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JONNATHAN RICHEDS DA SILVA SALES

PEGADA DE CARBONO DO CAJU EM DIFERENTES SISTEMAS DE CULTIVO: MÉTODOS DE QUANTIFICAÇÃO DE GASES DE EFEITO ESTUFA E PROJEÇÕES

FORTALEZA
2026

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Tese de Doutorado apresentado ao Programa de Pós-Graduação em Engenharia Agrícola do Departamento de Engenharia Agrícola da Universidade Federal do Ceará, como parte dos requisitos para obtenção do título de Doutor em Engenharia Agrícola. Área de concentração: Irrigação e Drenagem

Orientador: Dr. Claudivan Feitosa de Lacerda
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RESUMO

Diante da crise climática, as cadeias de suprimento de alimentos estão cada vez mais buscando a aplicação de práticas sustentáveis de produção, a exemplo, temos os estudos voltados para o setor de frutíferas. A cajucultura desempenha uma importante contribuição socioeconômica para a agricultura no Brasil, especialmente para a região Nordeste. Desta forma, objetivou-se avaliar, comparar e integrar abordagens metodológicