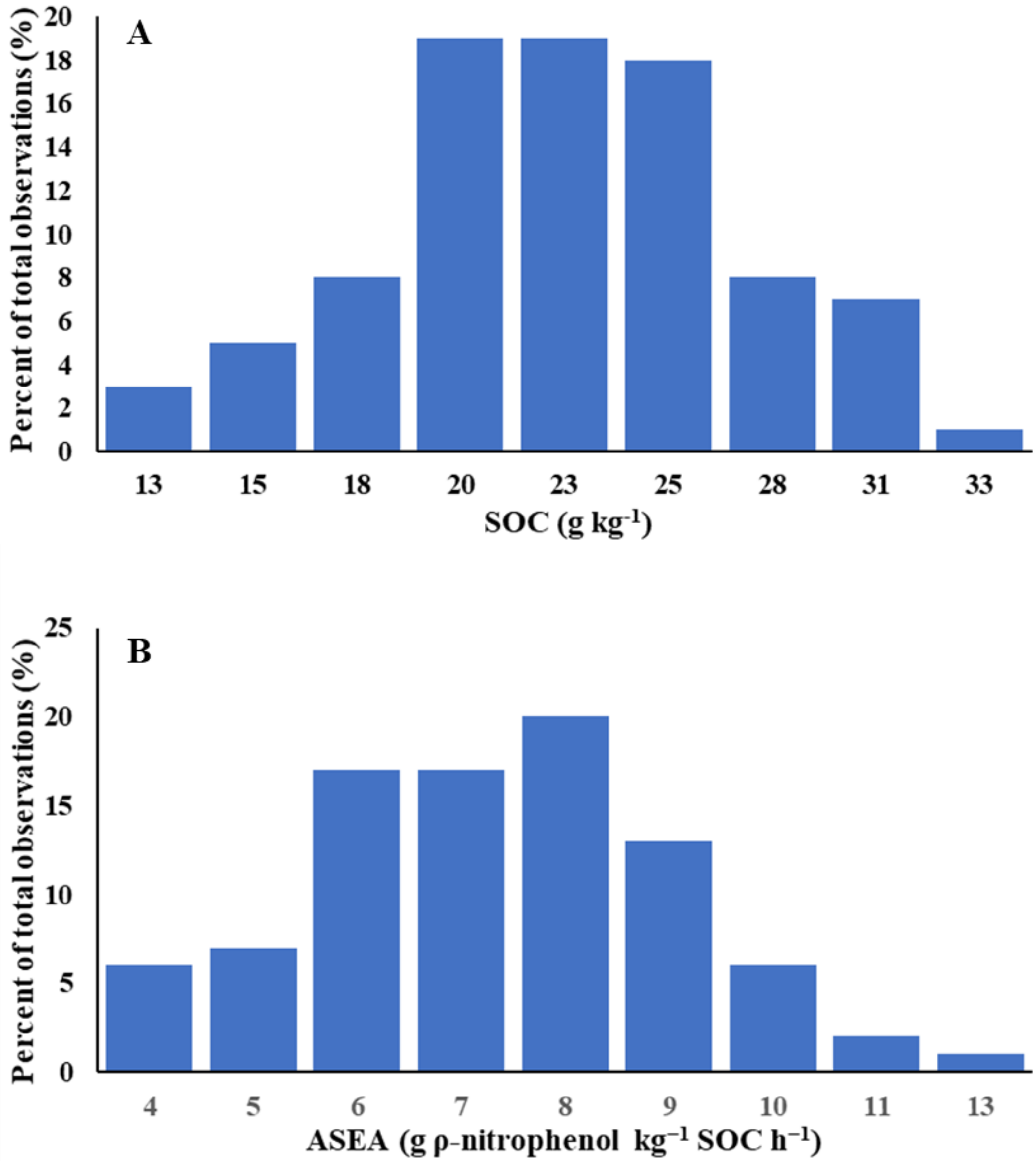


Figure S3. Histograms of the observed distribution of measured values of SOC (A) and ASEA (B) from commercial vegetable-producing farms at the Federal District, Brazil.

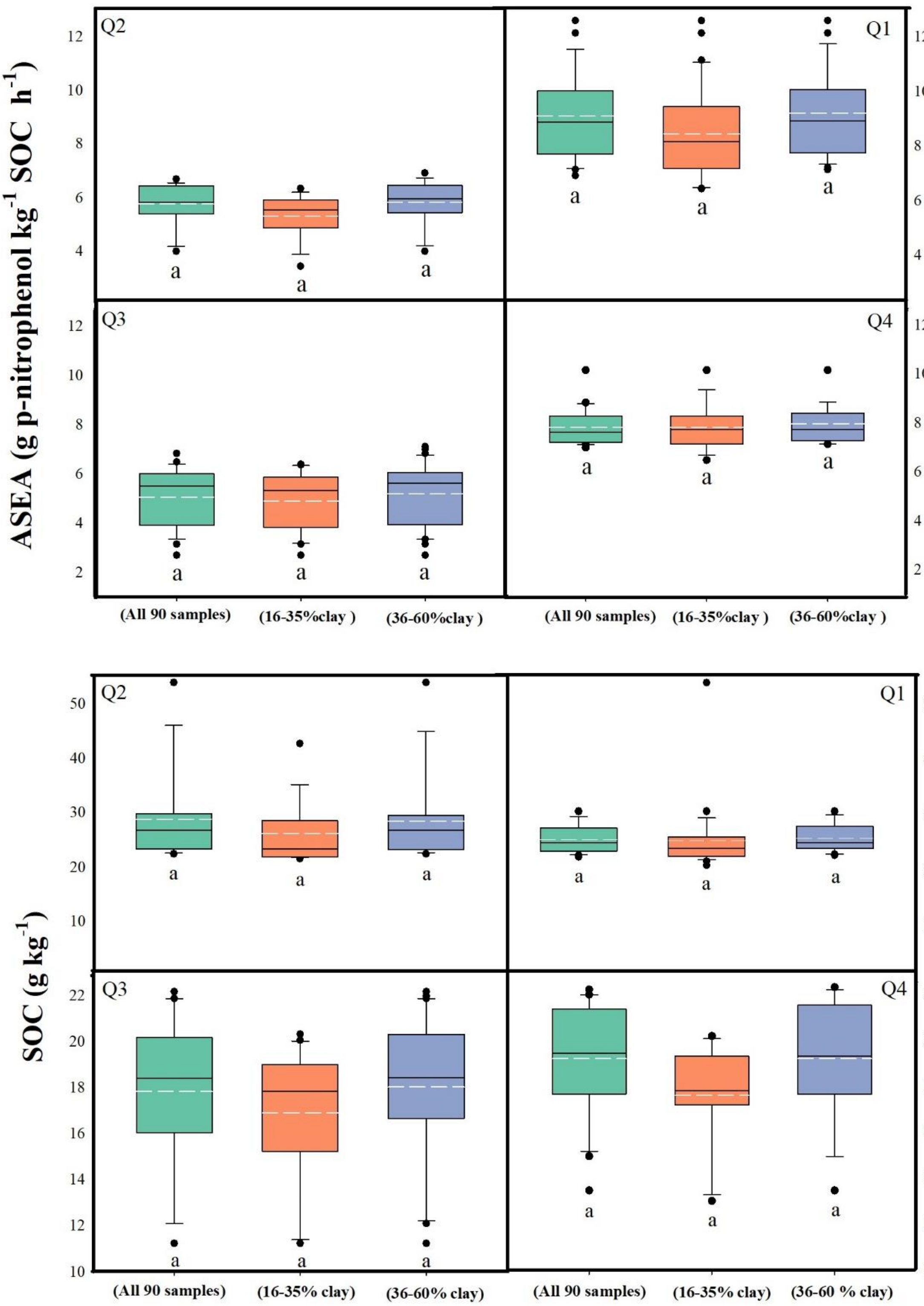


Figure S4. Comparison of ASEA and SOC values in each quadrant according to the different limits established, which varied according to soil texture (samples with 16-35%, 36-60% clay content and all 90 samples). The Kruskal-Wallis test was used with a 5% significance level.

CHAPTER II

CONNECTED APPROACH OF SOIL ORGANIC FRACTIONS AND SOIL HEALTH INDICATORS TO ASSESS CONVENTIONAL AND ORGANIC VEGETABLE PRODUCTION SYSTEMS IN THE BRAZILIAN CERRADO

7. Connected approach of soil organic fractions and soil health indicators to assess conventional and organic vegetable production systems in the Brazilian Cerrado

7.1. Abstract

One of the challenges of sustainable horticulture is to preserve soil quality (SQ) by reducing the intensity of tillage operations and adopting practices that maintain soil organic carbon (SOC). Relationships between best soil management practices, organic matter fractions and soil health in organic and conventional vegetable production systems (VPS) are still unclear. This study aimed to evaluate the relationships between SOC fractions and biological indicators of SQ, looking for potential indicators of the impacts of best soil management practices (BMP) in VPS. The degree of adoption of best management practices in all studied areas was assessed. Ninety soil samples were collected at 0-10 cm depth (48 organic and 42 conventional systems) from 53 vegetable producing areas in the Federal District, Brazil. SOC, total carbon (TC), particulate organic carbon (POC), potassium permanganate oxidizable carbon (POX-C), mineral-associated organic carbon (MOC), fulvic acids (FA) and humic acids (HA), humin (HU), fractions F1, F2, F3, F4, β-glucosidase (GLU) and Arylsulfatase (ARYL) activity were determined. In the field, farmers answered a semi-structured questionnaire relating the management practices adopted in the VPS. ARYL activity levels, labile and stable fractions of SOC were higher in the samples from the organic areas than in the conventional ones, except for F3. ARYL showed moderate and strong correlations with POC, POX-C, F1, F2, HA, HU, SOC and TC, while GLU showed weak correlations with the C fractions analyzed. According to a principal component analysis, the indicators that most differentiated organic and conventional VPS were POC, POX-C, F1, F2, HA, HU, SOC, TC and ARYL. Organic systems can serve as a reference for the search for SQ in vegetable production as they maintain good relationships between organic matter fractions and SQ.

Keywords: Soil quality, soil enzymes, soil organic matter, soil organic matter fractions, organic farming.

7.2. Introduction

It is possible to develop sustainable and productive vegetable production systems (VPS) that not only maintain but enhance soil quality, essential ecosystem services, and food security, while also promoting environmental conservation and contributing to climate change mitigation and adaptation (Altieri et al., 2015; Norris and Congreves, 2018; Resende Filho et al., 2019; Sánchez-Navarro et al., 2019). To achieve greater sustainability, it is essential to reverse soil degradation and preserve its productive capacity along with its complex network of interactions. This can only be accomplished through management practices that enhance soil quality, support biodiversity, and uphold soil ecosystem functions (Srivastava et al., 2016; Palomo-Campesino et al., 2022).

In this context, adopting sustainable management practices that promote the accumulation of SOC is fundamental (Lal, 2016; Obalum et al., 2017). The accumulation of the labile and stable fractions of SOC can be achieved by adopting practices such as the use of cover crops, no-till (NT), agroforestry systems (AFS), crop-livestock integration and composting (Souza et al., 2014; Adeli et al., 2017; Sheoran et al., 2019; Hu et al., 2023; Nanda et al., 2024; Kubar et al., 2024). These practices, which increase plant diversity, also create a positive SOC balance (Sá et al., 2018) and favor the diversification of soil biota (Niemi et al., 2008; Lal, 2016). As a result, various processes are activated such as ecological mechanisms related to nutrient cycling, disease suppression, suitable conditions for root development and better physiological functioning of cultivated plants (Lal, 2016; Palomo-Campesino et al., 2022).

Soil organic matter (SOM) is considered a key indicator of soil quality, due to its positive influence on biological, chemical and physical soil attributes (Karlen et al., 2001; Sparling et al., 2003), such as nutrient cycling, aggregate formation and stability, water retention and cation exchange capacity, provision of habitat and energy for biodiversity (Blanco-Canqui et al., 2013; Obalum et al., 2017, Mendes et al., 2019a), and suppression of plant diseases (Lal, 2016). In addition, several studies show a close association between SOM accumulation and increased crop productivity (Johnston et al., 2009; Lopes et al., 2013; Garratt et al., 2018; Mendes et al., 2019b; Mi et al., 2019; Oldfield et al., 2019; Avasiloaiei et al., 2023).

In conventional VPS, management practices often involve intensive soil use and reliance on industrial inputs. Such systems promote soil degradation through frequent tillage, high application of soluble mineral fertilizers, intensive cultivation of short-cycle crops, and minimal crop rotation. These practices lead to a decline in soil organic matter

(SOM), deterioration of soil structure, loss of biodiversity, and an overall reduction in soil quality (Willekens et al., 2014; Lima et al., 2018).

A key challenge in VPS is the need to preserve soil's productive capacity (Valarini et al., 2011; Lima et al., 2018). Declining SOM levels represent a significant threat to the sustainability of these agricultural systems. Enhancing soil quality by increasing soil organic carbon (SOC) is a valuable strategy for boosting yields, improving crop quality, and supporting the sustainability of agroecosystems (Morra et al., 2021). In a healthy soil, the biological component is closely interrelated with the physical and chemical components, influencing crop productivity and the sustainability of agricultural systems (Mendes et al., 2019a). Knowledge about the functions and forms of conservation of SOM and the biological component can contribute to the assessment of SQ, allowing decisions to be made in favour of more sustainable forms of soil management, optimizing its productive capacity.

If SOM and its biological components are fundamental to the soil, it is important to investigate which management practices are best suited to conserving and boosting them. To this end, agricultural research has been developing methods that involve laboratory analysis and field evaluations covering chemical, physical and biological aspects (Plaza-Bonilla et al., 2014; Duval et al., 2018; Bongiorno et al., 2019; Mendes et al., 2019b; Bíla et al., 2020; Comin et al., 2024). Although SOM is among the most cited indicators for assessing SQ (Bünemann et al., 2018; Oldfield et al., 2019), differences in SOC levels of less than 0.5% may not be able to indicate changes in SQ due to the adoption of conservation or conventional management systems (Hargreaves et al., 2019). Several studies have demonstrated the potential and sensitivity of using the more labile fractions of SOC, such as POC and POX-C to assess SQ (Figueiredo et al., 2010; Bertini et al., 2014; Thomazini et al., 2015; Duval et al., 2018; Sá et al., 2018; Santos et al., 2024).

Although numerous studies have investigated the impacts of land-use systems on soil organic matter (SOM) fractions and soil quality (SQ), most of these studies take a fragmented approach to soil indicators, limiting the understanding of relationships between chemical and biological indicators. Chaer et al. (2023), based on soil samples collected at a 0-10 cm depth in areas with annual cropping systems, proposed a 4-quadrant model (4QM) to assess soil health by combining two soil enzymes (arylsulfatase and β-glucosidase) with soil organic carbon (SOC). This model was able to identify four distinct patterns of soil health in tropical agricultural systems: healthy, getting sick, unhealthy and recovering. Such comprehensive studies are rare in VPS (both organic and conventional), where SQ assessments often overlook a detailed diagnosis of the diverse soil and crop management practices used by producers. Carneiro et al. (2024) evaluated the activity of ARYL and GLU, relating these configurations to COS and developing a model for evaluating SQ for VPS. In the present study, the relationship of these enzymes with SOM fractions was investigated, in an attempt to understand more systematically the dynamics of these interruptions in VPS according to soil management practices and production systems.

This on-farm research aimed to evaluate organic and conventional VPS, with a focus on: i) the adoption of best management practices (BMP); ii) assessment of labile and stable fractions of soil organic matter (SOM); and iii) the relationships between SOM fractions and two soil quality (SQ) bioindicators, arylsulfatase (ARYL) and β-glucosidase (GLU). The study tested the hypothesis that adopting BMP in organic VPS enhances SQ by increasing soil biological activity as well as both labile and stable SOM fractions.

7.3. Material and methods

7.3.1. Study area

The study began in 2022 with soil sampling carried out in the rural area of the Federal District, located between the parallels of 15°30 and 16°03 south latitude and 47°20′ and 48°10′ west longitude, in the center-west region of Brazil. According to the Köppen classification, the regional climate is Cwa type, with 1500 mm of average annual rainfall, a defined dry season from May to September and a wet season from October to April. The region has a mild climate with average maximum temperatures of 26.4°C and a minimum of 15.9°C.

The selected 53 commercial areas for this study included a total of 48 fields representative of organic and 42 of conventional production systems and their variations, with different implementation times and within farms ranging from 1 to 20 hectares, in general. The locations representing the whole of the Federal District and were selected with the support of the Technical Assistance and Rural Extension Company of the Federal District (Emater-DF), a government rural development agency (Fig. 6). There were 18 sites with an establishment time between 0 and 5 years, 22 between 6 and 11 years and 50 with more than 12 years.

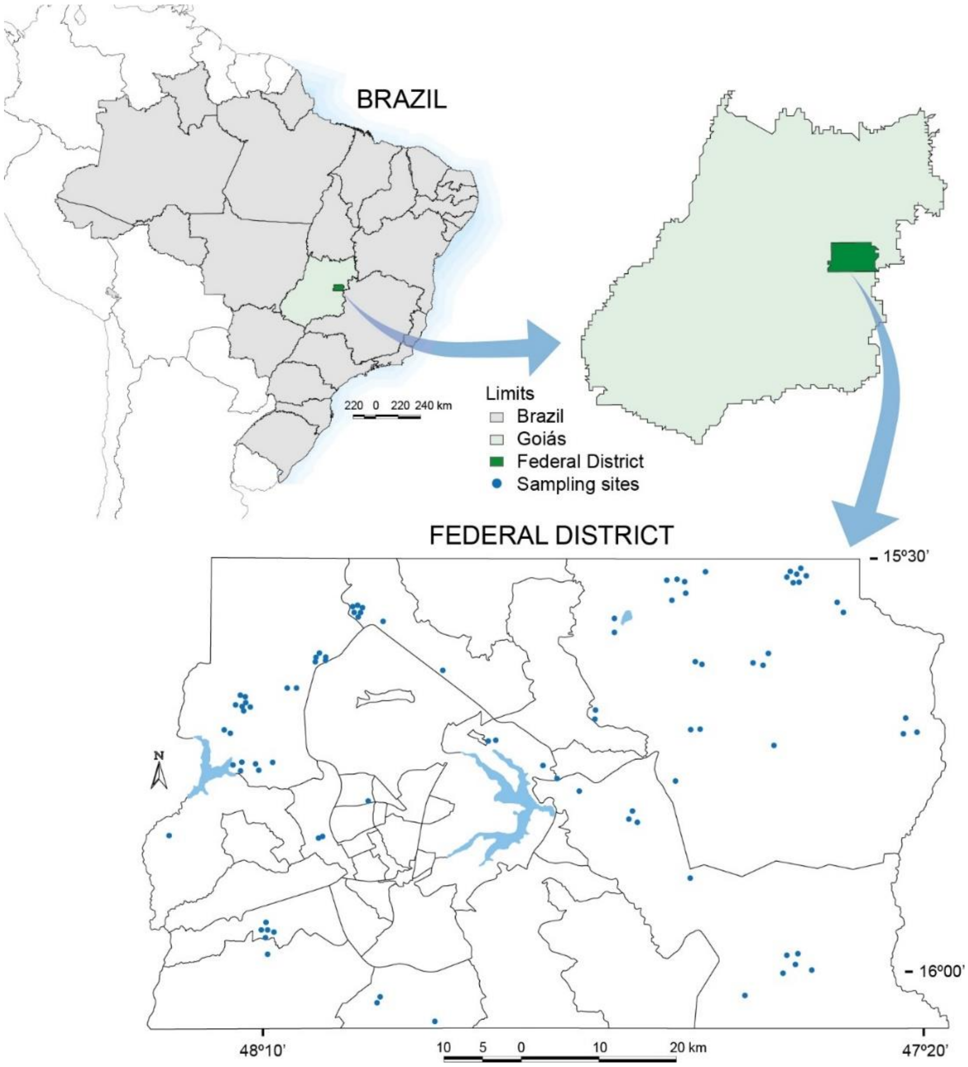


Figure 6. Location of sampled areas in the Federal District, Brazil.

Soil samples were collected predominantly at the beginning of the harvest and at the end of the crop cycle from different botanical families, with Solanaceae, Asteraceae and Brassicaceae predominating. The same area was often cultivated 2-3 times a year.

7.3.2. Soil sampling and analyses

The soil sampling was conducted in June and July 2022 in areas classified as Typic Dystrophic Oxisols according to the Brazilian Soil Classification System (Santos et al., 2018) with a range of soil textures from 16 to 64% clay content. Soil samples representing a layer (0-10 cm depth) and were collected using a soil probe (5 cm in diameter). Each soil sample at 0-10 cm depth was a composite mixture of 10 sampling points. Soil texture was determined from air-dried samples using the pipette method, which uses 10 ml of 1 mol L^{-1} sodium hydroxide solution to disperse the soil samples. Then the samples were passed through sieving and sedimentation steps to determine the percentage of sand, silt and clay (Teixeira et al., 2017).

Chemical analyses were carried out to characterize the samples. Ca^{2+} and Mg^{2+} were extracted with 1N KCl and determined using atomic absorption; P and K^+ were determined using Mehlich 1 (0.0125M H_2SO_4 + 0.05M HCl) using flame spectrophotometry for K^+ and the blue-Mo method for P (Teixeira et al., 2017). Potential acidity (H + Al^{3+}) was determined with sodium acetate buffer pH=7.0 and volumetric analysis with NaOH in the presence of phenolphthalein as an acid-base indicator. Cation exchange capacity (CEC) was estimated as the sum of H + Al^{3+}, Ca^{2+}, Mg^{2+} and K^+, expressed in $cmol_c\ dm^{-3}$.

7.3.3 Soil management history

There was a great variation in the way the soil was prepared for planting, with soil preparation equipment such as a motor cultivator, heavy disc harrow, levelling harrow or disc plough being used between 1 and 7 times per planting. No-till or reduced tillage was practiced in around 10% of the areas. Crop rotation, soil cover and green manure, intercropping combining vegetables or with green manures were practices commonly observed in organic production areas, mainly through the use of crotalaria (*Crotalaria sp.*), pearl-millet (*Pennisetum glaucum*), oats (*Avena strigosa*), Velvet bean (*Mucuna aterrima*), castor beans (*Ricinus communis*) and turnip rape (*Raphanus sativus*). Some cited practices were also observed in the conventional areas, but to a lesser extent. Organic farms were certified by an auditing or participatory organic conformity assessment system. In some cases, they were registered as organic by the Ministry of Agriculture, Livestock and Supply through a Family Farming Social Control Organization. Although most conventional producers have used chicken litter, castor bean cake and organic waste compost when planting, chemical fertilizers were intensively used in these areas, forming the basis of their fertility management. In the organic production systems, there was a more complex strategy for managing the system's fertility with a predominance of "Bokashi" compost or compost made with straw and animal manure in varying proportions.

In order to obtain data on the history of the 90 soil sampling areas, the two years prior to sampling were taken into account. The information was obtained through semi-structured interviews, which also took note of farmers' comments while walking around the sampling areas and observing the soil management adopted in each case on site. The number of continuous years with the same cultivation system was recorded. Various observations were made, but some specific practices adopted were recorded such as (i) history of crop rotation; (ii) soil tillage regime (types, number per crop or year); (iii) application of mineral and organic correctives (type and rate of application per year); (iv) use of biofertilizers; (v) history of green manuring; (vi) cover crops; (vii) intercropping or agroforestry practices. These observations generated a database on adopting sustainable or harmful soil management practices. This data and the information generated were intended to help understand the differences between the content of SOM fractions due to the management adopted in the various production systems evaluated. To understand how much the BMP contributed to soil quality (SQ) indicators, a database was generated with information on the adoption of these practices in the VPS participating in the study.

7.3.4. Best soil management practices (BMP)

The adoption level of each BMP was assessed by assigning scores ranging from 1 to 10. Score 1 corresponded to the least desirable situation, i.e. no adoption of BMP; score 5 was assigned when a practice was adopted that reasonably contributed to SQ; and 10 was the score corresponding to the adoption of the practice that contributed most to SQ adapted of Comin et al. (2024). For each soil sample, the maximum total score was 90, which would mean a score of 10 for each of the 9 practices evaluated, described below. The average of the total scores (Fig. 7A) was calculated by adding the scores for each sample within the organic or conventional system and dividing by 48 or 42, respectively. The average score for a given practice, per system evaluated (Fig. 7B) was calculated by adding the score for the same practice for all the organic samples and then for all the conventional samples and dividing it by 48 or 42, respectively. Nine different soil management practices were evaluated: best soil preparation practices (Bspp), which includes lower intensity of soil preparation, minimum cultivation, NT; best mineral fertilization practice (Bmin) through the preferential use of natural mineral fertilizers; best organic fertilization at planting practice (Borg) through the preferential use of compost; best top-dressing practice (Btop) through the preferential use of organic fertilizers; use of biofertilizers (Biof); crop rotation (Crot); green manure (Gman); soil cover (Scov); intercropping/agroforestry systems (Iafs).

7.3.5. Soil organic matter fractions

7.3.5.1. Organic and total soil carbon

The SOC content was determined using the Walkley and Black method (Nelson and Sommers, 1996) and calculated according to Jackson (1958). Total soil carbon (TC) was determined by dry combustion in an elemental analyzer (Perkin Elmer Series II CHNS/O 2400).

7.3.5.2. Particulate organic carbon and mineral-associated organic carbon

Physical granulometric fractionation was carried out according to Cambardella and Elliot (1992). Twenty grams of fine, air-dried soil was sieved through a 2 mm sieve and stirred with 80 ml of sodium hexametaphosphate solution (5 g L^{-1}). After stirring, the material was passed through a 53µm sieve with the aid of water jets and the material retained on the sieve was dried in an oven at 50 °C until it reached a constant weight and then ground very fine (< 0.149 mm) in a porcelain grater to assess the organic C content of POC. The POC content was determined according to Walkley and Black (Nelson and Sommers, 1996). The MOC was estimated by the difference between TC and POC.

7.3.5.3. Labile carbon oxidizable in $KMnO_4$

The procedure was carried out according to Blair et al. (1995), adapted by Shang and Tiessen (1997), in which labile carbon is represented as the C oxidizable by the $KMnO_4$ solution (POX-C) 0.033 mol L^{-1}. To do this, 1 gram of air-dried soil sieved through a 0.5 mm mesh was stirred and centrifuged in the presence of $KMnO_4$ 0.033 mol L^{-1}. After centrifugation, 1 ml of the supernatant was pipetted into 250 ml volumetric flasks and topped up with distilled water. The reading was carried out in a spectrophotometer at 565 nm using a standard curve drawn up from a solution containing 0.00060 mol L^{-1} of $KMnO_4$ as a reference.

7.3.5.4. Chemical fractionation of humic substances

The carbon of fulvic acids (FA), humic acids (HA) and humin (HU) was determined according to the methodology described by Sato et al. (2019). Samples of 1 g of soil were shaken in 20 mL of 0.1 mol L^{-1} NaOH and then centrifuged. The HU fraction was represented by all the insoluble residue retained in the centrifuge tube. The supernatant was acidified to a pH between 1.3 and 1.5, producing a precipitate representing the HA fraction. The FA fraction was represented and obtained from the soluble part. The C content of each fraction was determined by oxidation in an acidic medium with a 0.042 mol L^{-1} solution of $K_2Cr_2O_7$ and an external heat source for the determination of C-FA and C-HA and another 0.1667 mol L^{-1} solution of $K_2Cr_2O_7$ for the determination of C-HU. Titration was carried out with ammonium iron (II) sulphate.

7.3.5.5. Oxidizable carbon fractions in different concentrations of sulphuric acid

The sequential fractionation of C was carried out according to the procedure presented by Chan et al. (2001). For each sample, 0.5g of air-dried soil was passed through a 0.5 mm sieve and subjected to oxidation with 10 ml of potassium dichromate ($K_2Cr_2O_7$) 0.167 mol L^{-1}. The samples were then given three volumes of concentrated H_2SO_4 (5, 10 and 20 ml), corresponding to 6, 9 and 12 mol L^{-1} concentrations, respectively. The soil and reagents were mixed and left to stand for 30 minutes. This fractionation resulted in four fractions: Fraction 1 (F1): C oxidized by $K_2Cr_2O_7$ in acidic media with 6 mol L^{-1} of H_2SO_4; Fraction 2 (F2): difference in C oxidized by $K_2Cr_2O_7$ in acidic media with 9 and 6 mol L^{-1} of H_2SO_4 ; Fraction 3 (F3): difference of the C oxidized by $K_2Cr_2O_7$ in acid medium with 12 and 9 mol L^{-1} of H_2SO_4 ; Fraction (F4): difference of the TC and the carbon oxidized by $K_2Cr_2O_7$ in acid medium with 12 mol L^{-1} of H_2SO_4. Fractions F1 and F2 are considered the most oxidizable or labile fractions, highly correlated with mineralizable nitrogen, while F3 and F4 are considered more stable or passive (Chan et al., 2001) and can also be classified as very labile (F1), labile (F2), slightly labile (F3) and non-labile (F4) fractions (Nanda et al., 2024). After resting, titration was carried out with ammoniacal ferrous sulphate $[(NH4)_2Fe(SO4)_2.6H_2O)]$ 1 mol L^{-1}. TC was determined by dry combustion in a Perkin Elmer Series II CHNS/O 2400 elemental analyzer.

7.3.5.6. Activity of Arylsulfatase and β-glucosidase

The activities of the enzymes ARYL and GLU were determined according to Tabatabai (1994) based on the colorimetric determination of the p-nitrophenol released by these enzymes when the soil was incubated with a buffered solution of substrates specific to each enzyme. soil samples were air-dried at room temperature for at least two weeks, passed through a 2 mm sieve and stored at room temperature until the analyses were performed within a period of one week after air-drying. Two analytical replicates plus a control were used for each sample. Due to the short incubation period (one hour), toluene was omitted from the assays. The values of enzyme activities are expressed in mg p-nitrophenol kg^{-1} h^{-1} (mg PNP kg^{-1} h^{-1}).

7.3.5.7. Statistical approach

The normality of the residuals was assessed using the Shapiro-Wilk test. As this criterion was not met for all the analytical variables studied, the non-parametric Mann-Whitney test (for comparing two independent groups) was used using the "Wilcoxon.test" function ($P < 0.05$) to compare the organic and conventional systems in relation to the study parameters.

In order to understand the extent to which best soil management practices (BMP) contributed to SQ indicators, a database was generated with information on the adoption of these practices in organic and conventional VPS. The Mann-Whitney non-parametric test was applied to this data set to analyze whether there were differences in the adoption of BMP between organic and conventional systems ($P < 0.05$).

The R project software (R Core Team, 2019) version 4.3.0 was used to carry out the statistical procedures described above.

Box plots for descriptive statistics (mean, median, minimum, maximum, first and third quartiles) were used to characterize the differences in BMP adoption between organic and conventional systems.

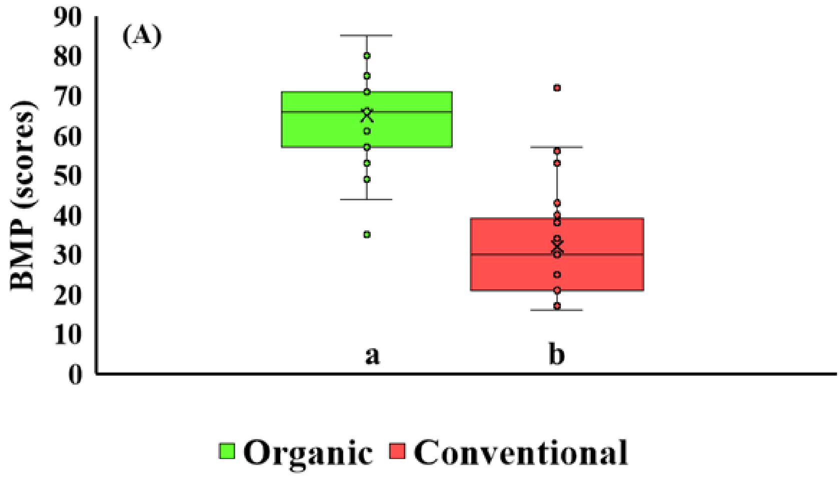
The relationship between the SOM fractions, enzymatic activity, level of adoption of BMP and how these analytical and qualitative variables relate to the production systems was interpreted using principal component analysis (PCA), normalized by the Z-score and using XLSTAT® ($P < 0.05$). The PCA was carried out on a data set with 90 rows comprising cultivation systems (organic and conventional) and 15 columns comprising the carbon fractions (POC, POX-C, SOC, TC, MOC, FA, HA, HU, F1, F2, F3, F4) activities of ARYL and GLU and BMP.

7.4. Results and discussion

7.4.1. Chemical properties and best soil management practices adopted in organic and conventional systems

The organic and conventional VPS showed high levels of nutrients and base saturation at 0-10 cm (Table S1) and a significant difference in the mineral and organic inputs used. Thermophosphate, K_2SO_4, KMag (langbeinite), rock dust, compost, castor bean meal and bone meal are the primary inputs in organic areas. In conventional areas, various formulas of N-P-K, potassium chloride, simple superphosphate, monoammonium phosphate, urea, potassium nitrate, calcium nitrate, chicken litter, chicken manure and uncomposted cattle manure predominate.

According to the interviews and observations made in the field, organic systems had a higher level of adoption of potentially SQ-improving practices than conventional systems. Figure 7A shows a general comparison in terms of the level of adoption of BMP and figure 7B compares the adoption of each of the BMP evaluated in the research.



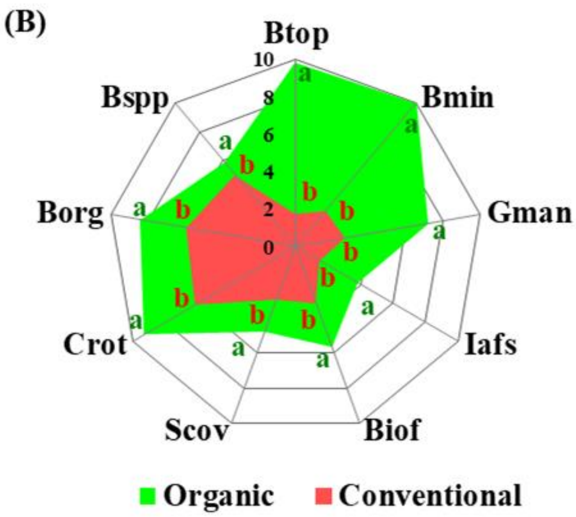


Figure 7. Comparison of 48 organic and 42 conventional areas based on: (A) the average total scores for adopting best management practices (BMP); and (B) the average scores for each individual practice, including best top-dressing practices (Btop), best mineral fertilization practices (Bmin), green manure (Gman), intercropping/agroforestry systems (Iafs), biofertilizers (Biof), soil cover (Scov), crop rotation (Crot), best organic fertilization at planting (Borg) and best soil preparation practices (Bspp). Different letters for the overall score or each soil management practice indicate statistical differences based on the Mann-Whitney test ($P < 0.05$).

In terms of the overall score, the organic production areas achieved a level of adoption of BMP about 2 times higher than the conventional areas ($P < 0.05$) (Fig. 7A).

All BMP significantly differentiated the two systems, always with a higher score for the organic areas compared to the conventional ones (Fig. 7B). Btop, Bmin, Gman, Iafs, Biof, Scov, Crot, Borg and Bspp achieved scores 5.4, 4, 2.7, 2.5, 1.8, 1.6, 1.5, 1.4, and 1.2 times higher ($P < 0.05$) in organic areas compared to conventional ones, respectively. In organic systems, the greater diversification and addition of organic residues through green manure, soil cover, consortia and gardens in agroforestry, as well as biofertilizers and composts, contributed to better results for SOM fractions (Souza et al., 2014; Thomazini et al., 2015; Hu et al., 2023), as shown below.

7.4.2. Total carbon and soil organic carbon

Organic systems promoted higher SOC (32.5 g kg^{-1}) and TC (38.1 g kg^{-1}) contents than conventional ones, which reached 26.1 and 28.1 g kg^{-1} for SOC and TC, respectively ($P < 0.05$) (Fig. 8).

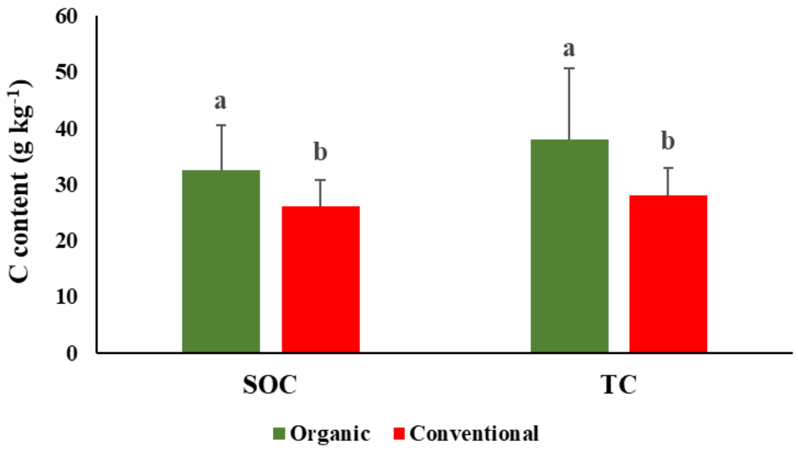


Figure 8. Soil organic carbon (SOC) and total carbon (TC) contents of 90 soil samples from organic and conventional systems. Averages with different letters show statistical differences according to the Mann-Whitney test ($P < 0.05$). Error bars indicate the standard deviation.

In the present study, there was a greater accumulation of C in the soil compared to the grain-growing areas reported in other studies (Figueiredo et al., 2010; Lopes et al., 2013; Rosset et al., 2016; Carvalho et al., 2022). These differences can be explained by the frequent contributions of organic inputs common in organic vegetable areas, which were also observed in the conventional areas evaluated. In some conventional areas, even less frequently than in the organic areas, the adoption of practices beneficial to the soil was observed, such as composting, bio-fertilizers, green manuring and crop rotation (Fig. 7B). In this study, 100% of the organic areas and 95% of the conventional ones received organic fertilizers at planting. The situation was different for top dressings, where 96% of the organic areas received organic fertilizers, while only 19% of the conventional areas received this type of fertilizer. In fact, higher inputs of organic fertilizers in organic systems may explain their higher C contents. However, large inputs of these fertilizers do not always result in large stocks of SOC, as the conversion efficiency rate depends on intrinsic factors, environmental conditions and soil management (Zhao et al., 2020). In addition, C accumulation can reach a level of equilibrium between organic input and mineralization, as verified by Zhang et al. (2022), after 15 years of intense fertilization with chicken litter.

In general, the organic and conventional systems showed different levels of quality of the inputs used. The best organic fertilization at planting practice (Borg) were adopted in 70% of the organic areas and 17% of the conventional ones ($P < 0.05$) (Fig. 7B). It should be noted that composting manure from outside the property is mandatory in organic systems under Brazilian legislation (MAPA, 2024). This difference in the quality of the organic input may be enough to differentiate SOC values between production systems (Hepperly et al., 2009; Sissoko and Kpomblekou-A, 2010; Ugarte et al., 2014). According to Liang et al. (2021), the type of manure and its use may have more influence on soil C retention than climatic aspects or manure application rates. For example, composted poultry litter may have a higher C retention rate in more stable fractions compared to the use of fresh poultry litter, due to the additional stabilization of this element during composting (Adeli et al., 2017) and the same may occur with compost made from cattle manure (Ouyang et al., 2022). The application of composted poultry litter results in higher total C and N reserves in the soil than conventional fertilizers (N-P-K) and has the potential to promote a more sustainable agroecosystem (Moeskops et al., 2010; Adeli et al., 2017).

In addition to the quantity and quality of the organic input applied, the higher levels of SOC, TC and their fractions in organic systems may generally result from their more conservationist management practices compared to conventional systems (Figs. 7A and 7B). The decline in SOC, deterioration of soil structure and loss of biodiversity can occur due to the intensity of soil preparation, high inputs of mineral N sources, continuous short-cycle crops and limited rotations (Willekens et al., 2014).

In this study, the management practices that led to the accumulation of SOC were based on a redesign of the production system, in which diversity was a basic element, as reported by Altieri et al. (2015) and Lal et al. (2016). And it was in the organic systems where the redesign of agroecosystems was most observed, with crop rotations, green manure, soil cover, AFS, biofertilizers and better soil preparation practices being more frequently included (Fig. 7B). In the present study, soil cover was higher in the organic areas ($P < 0.05$), with 54% of these soils containing cover with plant residues or living cover compared to 10% in the conventional areas, which represents great potential for C accumulation in the soil. Souza et al. (2014) and Lima et al. (2016) reported higher levels of total organic C in soils covered with straw from a consortium of *Zea Mays* and *Mucuna sp.*, while Muchanga et al. (2020) reported an increase in SOC in tomato crops on rye (*Secale cereale* L.) and vetch (*Vicia villosa*) straw. Crop rotation and intercropping, including AFS, which were also more present in organic systems in this study ($P < 0.05$) (Fig. 7B), may be decisive for the increase in SOC levels compared to monocultures due to the greater production of root biomass and the consequent increase in microbial carbon biomass (McDaniel et al., 2014; Cong et al., 2015; Kubar et al., 2024; Li et al., 2024). It is important to note that organic systems, by accumulating more C in the soil, mitigate the negative effects caused by cropping intensity, which is common in vegetable plantations (Paliaga et al., 2024).

7.4.3. Labile soil organic carbon fractions

Significant increases in the labile fractions of SOC in organic systems ($P < 0.05$) also were observed. POC, POX-C and the sum of the labile fractions F1 and F2 by the method of Chan et al. (2001) were 1.3, 1.4 and 1.3 times higher in organic systems compared to conventional systems, respectively (Fig. 9).

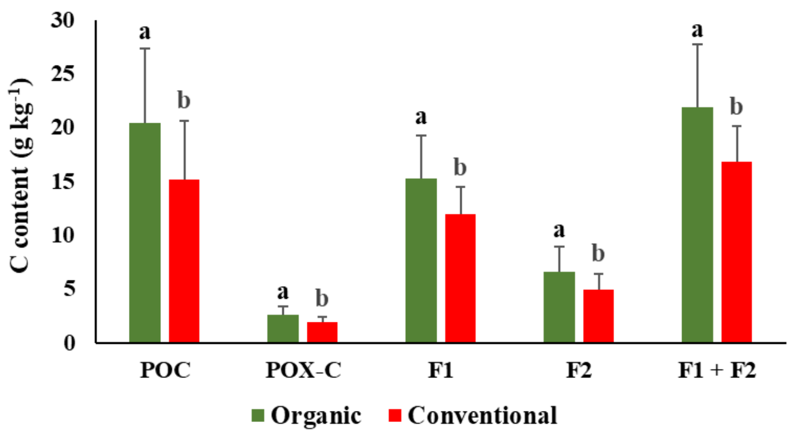


Figure 9. Carbon content of labile fractions of SOM represented by particulate organic carbon (POC), carbon oxidizable by $KMnO_4$ (POX-C) and fractions oxidizable by modified Walkley-Black (F1+F2). Averages with different letters show statistical

differences according to the Mann-Whitney test ($P < 0.05$). Error bars represent the standard deviation.

In this study, the increase in the content of the labile fractions of the SOM in the organic systems compared to the conventional ones was probably due to the greater contributions of compost over the long term, which is in line with the studies by Lou et al. (2011) and Knewtson et al. (2012). In the present study, of the 48 samples from organic areas, 14 had been planted between 6 and 11 years ago, 14 between 12 and 20 years ago and 8 had been planted for more than 20 years. Li et al. (2018) and Zhang et al. (2022) also reported the positive influence of compost by increasing POC (including in aggregates), POX-C and dissolved organic carbon (DOC).

Organic or conventional VPS that incorporate a high amount of organic residues above and below the soil surface into the system, in addition to stimulating its biota, tend to increase its POC content and other labile fractions, compensating for the loss of SOC due to soil preparation (Bajgai et al., 2014, Kubar et al., 2024).

In organic areas, in addition to composting, other frequently used practices, such as green manure, soil cover crops, vegetated fallow land, intercropping and vegetable gardens in AFS, contributed to the higher C content in labile fractions ($P < 0.05$) (Fig. 7B). In the study by Hu et al. (2023), for example, cover crops showed an increase of 15% in POC, 18% in DOC, and 13% in POX-C compared to management with bare soil. NT using intercropping of maize (*Zea Mays*) and mucuna (*Mucuna sp.*) or maize alone as cover crops can increase labile fractions, especially in the upper layers of the soil (Souza et al., 2014; Melo et al., 2016; Lima et al., 2016). In vegetable rotation and NT schemes, other plant families used for cover crops (grasses, legumes and brassicas) can also substantially increase POC (Ferreira et al., 2018). The results of these authors reinforce the idea that green manuring, in the present study adopted in 65% of the organic systems and 19% of the conventional ones, and soil cover, which was greater in the organic systems, contributed to the differentiation of the labile fractions between the systems studied. This possibility is also corroborated by the study by Nanda et al. (2024), in which the labile (F1, F2) and stable (F3, F4) fractions were higher in organic systems, similar to the present study, due to the joint contribution of green manure with legumes, vermicomposting and fertilization with cattle manure.

In the present study, the fractionation of Chan et al. (2001) also resulted in higher C contents in the labile fractions F1 and F2 ($P < 0.05$), consistent with the results of POC, POX-C and corroborating the observed trend of increased C in these more labile fractions in organic systems compared to conventional ones. The main species used in the organic systems were *Crotalaria sp., Mucuna pruriens, Mucuna aterrima, Avena strigosa, Pennisetum glaucum, Canavalia ensiformis, Fagopyrum esculentum, Raphanus sativum, Helianthus annus, Ricinus communis*. In conventional systems, this practice was only carried out with *Pennisetum glaucum* and *Crotalaria sp.* In some areas of this study, intercropping of these green manures containing grasses, legumes and other plant families were observed. This improved practice, in addition to storing C in the soil in low or non-labile forms, increases the labile C content, more than monocultures of green manures (Thomazini et al., 2015). This composition provides organic material with an intermediate C/N ratio (up to 20/1), enables slow decomposition rates, extends the period of soil cover, increases the rate of humification and the accumulation of SOM over time, as well as synchronizing the supply and demand of N by crops (Vachon and Oelbermann, 2011). Green manuring can also minimize soil disturbance, the breakdown of aggregates and exposure of SOM to oxidation, as well as contribute to an increase in C in macroaggregates and the content of light fractions of C, POC and DOC (Gura et al., 2021; Silva et al., 2024).

Organic areas also more frequently included practices such as AFS and intercropping (Fig. 7B). In this study, AFS were practiced in 17% and 0% of the areas with organic and conventional systems, respectively. In addition, 31% of organic and 12% of conventional areas contained simpler intercropping. This condition may have led to differentiations between the two systems regarding the quality and quantity of plant residues added to the systems (Xu et al., 2023; Macedo et al., 2024).

7.4.4. Carbon in stable fractions of soil organic matter

Following the trend of the labile fractions, the organic systems showed higher SOC levels in stable fractions than the conventional ones, except the F3 fraction of the Chan fractionation (Fig. 10). It is important to note the consistency of the results of the analyses of MOC, HU and F3+F4, which represent more stable fractions of SOM, reinforcing the idea that organic systems have a great capacity to protect their organic matter, stabilizing C and providing charges for the soil.

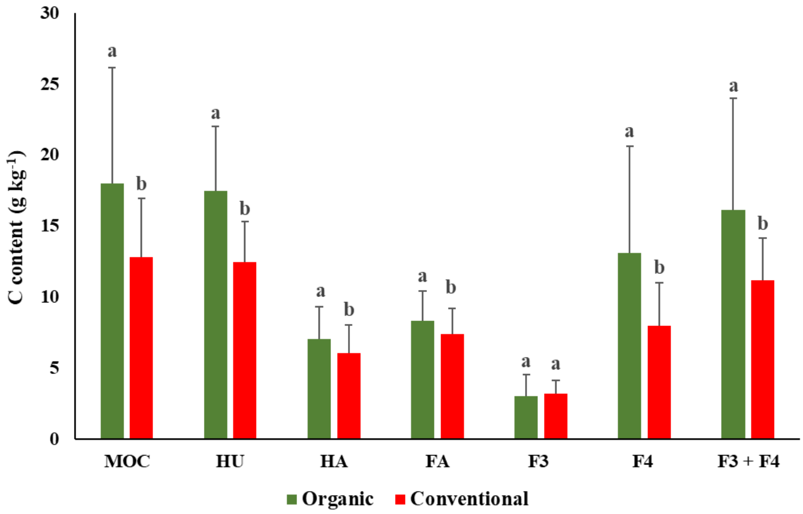


Figure 10. Recalcitrant soil organic carbon fractions represented by organic carbon associated with minerals (MOC), humin (HU), humic acids (HA), fulvic acids (FA) and fractions oxidizable by modified Walkley-Black (F3 and F4). Averages with equal letters do not differ statistically according to the Mann-Whitney test ($P < 0.05$). Error bars indicate the standard deviation.

The MOC and HU values were similar within each system, reaching around 18 g kg^{-1} for the organic systems and 13 g kg^{-1} for the conventional areas. The sum of the F3 and F4 fractions, considered recalcitrant according to Chan et al. (2001), resulted in 16.2 g kg^{-1} in the organic areas, a value similar to that of the stable humin and MOC fractions. In conventional areas, F3+F4 reached a content of 11.2 g kg^{-1}. In the organic areas, the HU, HA and FA fractions were 40%, 16% and 13% higher than in the conventional ones ($P < 0.05$) (Fig. 10). In general, HU represented around 45% of the TC for the two production systems, while the sum of the humic fractions represented 87 and 93% of the TC in organic and conventional systems, respectively. It is possible that conservation management of organic areas, by increasing SOC, also increases the content and conservation of SOM in the form of HU, as occurs in Latosols in native areas (Santos et al., 2013; Rosset et al., 2016).

The formation of HA and HU is favored in systems with less soil disturbance, greater input of plant residues, organic fertilizers and green manure, which is not always the case with FA (Souza et al., 2014; Melo et al., 2016; Mi et al., 2019). In the study by Rosset et al. (2016), the most labile fractions of C and their stock in the humified fractions, with a predominance of HU, increased as a function of the time the NT was implemented. The greater polymerization of humic compounds in less disturbed and diversified systems and the greater porosity of the soils in these areas facilitate the translocation of FA to layers below 10 cm in depth (Loss et al., 2010). This may explain the lower increase in FA in relation to HU and HA in the organic systems compared to the conventional ones in this study. The accumulation of MOC, observed consistently in the organic systems in the present study (Fig. 10), is also in line with the adoption of conservation practices, which strengthen the soil structure and induce the accumulation of a large part of the C in this fraction, as reported by Lima et al. (2016) in NT and minimum cultivation vegetable systems.

The most frequently adopted BMP in organic areas allowed for a certain balance between labile and stable fractions of C in the soil, indicating that in organic systems, in general, managements are carried out that promote SQ in agricultural areas.

In this research, with the exception of the most stable fraction F3 (Chan et al., 2001), the fractions evaluated showed consistent increases, ensuring the retention of carbon in the various forms essential for the proper functioning of the soil. A system that only sequesters C but loses it quickly would not be effective. This balance between the carbon fractions is characteristic of conservation farming systems, such as organic farming, NT and reduced tillage.

7.4.5. Relationships between best soil management practices, C accumulation in the labile and non-labile fractions, enzyme activity and soil quality

7.4.5.1. Arylsulfatase and β-glucosidase activity

Previously, the activity of the ARYL and GLU enzymes in the 90 samples was evaluated by Carneiro et al. (2024). Only the levels of ARYL were able to differentiate the two systems evaluated, with an average activity of this enzyme 2 times higher in the organic areas compared to the conventional ones (Fig. 11).

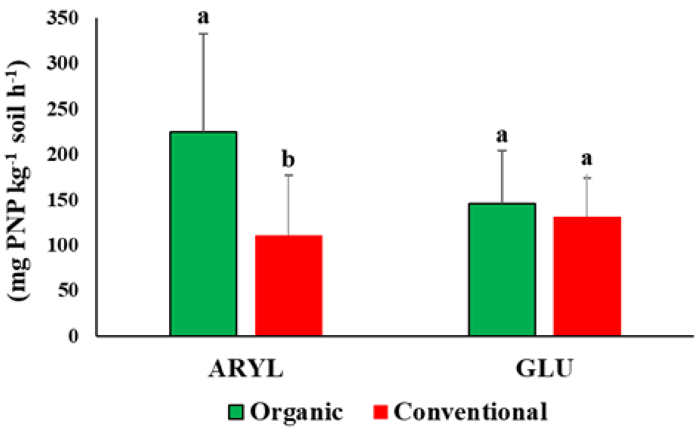


Figure 11. ARYL and GLU activity in vegetable-growing areas under organic and conventional management. Columns with similar letters show no statistical difference according to the Mann-Whitney test ($P < 0.05$). Error bars indicate the standard deviation. Adapted from Carneiro et al. (2024).

7.4.5.2. Systemic view of SQ in organic and conventional systems using principal component analysis (PCA)

More systemic approaches that incorporate components of management practices can differentiate organic and conventional systems, contribute to the interpretation of ecological aspects related to the effect of the cultivation system (Burgio et al., 2015; Fess and Benedito, 2018) and identify good indicators of SQ. Therefore, a PCA was carried out involving the BMP, the SOC and TC contents and their fractions, as well as biological indicators represented by the ARYL and GLU enzymes, in order to understand the relationships between these soil attributes and their potential as indicators of SQ.

As shown in figure 12, components PC1 and PC2 of the PCA explained 57.7% and 12.6% of the total variance, respectively. The scores for each cultivation system were plotted on the plane formed by principal components 1 and 2. All the vectors were positive, with the fractions of SOC and enzymatic activities in line with the BMP. In addition, all the attributes related to SOC and enzymatic activity, as well as BMP, were related to most organic areas, demonstrating great coherence between the indicators studied. The conventional areas were predominantly to the left of the graph, in the opposite direction to the vectors of the attributes evaluated. This distribution showed that the management of organic production areas is related to an increase in TC, the labile and stable fractions of SOC, ARYL and GLU and the adoption of BMP. This result is similar to the study by Comin et al. (2024), in which systems with less soil disturbance or that were more conservative showed a strong relationship with TOC, POC, soil structuring and biological activity. In the present research, the relationships observed in the PCA corroborate the relationships between BMP, derived from field information and observations, and the chemical and biological indicators of SQ in the two systems evaluated. Comin et al. (2024) using the Practical Guide for Participatory Assessment of Soil Quality (PGPA-SQ) reported correlations between the quantitative indicators POC and TOC with the qualitative assessment of SQ. Valani et al. (2020) also reported a correlation between the PGPA-SQ and the Soil Management Assessment Framework (SMAF), which, among other quantitative variables, assesses TOC and soil microbial biomass.

The indicators that most differentiated the organic systems from the conventional ones were ARYL activity and the HA, POC, F1, F2, SOC, POX-C, HU and TC fractions, which were at the opposite end of the spectrum to most conventional samples. The PCA showed the relationship between BMP and organic systems, promoting the accumulation of labile and stable fractions of SOM, increased enzyme activity and, consequently, healthier soil.

The strong association of SOC and its labile fractions (POC, POX-C, F1 and F2) with BMP in organic systems shows that the losses of organic matter caused by tillage are compensated for by the constant addition of residues in the form of compost, green manures or crop rotations, which tend to be more diverse and longer-lasting in these systems (Marriott and Wander, 2006; Nanda et al., 2024).

As can also be seen in figure 10, the F3 fraction was the indicator that least distinguished organic from conventional areas and explained very little of the differences between these systems.

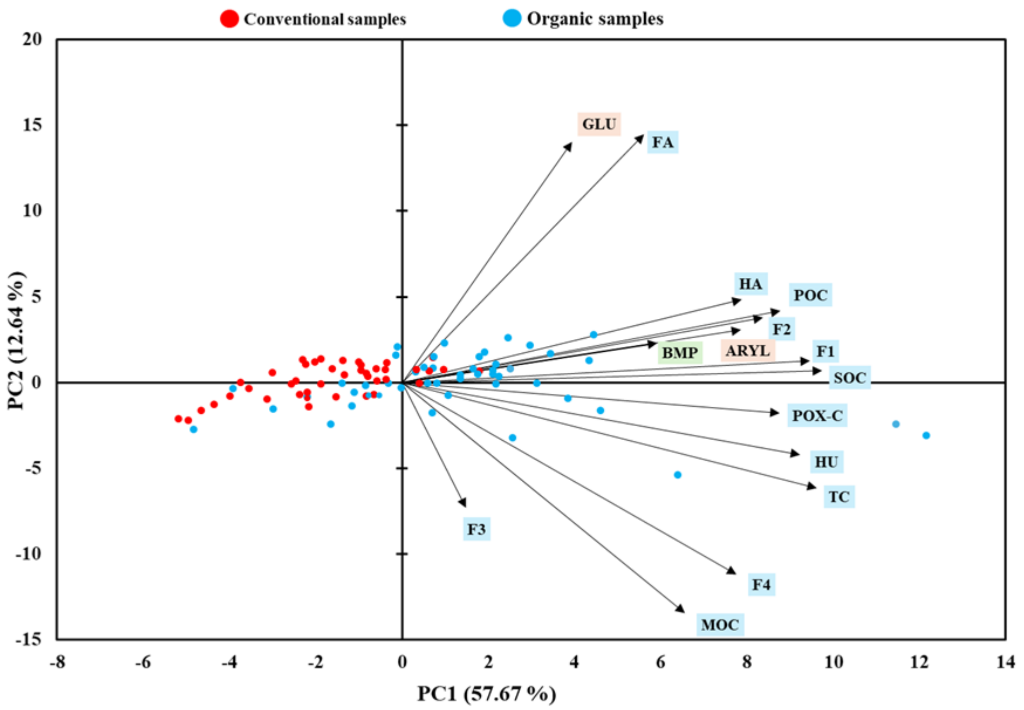


Figure 12. Principal component analysis (PCA) of BMP, soil health and labile and stable fractions of SOM from 90 soil samples from organic and conventional areas in the Federal District, Brazil. Variables analyzed: arylsulfatase activity (ARYL), β-glucosidase activity (GLU), fulvic acid (FA), best soil management practices (BMP), labile fraction oxidizable by modified Walkley-Black (F2), humic acid (HA), particulate organic carbon (POC), most labile fraction oxidizable by modified Walkley-Black (F1), soil organic carbon

(SOC), carbon oxidizable by $KMnO_4$ (POX-C), humin (HU), total carbon (TC), most stable fraction oxidizable by modified Walkley-Black (F4), organic carbon associated with minerals (MOC), stable fraction oxidizable by modified Walkley-Black (F3).

Similar to the findings of this study, several studies in the literature show that farmers with an organic production profile adopt more agroecological practices, which include BMP, compared to conventional farmers (Maharjan et al., 2017; Fess and Benedito, 2018; Palomo-Campesino et al., 2022; Nanda et al., 2024). The simultaneous adoption of agroecological management practices promotes an increase in SOC and its fractions, an improvement in SQ and ecosystem services (Lal, 2016; Garbach et al., 2017; Palomo-Campesino et al., 2022).

It's important to note that some samples, even though they came from organic areas, tended towards zero or the opposite direction of the SQ determining vectors. These farms had a relatively lower level of adoption of BMP, which did not affect the clear trend observed in the study of better SQ in organic systems. With the same set of 90 samples used in this study, similar results were reported by Carneiro et al. (2024), using the 4Q approach to assess soil health. Thus, using 4Q and the PCA approaches, including all the SOM fractions, SQ was higher for organic systems and was related to the greater adoption of BMP, although there were exceptions for organic areas with low SQ and conventional areas with high SQ.

Since soil enzymes are organic molecules, management conditions that stabilize, store and maintain higher organic matter contents will likely also result in higher enzyme activity (Mendes et al., 2019a). In the present research, moderate and strong correlations were observed between ARYL, an enzyme related to SQ in vegetable areas (Carneiro et al. 2024), and the fractions POC, POX-C, F1, F2, HA, HU, as well as SOC and TC (Fig. 13). These correlations were reflected in the PCA in which the organic systems and BMP were more strongly related to these same fractions and to ARYL and moderately to the MOC, F4, FA fractions and GLU activity. Enzymes secreted by living cells and abiotic enzymes remain in the soil protected in clay-enzyme, SOM-enzyme complexes (Yan et al., 2010; Wallenstein and Burns, 2011; Tejada and Benítez, 2017). Thus, correlations between GLU and ARYL with the POC and POX-C fractions can be attributed to these interactions, as well as to the greater activity of microorganisms, the main source of enzymes in the soil, induced by the more labile C fractions (Kalambukattu et al., 2013).

On the other hand, GLU did not show strong correlations with the different fractions of SOC, registering values below 0.5 (Fig. 13).

	POC	POX-C	SOC	TC	MOC	FA	HA	HU	F1	F2	F3	F4	ARYL	GLU
POC	**1**													
POX-C	**0,684**	**1**												
SOC	**0,905**	**0,807**	**1**											
TC	**0,766**	**0,810**	**0,892**	**1**										
MOC	**0,273**	**0,598**	**0,524**	**0,809**	**1**									
FA	**0,534**	**0,378**	**0,540**	**0,359**	0,026	**1**								
HA	**0,640**	**0,611**	**0,731**	**0,674**	**0,427**	**0,666**	**1**							
HU	**0,773**	**0,766**	**0,868**	**0,874**	**0,624**	**0,303**	**0,611**	**1**						
F1	**0,899**	**0,765**	**0,972**	**0,864**	**0,490**	**0,559**	**0,704**	**0,835**	**1**					
F2	**0,676**	**0,707**	**0,756**	**0,738**	**0,499**	**0,571**	**0,679**	**0,686**	**0,651**	**1**				
F3	**0,255**	0,157	**0,329**	0,195	0,053	-0,203	0,043	**0,261**	**0,298**	**-0,231**	**1**			
F4	**0,500**	**0,665**	**0,632**	**0,914**	**0,918**	0,130	**0,500**	**0,720**	**0,608**	**0,586**	0,039	**1**		
ARYL	**0,659**	**0,619**	**0,715**	**0,637**	**0,355**	**0,419**	**0,521**	**0,741**	**0,697**	**0,614**	0,103	**0,450**	**1**	
GLU	**0,415**	**0,345**	**0,372**	0,206	-0,071	**0,477**	**0,375**	0,207	**0,377**	**0,357**	-0,056	0,019	**0,365**	**1**

Figure 13 - Pearson correlation matrix between analytical variables studied in organic and conventional systems. Values in bold were significant (*P < 0.05*). Correlations in white were not significant and the correlation strength increased from yellow to dark green (*P < 0.05*). POC: particulate organic carbon; POX-C: carbon oxidizable by $KMnO_4$; SOC: soil organic carbon; TC: total carbon; MOC: organic carbon associated with minerals; FA: fulvic acid; HA: humic acid; HU: humin; F1: most labile fraction oxidizable by modified Walkley-Black; F2: labile fraction oxidizable by modified Walkley-Black; F3: stable fraction oxidizable by modified Walkley-Black; F4: most stable fraction oxidizable by modified Walkley-Black; ARYL: arylsulfatase activity; GLU: β-glucosidase activity.

In general, the relationships observed between ARYL, GLU, labile fractions (Fig. 8) and the BMP (Fig. 12) used in organic areas reflect the greater amount of organic residues from compost, green manures, crop rotations, soil cover in these systems, which tend to increase the soil's microbial biomass (Hok et al., 2018). The labile fractions provide nutrients and energy for microorganisms (Lal, 2016; Hok et al., 2018). The input of organic matter from various management practices is the most important factor in increasing C content and improving microbial attributes (Maharjan et al., 2017; Sá et al., 2018).

7.5. Conclusions

The BMP adopted in organic systems favored an increase in the labile and non-labile fractions of SOC, as well as in enzymatic activity, in soil samples collected at a depth of 0-10cm.

Organic VPS promoted higher levels of carbon in the labile and stable fractions, demonstrating their potential to protect organic matter by stabilizing C, increasing the soil's electrical charge and making nutrients available to plants.

The POC, POX-C, HA, HU, F1 and F2 fractions, together with ARYL, proved to be suitable indicators for differentiating organic and conventional systems or more sustainable systems from those that degrade SQ in VPS, regardless of the inherent sensitivity of each indicator.

The labile and stable fractions of SOM were correlated with the parameters used in the 4Q approach, especially ARYL and SOC, in order to detect differences in SQ caused by different soil management systems.

Areas with better managed organic systems can serve as a reference for the search for SQ in vegetable production due to their potential to keep nutrient cycling and storage processes more active. There is considerable opportunity for technological progress in vegetable cultivation by increasing the use of BMP, which will make agroecosystems more sustainable.

7.6. References

Adeli, A., Read, J., Feng, G., McGrew, R., Jenkins, J., 2017. Organic Amendments and Nutrient Leaching in Soil Columns. Agron. J. 109, 1294-1302. https://doi.org/10.2134/agronj2016.11.0634

Altieri, M.A., Nicholls, C.I., Henao, A., Lana, M.A., 2015. Agroecology and the design of climate change-resilient farming systems. Agron. Sustain. Dev. 35, 869-890. https://doi.org/10.1007/s13593-015-0285-2

Avasiloaiei, D.I., Calara, M., Brezeanu, P.M., Gruda, N.S., Brezeanu, C., 2023. The Evaluation of Carbon Farming Strategies in Organic Vegetable Cultivation. Agronomy 13, 2406. https://doi.org/10.3390/agronomy13092406

Bajgai, Y., Kristiansen, P., Hulugalle, N., McHenry, M., 2014. Changes in soil carbon fractions due to incorporating corn residues in organic and conventional vegetable farming systems. Soil Res. 52, 244-252. https://doi.org/10.1071/SR13295

Bertini, S.C.B., Azevedo, L.C.B., Mendes, I.C ., Cardoso, E.J.B.N., 2014. Hierarchical partitioning for selection of microbial and chemical indicators of soil quality. Pedobiologia 57, 293-301. https://doi.org/10.1016/j.pedobi.2014.06.001

Bíla, P., Sarapatka, B., Horňák, O., Novotná, J., Brtnický, M., 2020. Which quality indicators reflect the most sensitive changes in the soil properties of the surface horizons affected by the erosion processes**?** Soil Water Res. 15, 116-124. http://dx.doi.org/10.17221/71/2019-swr

Blair, G., Lefroy, R., Lisle, L., 1995. Soil carbon fractions based on their degree of oxidation, and the development of a carbon management index for agricultural systems. Aust. J. Agric. Res. 46, 1459. https://doi.org/10.1071/AR9951459

Blanco-Canqui, H., Shapiro, C.A., Wortmann, C.S., Drijber, R.A., Mamo, M., Shaver, T.M., Ferguson, R.B., 2013. Soil organic carbon: The value to soil properties. J. Soil Water Conserv. 68, 129A-134A. https://doi.org/10.2489 /jswc.68.5.129A

Bongiorno, G., Bünemann, E.K., Oguejiofor, C.U., Meier, J., Gort, G., Comans, R., Mäder, P., Brussaard, L., De Goede, R., 2019. Sensitivity of labile carbon fractions to tillage and organic matter management and their potential as comprehensive soil quality indicators across pedoclimatic conditions in Europe. Ecol. Indic. 99, 38-50. https://doi.org/10.1016/j.ecolind.2018.12.008

Bünemann, E.K., Bongiorno, G., Bai, Z., Creamer, R.E., De Deyn, G., De Goede, R., Fleskens, L., Geissen, V., Kuyper, T.W., Mäder, P., Pulleman, M., Sukkel, W., Van Groenigen, J.W., Brussaard, L., 2018. Soil quality - A critical review. Soil Biol. Biochem. 120, 105-125. https://doi.org/10.1016/j.soilbio.2018.01.030

Burgio, G., Campanelli, G., Leteo, F., Ramilli, F., Depalo, L., Fabbri, R., Sgolastra, F., 2015. Ecological Sustainability of an Organic Four-Year Vegetable Rotation System: Carabids and Other Soil Arthropods as Bioindicators. Agroecol. Sust. Food Syst. 39, 295-316. https://doi.org/10.1080/21683565.2014.981910

Cambardella, C.A., Elliott, E.T., 1992. Particulate soil organic-matter changes across a grassland cultivation sequence. Soil Sci. Soc. Am. J. 56, 777-783

Carneiro, R.G., Figueiredo, C.C.D., Malaquias, J.V., Mendes, I.C., 2024. A soil health assessment tool for vegetable cropping systems in tropical soils based on beta-glucosidase, arylsulfatase, and soil organic carbon. Appl. Soil Ecol. 198, 105394. https://doi.org/10.1016/j.apsoil.2024.105394

Carvalho, A.M., Ribeiro, L.R.P., Marchão, R.L., de Oliveira, A.D., Pulrolnik, K., Figueiredo, C.C., 2022. Chemical composition of cover crops and soil organic matter pools in no-tillage systems in the Cerrado. Soil Use Manag. 38, 940-952. https://doi.org/10.1111/sum.12746

Chaer, G.M., Mendes, I.C., Dantas, O.D., Malaquias, J.V., Reis Junior, F.B., Oliveira, M.I.L., 2023. Evaluating C trends in clayey Cerrado Oxisols using a four-quadrant model based on specific arylsulfatase and β-glucosidase activities. Appl. Soil Ecol. 183, 104742. https://doi.org/10.1016/j.apsoil.2022.104742

Chan, K.Y., Bowman, A., Oates, A., 2001. Oxidizable organic carbon fractions and soil quality changes in an oxic paleustalf under different pasture ley. Soil Sci. 166, 61-67.

Comin, J.J., Bourscheid, C.A., Giumbelli, L.D., Souza Teixeira, M., Couto, R. da R., Lovato, P.E., Brunetto, G., Vezzani, F.M., Lourenzi, C.R., Loss, A., 2024. Qualitative soil quality assessment is efficient in a grazing system with or without trees. J. Sci. Food Agric. 104, 1962-1970. https://doi.org/10.1002/jsfa.13084

Cong, W., Hoffland, E., Li, L., Six, J., Sun, J., Bao, X., Zhang, F., Van Der Werf, W., 2015. Intercropping enhances soil carbon and nitrogen. Global Change Biology 21, 1715-1726. https://doi.org/10.1111/gcb.12738

Duval, M.E., Galantini, J.A., Martínez, J.M., Limbozzi, F., 2018. Labile soil organic carbon for assessing soil quality: influence of management practices and edaphic conditions. Catena 171, 316-326. http://dx.doi.org/10.1016/j.catena.2018.07.023

Ferreira, L.B., Loss, A., Giumbelli, L.D., Ventura, B.S., Souza, M., Mafra, Á.L., Kurtz, C., Comin, J.J., Brunetto, G., 2018. Organic carbon and nitrogen contents and their fractions in soils with onion crops in different management systems. Soil Res. 56, 846. https://doi.org/10.1071/SR18167

Fess, T., Benedito, V., 2018. Organic versus Conventional Cropping Sustainability: A Comparative System Analysis. Sustainability 10, 272. https://doi.org/10.3390/su10010272

Figueiredo, C.C.D., Resck, D.V.S., Carneiro, M.A.C., 2010. Labile and stable fractions of soil organic matter under management systems and native cerrado. Rev. Bras. Ciênc. Solo 34, 907-916. https://doi.org/10.1590/S0100-06832010000300032

Garbach, K., Milder, J.C., DeClerck, F.A.J., Montenegro de Wit, M., Driscoll, L., Gemmill-Herren, B., 2017. Examining multi-functionality for crop yield and ecosystem services in five systems of agroecological intensification. Int. J. Agr. Sustain. 15, 11-28. https://doi.org/10.1080/14735903.2016.1174810

Garratt, M.P.D., Bommarco, R., Kleijn, D., Martin, E., Mortimer, S.R., Redlich, S., Senapathi, D., Steffan-Dewenter, I., Świtek, S., Takács, V., Van Gils, S., Van Der Putten, W.H., Potts, S.G., 2018. Enhancing Soil O rganic Matter as a Route to the Ecological Intensification of European Arable Systems. Ecosystems 21, 1404-1415. https://doi.org/10.1007/s10021-018-0228-2

Gura, I., Mnkeni, P., du Preez, C., Barnard, J., 2021. Response of soil carbon fractions in a Haplic Cambisol to crop rotation systems and residue management practices under no tillage in the Eastern Cape, South Africa. S. Afr. J. Plant Soil 38, 372-380. https://doi.org/10.1080/02571862.2021.1938261

Hargreaves, S.K., Dejong, P., Laing, K., Mcquail, T., Van Eerd, L.L., 2019. Management sensitivity, repeatability, and consistency of interpretation of soil health indicators on organic farms in southwestern Ontario. Can. J. Soil Sci. 99, 508-519. http://dx.doi.org/10.1139/cjss-2019-0062

Hepperly, P., Lotter, D., Ulsh, C.Z., Seidel, R., Reider, C., 2009. Compost, Manure and Synthetic Fertilizer Influences Crop Yields, Soil Properties, Nitrate Leaching and Crop Nutrient Content. Compost Sci. Util. 17, 117-126. https://doi.org/10.1080/1065657X.2009.10702410

Hok, L., de Moraes Sá, J.C., Reyes, M., Boulakia, S., Tivet, F., Leng, V., Kong, R., Briedis, C., da Cruz Hartman, D., Ferreira, L.A., Inagaki, T.M., Gonçalves, D.R.P., Bressan, P.T., 2018. Enzymes and C pools as indicators of C build up in short-term conservation agriculture in a savanna ecosystem in Cambodia. Soil Tillage Res. 177, 125-133. https://doi.org/10.1016/j.still.2017.11.015

Hu, Q., Thomas, B.W., Powlson, D., Hu, Y., Zhang, Yu, Jun, X., Shi, X., Zhang, Yuting, 2023. Soil organic carbon fractions in response to soil, environmental and agronomic factors under cover cropping systems: A global meta-analysis. Agric. Ecosyst. Enviro. 355, 108591. https://doi.org/10.1016/j.agee.2023.108591

Jackson, M.L., 1958. Soil Chemical Analysis. Prentice Hall, Englewood Cliffs, NJ.

Johnston, A.E., Poulton, P.R., Coleman, K., 2009. Chapter 1 Soil Organic Matter, in: Adv. Agron. 1-57. https://doi.org/10.1016/S0065-2113(08)00801-8

Kalambukattu, J.G., Singh, R.D., Patra, A.K., Arunkumar, K., Pote, J., 2013. Land use practices in the Central Himalayan region affect soil enzyme activities and their relationship with carbon pools. Acta Agr. Scand. B-S P 63, 403-408. https://doi.org/10.1080/09064710.2013.789124

Knewtson, S.J.B., Kirkham, M.B., Janke, R.R., Murray, L.W., Carey, E.E., 2012. Soil Quality After Eight Years Under High Tunnels. HortScience 47, 1630-1633. https://doi.org/10.21273/HORTSCI.47.11.1630

Kubar, K.A., Ali, Q., Kalhoro, S.A., Memon, S.A., Nehela, Y., Korai, P.K., Ahmed, M., Narejo, M.N., 2024. Dynamics of Organic Carbon Fractions, Soil Fertility, and Aggregates Affected by Diverse Land-Use Cultivation Systems in Semiarid Degraded Land. J. Soil Sci. Plant. Nutr. 24, 524-536. https://doi.org/10.1007/s42729-023-01562-3

Lal, R., 2016. Soil health and carbon management. Food Energy Secur. 5, 212-222. https://doi.org/10.1002/fes3.96

Li, J., Wen, Y., Li, X., Li, Y., Yang, X., Lin, Z., Song, Z., Cooper, J.M., Zhao, B., 2018. Soil labile organic carbon fractions and soil organic carbon stocks as affected by long-term organic and mineral fertilization regimes in the North China Plain. Soil Tillage Res. 175, 281-290. https://doi.org/10.1016/j.still.2017.08.008

Li, P., Jia, L., Chen, Q., Zhang, H., Deng, J., Lu, J., Xu, L., Li, H., Hu, F., Jiao, J., 2024. Adaptive evaluation for agricultural sustainability of different fertilizer management options for a green manure-maize rotation system: Impacts on crop yield, soil biochemical properties and organic carbon fractions. Sci. Total Environ. 908, 168170. https://doi.org/10.1016/j.scitotenv.2023.168170

Liang, C., Hao, X., Schoenau, J., Ma, B.-L., Zhang, T., MacDonald, J.D., Chantigny, M., Dyck, M., Smith, W.N., Malhi, S.S., Thiagarajan, A., Lafond, J., Angers, D., 2021. Manure-induced carbon retention measured from long-term field studies in Canada. Agric. Ecosyst. Environ. 321, 107619. https://doi.org/10.1016/j.agee.2021.107619

Lima, C.E.P., Fontenelle, M.R., Madeira, N.R., Silva, J., Guedes, I.M.R., Silva, L.R.B. Soares, D.C., 2016. Organic carbon compartments in Latosol cultivated with vegetables under different management Organic carbon compartments in Latosol cultivated with vegetables under different management. Pesq. Agropec. bras. 51(4) 378-387. https://doi.org/10.1590/S0100-204X2016000400011

Lima, C.E.P, Guedes, I.M.R., Silva, J., Alcântara, F.A., Madeira, N.R., Carvalho, A.D.F., Fontenelle, M.R., 2018. Effects of Five Years Adoption of No-Tillage Systems for Vegetables Crops in Soil Organic Matter Contents. Agric. Sci. 09, 117-128. https://doi.org/10.4236/as.2018.91009

Lopes, A., Sousa, D.M.G., Chaer, G.M., Reis Junior, F.B., Goedert, W.J., Mendes, I.C., 2013. Interpretation of Microbial Soil Indicators as a Function of Crop Yield and Organic Carbon. Soil Sci. Soc. Am. J. 77, 461-472. https://doi.org/10.2136/sssaj2012.0191

Loss, A., Pereira, M.G., Schultz, N., Anjos, L.H.C.D., Silva, E.M.R.D., 2010. Quantification of humic substances carbon in different land use systems and evaluation periods. Bragantia 69, 913-922. https://doi.org/10.1590/S0006-87052010000400018

Lou, Y., Xu, M., Wang, W., Sun, X., Liang, C., 2011. Soil organic carbon fractions and management index after 20 yr of manure and fertilizer application for greenhouse vegetables. Soil Use Manag. 27, 163-169. https://doi.org/10.1111/j.1475-2743.2010.00325.x

Macedo, R.S., Moro, L., Sousa, C.S., Carneiro, K.A.A., Campos, M.C.C., Bakker, A.P., Beirigo, R.M., 2024. Agroforestry can improve soil fertility and aggregate-associated carbon in highland soils in the Brazilian northeast. Agroforest. Syst. 98, 1167-1179. https://doi.org/10.1007/s10457-023-00875-7

Maharjan, M., Sanaullah, M., Razavi, B.S., Kuzyakov, Y., 2017. Effect of land use and management practices on microbial biomass and enzyme activities in subtropical top- and sub-soils. Appl. Soil Ecol. 113, 22-28. https://doi.org/10.1016/ j.apsoil.2017.01.008

MAPA - Ministry of Agriculture, Livestock and Food Supply, 2024. MAPA Ordinance 52 (in Portuguese). https://www.gov.br/agricultura/pt-br/ assuntos/sustentabilidade/organicos/legislação/portugues/PORTARIAMAPAN52.2021.pdf (accessed 10.29.24).

Marriott, E.E., Wander, M.M., 2006. Total and Labile Soil Organic Matter in Organic and Conventional Farming Systems. Soil Sci. Soc. Am. J. 70, 950-959. https://doi.org/10.2136/sssaj2005.0241

McDaniel, M.D., Tiemann, L.K., Grandy, A.S., 2014. Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis. Ecol. Appl. 24, 560-570. https://doi.org/10.1890/13-0616.1

Melo, G.B., Pereira, M.G., Perin, A., Guareschi, R.F., Soares, P.F.C., 2016. Stocks and fractions of soil organic matter under no-till and conventional cabbage systems. Pesq. agropec. bras. 51, 1511–1519. https://doi.org/10.1590/s0100-204x2016000900050

Mendes, I.C., Sousa, D.M.G., Reis Junior, F.B., Lopes, A.A.C., Souza, L.M., Chaer, G.M., 2019a. Soil bioanalysis: theoretical and practical aspects. Topics. Ci. Solo 10, 1-64

Mendes, I.D., Souza, L.M., Sousa, D.M.G., Lopes, A.A.C., Reis Junior, F.B., Lacerda, M.P.C., Malaquias, J.V., 2019b. Critical limits for microbial indicators in tropical Oxisols at post-harvest: The FERTBIO soil sample concept. Appl. Soil Ecol. 139, 85-93. https://doi.org/10.1016/j.apsoil.2019.02.025

Mi, W., Sun, Y., Gao, Q., Liu, M., Wu, L., 2019. Changes in humus carbon fractions in paddy soil given different organic amendments and mineral fertilizers. Soil Tillage Res. 195, 104421. https://doi.org/10.1016/j.still.2019.104421

Moeskops, B., Sukristiyonubowo, Buchan, D., Sleutel, S., Herawaty, L., Husen, E., Saraswati, R., Setyorini, D., Neve, S., 2010. Soil microbial communities and activities under intensive organic and conventional vegetable farming in West Java, Indonesia. Appl. Soil Ecol. 45, 112-120. https://doi.org/10.1016/ bj.apsoil.2010.03.005

Morra, L., Bilotto, M., Baldantoni, D., Alfani, A., Baiano, S., 2021. A seven-year experiment in a vegetable crops sequence: Effects of replacing mineral fertilizers with Biowaste compost on crop productivity, soil organic carbon and nitrates

concentrations. Sci. Hortic. 290, 110534. https://doi.org/10.1016/j.scienta.2021.110534
Muchanga, R.A., Hirata, T., Uchida, Y., Hatano, R., Araki, H., 2020. Soil carbon and nitrogen and tomato yield response to cover crop management. Agron. J. 112, 1636-1648. https://doi.org/10.1002/agj2.20098
Nanda, G., Singh, D.K., Chandra, S., Pandey, P.C., Srivastava, A., Ravisankar, N., Gupta, S., 2024. Differences in productivity and soil properties in rice-based cropping systems under long-term organic, integrated and conventional production. Biol. Agric. Hortic. 13, 205-224. https://doi.org/10.1080/01448765.2024.2370288
Nelson, D.W., Sommers, L.E., 1996. Total carbon, organic carbon, and organic matter. In: Methods of Soil Analysis: Part 3 Chemical Methods, vol. 5.3, 961-1010. https://doi. org/10.2136/sssabookser5.3.c34
Niemi, R.M., Vepsäläinen, M., Wallenius, K., Erkomaa, K., Kukkonen, S., Palojärvi, A., Vestberg, M., 2008. Conventional versus organic cropping and peat amendment: Impacts on soil microbiota and their activities. Eur. J. Soil Biol. 44, 419-428. https://doi.org/10.1016/j.ejsobi.2008.06.001
Norris, C.E., Congreves, K.A., 2018. Alternative Management Practices Improve Soil Health Indices in Intensive Vegetable Cropping Systems: A Review. Front. Environ. Sci. 6, 50. https://doi.org/10.3389/fenvs.2018.00050
Obalum, S.E., Chibuike, G.U., Peth, S., Ouyang, Y., 2017. Soil organic matter as sole indicator of soil degradation. Environ Monit Assess 189, 176. https://doi.org/10.1007/s10661-017-5881-y
Oldfield, E.E., Bradford, M.A., Wood, S.A., 2019. Global meta-analysis of the relationship between soil organic matter and crop yields. Soil 5, 15-32. https://doi.org/10.5194/soil-5-15-2019
Ouyang, Y., Reeve, J.R., Norton, J.M., 2022. The quality of organic amendments affects soil microbiome and nitrogen-cycling bacteria in an organic farming system. Front. Soil Sci. 2. https://doi.org/10.3389/fsoil.2022.869136
Paliaga, S., Muscarella, S.M., Lucia, C., Pampinella, D., Palazzolo, E., Badalucco, L., Badagliacca, G., Laudicina, V.A., 2024. Long-term organic management: Mitigating land use intensity drawbacks and enhancing soil microbial redundancy. J. Plant Nutr. Soil Sci. 187, 287-294. https://doi.org/10.1002/jpln.202300252
Palomo-Campesino, S., García-Llorente, M., Hevia, V., Boeraeve, F., Dendoncker, N., Gonzáles, J.A., 2022. Do agroecological practices enhance the supply of ecosystem services? A comparison between agroecological and conventional horticultural farms. Ecosyst. Serv. 57, 101474. https://doi.org/10.1016/j.ecoser.2022.101474
Plaza-Bonilla, D., Álvaro-Fuentes, J., Cantero-Martínez, C., 2014. Identifying soil organic carbon fractions sensitive to agricultural management practices. Soil Tillage Res., 139, 19-22. http://dx.doi.org/10.1016/j.still.2014.01.006
Resende Filho, M.A., Andow, D.A., Carneiro, R.G., Lorena, D.R., Sujii, E.R., Alves, R.T., 2019. Economic and productivity incentives to produce organically in Brazil: Evidence from strawberry production in the Federal District. Renew. Agric. Food Syst. 34, 155-168. https://doi.org/10.1017/S1742170517000412

Rosset, J.S., Lana, M. do C., Pereira, M.G., Schiavo, J.A., Rampim, L., Sarto, M.V.M., 2016. Chemical and oxidizable fractions of soil organic matter under different management systems in Red Latosol. Pesq. agropec. bras. 51, 1529–1538. https://doi.org/10.1590/S0100-204X2016000900052

Sá, J.C.M., Gonçalves, D.R.P., Ferreira, L.A., Mishra, U., Inagaki, T.M., Furlan, F.J.F., Moro, R.S., Floriani, N., Briedis, C., Ferreira, A.O., 2018. Soil carbon fractions and biological activity based indices can be used to study the impact of land management and ecological successions. Ecol. Indic. 84, 96-105. https://doi.org/10.1016/j.ecolind.2017.08.029

Sánchez-Navarro, V., Zornoza, R., Faz, Á., Fernández, J.A., 2019. Comparing legumes for use in multiple cropping to enhance soil organic carbon, soil fertility, aggregates stability and vegetable yields under semi-arid conditions. Sci. Hortic. 246, 835-841. https://doi.org/10.1016/j.scienta.2018.11.065

Santos, H.G., Jacomine, P.K.T., Anjos, L.H.C., Oliveira, V.A., Lumbreras, J.F., Coelho, M. R., Almeida, J.A., Araújo Filho, J.C., Oliveira, J.B., Cunha, T.J.F., 2018. Brazilian Soil Classification System, 5th ed. Embrapa, Brasília, DF.

Santos, J.A., Santos, A.D., Costa, C.R., Araujo, A.S., Leite, G.G., Coser, T.R., Figueiredo, C.C., 2024. Fractions of Organic Matter and Soil Carbon Balance in Different Phases of an Agroforestry System in the Cerrado: A Ten-Year Field Assessment. Soil Syst. 8, 44. https://doi.org/10.3390/soilsystems8020044

Santos, L.L. dos, Lacerda, J.J.J., Zinn, Y.L., 2013. Partitioning of humic substances in Brazilian soils. Rev. Bras. Ciênc. Solo 37, 955-968. https://doi.org/10.1590/S0100-06832013000400013

Sato, J.H., de Figueiredo, C.C., Marchão, R.L., de Oliveira, A.D., Vilela, L., Delvico, F.M., Alves, B.J.R., de Carvalho, A.M., 2019. Understanding the relations between soil organic matter fractions and N2O emissions in a long-term integrated crop-livestock system. Eur. J. Soil Sci. 70, 1183-1196. https://doi.org/10.1111/ejss.12819.

Shang, C., Tiessen, H., 1997. Organic matter lability in a tropical Oxisol: evidence from shifting cultivation, chemical oxidation, particle size, density, and magnetic fractionations. Soil Sci. 162, 795-807

Sheoran, H.S., Phogat, V.K., Dahiya, R., Kakar, R., 2019. Soil organic carbon stocks and carbon dynamics under organic and conventional farming systems in Indo-Gangetic Plains. Indian J. Agric. Sci. 89, 813-820. https://doi.org/10.56093/ijas.v89i5.89663

Silva, C.S.R.A., Araújo, E.S., Costa, L.S., Araújo, S.N., Silva Junior, J.B., Ziviani, M.M., Silva, M.S.R.A., Guerra, J.G.M., Espindola, J.A.A., Pinheiro, E.F.M., 2024. No-till system organic vegetable production under green manure: effect on yield and soil properties. Org. Agr. 14, 231-244. https://doi.org/10.1007/s13165-024-00460-x

Sissoko, A., Kpomblekou-A, K., 2010. Carbon decomposition in broiler litter-amended soils. Soil Biol. Biochem. 42, 543-550. https://doi.org/10.1016/j.soilbio.2009.10.007

Souza, R.F. de, Figueiredo, C.C. de, Madeira, N.R., Alcântara, F.A. de, 2014. Effect of management systems and cover crops on organic matter dynamics of soil under vegetables. Rev. Bras. Ciênc. Solo 38, 923-933. https://doi.org/10.1590/S0100-06832014000300024

Srivastava, P., Singh, R., Tripathi, S., Raghubanshi, A.S., 2016. An urgent need for sustainable thinking in agriculture - An Indian scenario. Ecol. Indic. 67, 611-622. https://doi.org/10.1016/j.ecolind.2016.03.015

Tejada, M., Benítez, C., 2017. Flazasulfuron behavior in a soil amended with different organic wastes. Appl. Soil Ecol. 117-118, 81-87. https://doi.org/10.1016/ j.apsoil.2017.05.009

Tabatabai, M.A., 1994. Soil enzymes. In: Weaver, R.W., Scott, A., Bottomley, P.J. (Eds.), Methods of Soil Analysis: Microbiological and Biochemical Properties. Soil Science Society of America, Madison, pp. 778-833.

Teixeira, P.C., Donagemma, G.K., Fontana, A., Teixeira, W.G., 2017. Manual of Soil Analysis Methods (in Portuguese), 3rd ed. Embrapa, Brasília, Brazil, p. 574p.

Thomazini, A., Mendonça, E.S., Souza, J.L., Cardoso, I.M., Garbin, M.L., 2015. Impact of organic no-till vegetable systems on soil organic matter in the Atlantic Forest biome. Sci. Hortic. 182, 145-155. https://doi.org/10.1016/j.scienta.2014.12.002

Ugarte, C.M., Kwon, H., Andrews, S.S., Wander, M.M., 2014. A meta-analysis of soil organic matter response to soil management practices: An approach to evaluate conservation indicators. J. Soil Water Conserv. 69, 422-430. https://doi.org/10.2489/jswc.69.5.422

Vachon, K., Oelbermann, M., 2011. Crop Residue Input and Decomposition in a Temperate Maize-Soybean Intercrop System. Soil Sci. 176, 157-163. https://doi.org/10.1097/SS.0b013e3182104213

Valani, G.P., Vezzani, F.M., Cavalieri-Polizeli, K.M.V., 2020. Soil quality: Evaluation of on-farm assessments in relation to analytical index. Soil Till Res. 198, 104565. https://doi.org/10.1016/j.still.2019.104565

Valarini, P.J., Oliveira, F.R., Schilickmann, S.D.F., Poppi, R.J., 2011. Soil quality in organic and conventional vegetable production systems. Hortic. Bras. 29, 485-491. https://doi.org/10.1590/S0102-05362011000400007

Wallenstein MD, Burns RG. Ecology of extracellular enzyme activities and organic matter degradation in soil: a complex community-driven process. In: Dick RP, editor. Methods of soil enzymology. Madison: Soil Sci. Soc. Am. 2011. p. 35-56.

Willekens, K., Vandecasteele, B., Buchan, D., De Neve, S., 2014. Soil quality is positively affected by reduced tillage and compost in an intensive vegetable cropping system. Appl. Soil Ecol. 82, 61-71. https://doi.org/10.1016/j.apsoil.2014.05.009

Xu, C., Qian, Z., Wang, B., Yang, T., Lin, Z., Tian, D., Ding, C., Tang, L., 2023. Effects of poplar agroforestry systems on soil nutrient and enzyme activity in the coastal region of eastern China. J. Soils Sediments 23, 3108-3123. https://doi.org/10.1007/s11368-023-03553-4

Yan, J., Pan, G., Li, L., Quan, G., Ding, C., Luo, A., 2010. Adsorption, immobilization, and activity of β-glucosidase on different soil colloids. J. Colloid Interface Sci. 348, 565-570. https://doi.org/10.1016/j.jcis.2010.04.044

Zhang, Y., Hagedorn, F., Guidi, C., Yang, L., 2022. Limited soil carbon storage under long-term organic fertilization in solar greenhouses. Soil Use Manag. 38, 1614-1627. https://doi.org/10.1111/sum.12832

Zhao, Y., Wu, S., Bol, R., Bughio, M.A., Wu, W., Hu, Y., Meng, F., 2020. Intensive organic vegetable production increases soil organic carbon but with a lower carbon conversion efficiency than integrated management. J. Plant Nutr. Soil Sci. 183, 155-168. https://doi.org/10.1002/jpln.201900308

7.7. Supplementary material – Chapter II

Table S1

Table S1. Average ± SD of soil chemical properties (0 to 10 cm depth) in 48 organically and 42 conventionally managed vegetable production systems.

System*	P	K	Ca	Mg	Al	H+Al	CEC	V	pH
	mg dm^{-3}		$cmol_c$ dm^{-3}					(%)	(H_2O)
Organic	281±288	315.±224	6.7±1.4	2.8±0.9	0.0	0.6±0.7	10.8±2.2	94±7	7.1±0.3
Conventional	361±290	259±192	6.0±1.4	1.9±0.6	0.0	2.5±1.4	11.1±2.1	78±12	6.5±0.4

8. Considerações finais

Esta tese de doutorado, conduzida com base em amostras de solo coletadas em fazendas comerciais de produção de hortaliças do DF, geralmente com áreas variando de 1 a 20 hectares contemplou duas vertentes de estudos relacionadas à QS na produção de hortaliças, as quais constituíram os capítulos da tese.

O primeiro capítulo resultou na elaboração de um modelo de avaliação da QS específico para hortaliças, baseado na combinação da estratégia proposta pela Universidade de Cornell (CASH) com o modelo de 4 quadrantes, proposto pela equipe que desenvolveu a tecnologia BioAS Embrapa, utilizando, como base, determinações de ARIL, GLI e SOC. O delineamento de uma estratégia de intepretação específica para áreas sob cultivo de hortaliças deveu-se a inadequação dos atuais algoritmos de interpretação, desenvolvidos para culturas anuais no Cerrado, para detectarem diferenças entre as áreas (vide laudo da BioAS no apêndice 1). Além disso, as particularidades dos sistemas de cultivos de hortaliças, com grande diversidade de plantas herbáceas, incluindo raízes, caules, folhas, botões florais, frutos e sementes comestíveis, dificulta interpretar os indicadores de saúde do solo em relação à produtividade vegetal. Consequentemente, nesses sistemas, estratégias para interpretar e pontuar os indicadores de saúde do solo não podem depender da produtividade das plantas, sendo necessárias novas alternativas.

Com a nova estratégia desenvolvida no capítulo 1 foi possível superar essas limitações permitindo classificar os solos das áreas comerciais onde o estudo foi feito em: saudáveis, degradados, em processo de degradação biológica ou de regeneração. Importante ressaltar que essa classificação, correlacionou com os resultados de manejo, refletindo os diferentes níveis de adoção das boas práticas de manejo de solo (BPMS) utilizados nas 53 propriedades rurais avaliadas. Conjugado com as análises químicas, a abordagem construída possibilita uma avaliação mais completa das condições do solo para os olericultores e técnicos de campo, contribuindo para tornar os agroecossistemas olerícolas mais sustentáveis e estáveis ao longo do tempo. O modelo proposto foi uma primeira aproximação, que precisa ser validada em áreas de olericultura de outros locais.

Importante salientar que, possivelmente, em cultivos de hortaliças realizados em grande escala, com diferenças marcantes no padrão tecnológico quanto à mecanização, insumos minerais e orgânicos utilizados, os parâmetros podem necessitar de adaptação.

O capítulo 2 envolveu o fracionamento da MOS e a relação destas frações com os diferentes manejos, com a QS e com a atividade da ARIL e GLI. O fracionamento da MOS revelou diferenças significativas na QS entre os sistemas orgânicos e convencionais, demonstrando a importância das frações lábeis e estáveis do COS para avaliação do efeito dos manejos adotados. As frações lábeis e estáveis da MOS foram correlacionadas com ARIL e COS, possibilitando estratégia complementar para avaliação da QS nos SPH.

Para o desenvolvimento dos dois capítulos, foi fundamental a realização de entrevistas (apêndice 2), observações em campo e sistematização dos dados. Assim, foi gerado um conjunto de informações sobre a adoção das BPMS nos sistemas orgânicos ou convencionais de hortaliças estudados, que contribuíram para interpretação dos parâmetros quantitativos avaliados. Os agricultores foram estimulados a revelar suas impressões e conceitos a respeito de: i) QS; ii) fertilidade do solo; iii) importância dos seres vivos habitantes do solo para a agricultura; iv) análise de solo, custos de produção. As respostas a estas indagações revelaram diversos níveis de conhecimento sobre o funcionamento dos agroecossistemas, visões mais mineralistas ou biológicas sobre fertilidade e qualidade do solo (dados não publicados), que resultarão em mais informações e possíveis estratégias de extensão rural relacionadas ao tema qualidade do solo

Com base nos estudos realizados nos dois capítulos, verificou-se que há caminhos e referências de sistemas produtivos, que podem levar ao alcance de graus maiores de sustentabilidade nos agroecossistemas olerícolas.

9. Apêndices

9.1. Apêndice 1

Laudo de bioanálise das 90 amostras de solo do presente estudo, utilizando a interpretação com algoritmos de cultivos anuais.

Embrapa — MÓDULO DE INTERPRETAÇÃO DA QUALIDADE DO SOLO — REDE EMBRAPA BioAS BIOANÁLISES DE SOLO

Hortaliças DF (2024) — v1400.5s

AMOSTRA	Arilsulfatase	β-Glicosidase	MOS	ARGILA	IQS FERTBIO	IQS Biológico	IQS Químico	CICLAGEM Nutrientes	ARMAZ. Nutrientes	SUPRIMENTO Nutrientes	MODELO
1- CONVENCIONAL	108	132	38	44	**0,93**	0,92	0,94	0,92	0,97	0,91	FertBIO
2- CONVENCIONAL	107	97	38	48	**0,85**	0,82	0,87	0,82	0,83	0,90	FertBIO
3- CONVENCIONAL	151	97	40	37	**0,94**	0,91	0,95	0,91	1,00	0,91	FertBIO
4- CONVENCIONAL	138	136	46	41	**0,95**	0,96	0,95	0,96	0,99	0,91	FertBIO
5- ORGÂNICO	135	177	33	23	**0,96**	1,00	0,94	1,00	1,00	0,89	FertBIO
6- ORGÂNICO	111	102	46	20	**0,95**	0,98	0,94	0,98	1,00	0,88	FertBIO
7- ORGÂNICO	254	176	48	22	**0,93**	1,00	0,90	1,00	1,00	0,79	FertBIO
8- ORGÂNICO	516	223	53	25	**0,94**	1,00	0,92	1,00	1,00	0,83	FertBIO
9- ORGÂNICO	229	286	43	19	**0,95**	1,00	0,93	1,00	1,00	0,85	FertBIO
10- ORGÂNICO	217	251	45	16	**0,90**	1,00	0,85	1,00	1,00	0,70	FertBIO
11- CONVENCIONAL	125	104	32	40	**0,91**	0,90	0,91	0,90	0,95	0,88	FertBIO
12- ORGÂNICO	210	143	49	39	**0,96**	0,97	0,95	0,97	1,00	0,90	FertBIO
13- ORGÂNICO	224	280	50	47	**0,96**	1,00	0,93	1,00	0,97	0,90	FertBIO
14- ORGÂNICO	152	162	47	40	**0,96**	0,98	0,95	0,98	0,99	0,90	FertBIO
15- ORGÂNICO	218	104	38	34	**0,91**	0,94	0,90	0,94	0,99	0,81	FertBIO
16- CONVENCIONAL	95	122	29	29	**0,95**	0,97	0,93	0,97	0,99	0,88	FertBIO
17- ORGÂNICO	207	259	47	34	**0,92**	1,00	0,89	1,00	0,99	0,79	FertBIO
18- ORGÂNICO	272	168	50	36	**0,93**	0,99	0,90	0,99	1,00	0,81	FertBIO
19- ORGÂNICO	173	158	40	42	**0,93**	0,98	0,90	0,98	0,98	0,82	FertBIO
20- ORGÂNICO	310	159	44	41	**0,92**	0,98	0,89	0,98	0,99	0,79	FertBIO
21- CONVENCIONAL	51	158	35	42	**0,88**	0,80	0,92	0,80	0,97	0,86	FertBIO
22- CONVENCIONAL	260	156	42	40	**0,95**	0,98	0,93	0,98	1,00	0,86	FertBIO
23- CONVENCIONAL	129	155	34	44	**0,91**	0,96	0,89	0,96	0,90	0,87	FertBIO
24- CONVENCIONAL	130	172	36	48	**0,93**	0,96	0,92	0,96	0,94	0,89	FertBIO
25- CONVENCIONAL	18	64	27	38	**0,76**	0,48	0,90	0,48	0,90	0,90	FertBIO
26- CONVENCIONAL	37	98	21	29	**0,85**	0,77	0,90	0,77	0,89	0,90	FertBIO
27- ORGÂNICO	115	113	23	30	**0,85**	0,96	0,80	0,96	0,89	0,71	FertBIO
28- ORGÂNICO	519	199	93	20	**0,93**	1,00	0,89	1,00	1,00	0,79	FertBIO
29- ORGÂNICO	393	116	44	40	**0,92**	0,94	0,91	0,94	1,00	0,82	FertBIO
30- CONVENCIONAL	142	157	40	51	**0,94**	0,94	0,93	0,94	0,98	0,89	FertBIO
31- CONVENCIONAL	155	147	26	41	**0,88**	0,97	0,83	0,97	0,79	0,87	FertBIO

LEGENDA	muito alto	alto	médio	baixo	muito baixo
	0,81 a 1	0,61 a 0,80	0,41 a 0,60	0,21 a 0,40	0 a 0,20

Embrapa — MÓDULO DE INTERPRETAÇÃO DA QUALIDADE DO SOLO — REDE EMBRAPA BioAS BIOANÁLISES DE SOLO

Hortaliças DF (2024) — v1400.5s

AMOSTRA	Arilsulfatase	β-Glicosidase	MOS	ARGILA	IQS FERTBIO	IQS Biológico	IQS Químico	CICLAGEM Nutrientes	ARMAZ. Nutrientes	SUPRIMENTO Nutrientes	MODELO
32- ORGÂNICO	270	66	52	35	**0,83**	0,82	0,84	0,82	1,00	0,68	FertBIO
33- ORGÂNICO	338	56	57	23	**0,84**	0,84	0,84	0,84	1,00	0,68	FertBIO
34- ORGÂNICO	222	151	43	37	**0,94**	0,98	0,92	0,98	1,00	0,83	FertBIO
35- ORGÂNICO	154	139	40	36	**0,95**	0,98	0,93	0,98	1,00	0,86	FertBIO
36- ORGÂNICO	55	41	22	22	**0,83**	0,72	0,88	0,72	0,99	0,77	FertBIO
37- ORGÂNICO	75	55	29	32	**0,80**	0,75	0,83	0,75	0,98	0,67	FertBIO
38- ORGÂNICO	160	157	40	44	**0,88**	0,97	0,83	0,97	0,96	0,69	FertBIO
39- ORGÂNICO	206	132	38	48	**0,91**	0,94	0,90	0,94	0,94	0,85	FertBIO
40- CONVENCIONAL	145	157	40	58	**0,91**	0,92	0,91	0,92	0,91	0,91	FertBIO
41- CONVENCIONAL	36	83	31	66	**0,61**	0,46	0,69	0,46	0,54	0,83	FertBIO
42- CONVENCIONAL	329	128	41	44	**0,92**	0,94	0,91	0,94	0,99	0,84	FertBIO
43- CONVENCIONAL	286	118	39	45	**0,93**	0,92	0,93	0,92	0,99	0,88	FertBIO
44- CONVENCIONAL	130	94	32	39	**0,84**	0,89	0,82	0,89	0,97	0,68	FertBIO
45- ORGÂNICO	219	196	39	47	**0,93**	0,99	0,89	0,99	0,91	0,87	FertBIO
46- ORGÂNICO	216	178	38	51	**0,92**	0,98	0,90	0,98	0,93	0,86	FertBIO
47- ORGÂNICO	227	188	44	40	**0,95**	0,99	0,93	0,99	0,99	0,87	FertBIO
48- CONVENCIONAL	44	192	31	30	**0,91**	0,85	0,94	0,85	1,00	0,89	FertBIO
49- CONVENCIONAL	118	154	30	41	**0,93**	0,96	0,92	0,96	0,94	0,90	FertBIO
50- CONVENCIONAL	105	177	32	44	**0,94**	0,95	0,93	0,95	0,95	0,91	FertBIO
51- CONVENCIONAL	122	233	35	35	**0,97**	0,99	0,95	0,99	0,99	0,91	FertBIO
52- CONVENCIONAL	31	95	19	32	**0,75**	0,70	0,78	0,70	0,76	0,80	FertBIO
53- CONVENCIONAL	37	69	17	33	**0,66**	0,64	0,67	0,64	0,64	0,70	FertBIO
54- ORGÂNICO	67	108	33	33	**0,85**	0,88	0,83	0,88	0,99	0,67	FertBIO
55- ORGÂNICO	79	73	38	33	**0,84**	0,82	0,84	0,82	1,00	0,69	FertBIO
56- CONVENCIONAL	44	99	32	42	**0,85**	0,68	0,93	0,68	0,95	0,91	FertBIO
57- CONVENCIONAL	43	138	26	42	**0,83**	0,75	0,87	0,75	0,84	0,89	FertBIO
58- CONVENCIONAL	61	233	31	42	**0,89**	0,86	0,91	0,86	0,92	0,90	FertBIO
59- CONVENCIONAL	124	182	41	32	**0,97**	1,00	0,96	1,00	1,00	0,91	FertBIO
60- ORGÂNICO	319	117	53	36	**0,95**	0,95	0,94	0,95	1,00	0,89	FertBIO
61- CONVENCIONAL	144	102	30	47	**0,86**	0,87	0,85	0,87	0,80	0,91	FertBIO
62- CONVENCIONAL	137	126	38	37	**0,95**	0,96	0,94	0,96	1,00	0,89	FertBIO

LEGENDA	muito alto	alto	médio	baixo	muito baixo
	0,81 a 1	0,61 a 0,80	0,41 a 0,60	0,21 a 0,40	0 a 0,20

MÓDULO DE INTERPRETAÇÃO DA QUALIDADE DO SOLO

REDE EMBRAPA BioAS BIOANÁLISES DE SOLO

Hortaliças DF (2024) — v1400.5s

AMOSTRA	Arilsulfatase	β-Glicosidase	MOS	ARGILA	IQS FERTBIO	IQS Biológico	IQS Químico	CICLAGEM Nutrientes	ARMAZ. Nutrientes	SUPRIMENTO Nutrientes	MODELO
63- CONVENCIONAL	85	165	39	39	**0,94**	0,94	0,94	0,94	1,00	0,88	FertBIO
64- ORGÂNICO	106	114	38	42	**0,81**	0,90	0,77	0,90	0,85	0,68	FertBIO
65- CONVENCIONAL	41	83	34	33	**0,79**	0,71	0,83	0,71	0,97	0,68	FertBIO
66- CONVENCIONAL	119	133	30	54	**0,84**	0,87	0,82	0,87	0,73	0,91	FertBIO
67- CONVENCIONAL	175	131	38	39	**0,95**	0,96	0,94	0,96	0,99	0,90	FertBIO
68- ORGÂNICO	252	98	36	28	**0,93**	0,95	0,93	0,95	1,00	0,85	FertBIO
69- ORGÂNICO	198	125	37	30	**0,94**	0,98	0,91	0,98	0,99	0,84	FertBIO
70- ORGÂNICO	311	167	41	44	**0,90**	0,98	0,87	0,98	0,87	0,86	FertBIO
71- ORGÂNICO	310	203	40	36	**0,96**	1,00	0,94	1,00	0,99	0,89	FertBIO
72- ORGÂNICO	322	159	73	40	**0,95**	0,98	0,93	0,98	1,00	0,85	FertBIO
73- ORGÂNICO	221	91	38	58	**0,82**	0,81	0,82	0,81	0,75	0,89	FertBIO
74- ORGÂNICO	74	78	32	44	**0,76**	0,72	0,78	0,72	0,89	0,68	FertBIO
75- ORGÂNICO	142	98	49	43	**0,86**	0,88	0,85	0,88	1,00	0,70	FertBIO
76- CONVENCIONAL	93	184	34	40	**0,94**	0,95	0,94	0,95	0,97	0,91	FertBIO
77- CONVENCIONAL	44	71	30	43	**0,78**	0,59	0,87	0,59	0,90	0,84	FertBIO
78- CONVENCIONAL	99	192	30	54	**0,81**	0,90	0,76	0,90	0,63	0,89	FertBIO
79- ORGÂNICO	198	102	32	42	**0,91**	0,90	0,91	0,90	0,95	0,87	FertBIO
80- CONVENCIONAL	95	82	22	27	**0,90**	0,91	0,90	0,91	0,90	0,89	FertBIO
81- CONVENCIONAL	116	111	31	34	**0,91**	0,94	0,89	0,94	0,90	0,88	FertBIO
82- ORGÂNICO	192	60	37	33	**0,83**	0,81	0,83	0,81	0,99	0,67	FertBIO
83- ORGÂNICO	107	119	34	26	**0,89**	0,98	0,84	0,98	0,99	0,68	FertBIO
84- ORGÂNICO	240	140	43	34	**0,91**	0,98	0,88	0,98	0,99	0,77	FertBIO
85- ORGÂNICO	157	132	39	38	**0,88**	0,97	0,84	0,97	0,92	0,76	FertBIO
86- ORGÂNICO	281	194	42	45	**0,93**	0,99	0,90	0,99	0,93	0,86	FertBIO
87- CONVENCIONAL	120	112	35	43	**0,88**	0,90	0,87	0,90	0,91	0,83	FertBIO
88- CONVENCIONAL	95	111	32	46	**0,88**	0,85	0,90	0,85	0,90	0,90	FertBIO
89- ORGÂNICO	414	185	41	42	**0,94**	0,99	0,91	0,99	0,95	0,87	FertBIO
90- ORGÂNICO	407	211	48	42	**0,95**	1,00	0,92	1,00	1,00	0,84	FertBIO

LEGENDA	muito alto	alto	médio	baixo	muito baixo
	0,81 a 1	0,61 a 0,80	0,41 a 0,60	0,21 a 0,40	0 a 0,20

9.2. Apêndice 2

Roteiro para entrevista sobre práticas de manejo do solo

1- Em sua opinião, o que é importante para a fertilidade do solo e o que você tem feito para aumentar ou manter esta fertilidade?
2- Qual o tamanho da área plantada no local onde foi feita a amostragem?
3- Desde que ano esta área é plantada com hortaliças orgânicas ou convencionais ou outras culturas?
4- Qual a produtividade estimada no plantio atual e a produtividade do plantio anterior nesta área?

5- De forma geral, comparando com outros produtores, você considera suas produtividades:

( ) altas ( ) médias ( ) baixas

6- Quais implementos e sequência de preparo de solo utilizados no plantio da área onde foi realizada a amostragem?
7- Ainda sobre o preparo do solo...
   ( ) Em todos os plantios repete a mesma sequência de implementos
   ( ) Alterna plantios com e sem preparo do solo
   ( ) Realiza plantio direto de hortaliças em cima da palha (não faz preparo de solo)?
   ( ) Não ( ) eventualmente ( ) frequentemente
8- Fez análise de solo para o plantio realizado na área de amostragem?
   a. Sim ( ) Não ( )
9- Se faz a análise de solo, com que frequência realiza este procedimento numa mesma área?
10- Quais adubos minerais foram utilizados no plantio onde foi feita a amostragem? Qual a quantidade por ha, m² ou metros de canteiro ?
11- Foi utilizado adubo orgânico no plantio onde foi realizada a amostragem? Qual a quantidade por ha, m² ou metros de canteiro ?
12- O adubo orgânico é utilizado de que forma ?
   a. ( ) sem curtir
   b. ( ) curtido por ( ) dias
   c. ( ) compostado com outros materiais

13- Utiliza biofertilizantes líquidos?

a. ( ) Bokashi líquido a cada ( ) dias
b. ( ) EM a cada ( ) dias
c. ( ) Biofertilizantes fórmula própria a cada ( ) dias
d. ( ) Outro biofertilizante. Qual?
e. ( ) Usa em fertirrigação ( ) vezes por semana Dose:

14- Faz fertirrigação com adubos minerais?

a. ( ) Sim ( ) Não

15- Quais adubos minerais são utilizados na fertirrigação ?

a. ( ) MAP ( ) vezes por semana Dose:
b. ( ) Nitrato de cálcio ( ) vezes por semana Dose:
c. ( ) Nitrato de K ( ) vezes por semana Dose:
d. ( ) MKP em tomate ( ) vezes por semana Dose:
e. ( ) ....( ) vezes por semana Dose:

16- Quais adubos minerais foram utilizados nos plantios anteriores? Quantidade por ha, m² ou metros de canteiro ?

17- Quais adubos orgânicos foram utilizados nos plantios anteriores? Quantidade por ha, m² ou metros de canteiro ?

18- Qual foi a sequência dos últimos 5 ou 6 cultivos/pousios na área de amostragem?

19- Usou adubação verde (plantas que melhoram o solo) na área onde foi realizada a amostragem?

a. ( ) Sim ( ) Não

20- Qual(is) adubos verdes foram utilizados?

a. ( ) Milheto
b. ( ) Crotalária
c. ( ) Mucuna preta ou cinza
d. ( ) Aveia
e. ....

21- Estrutura do solo

a. ( ) Solo pulverizado e/ou com presença de torrões compactados e/ou com presença de camadas compactadas
b. ( ) Solo bem estruturado, sem a presença de torrões compactados, poroso, com boa infiltração da água e penetração de raízes

c. ( ) Subsolador todo ano

22- Exposição do solo

a. ( ) Solo exposto
b. ( ) Menos de 50 % do solo coberto por palha ou cobertura viva
c. ( ) Mais de 50 % do solo coberto por palha ou cobertura viva
d. ( ) Mulching plástico

23- Presença de organismos vivos

a. ( ) Ausência ou poucas minhocas ou outros pequenos seres vivos
b. ( ) Presença abundante de minhocas ou pequenos seres vivos no solo

24- Quais suas ações para baixar custos com fertilizantes e outros insumos ?

25- O que você conhece sobre a importância das minhocas, bactérias, fungos, insetos e outros seres vivos do solo sobre a fertilidade ou controle de doenças?

26- Na sua opinião o que é um solo de boa qualidade?

27- Tem mais observações ou comentários sobre algum aspecto da conversa?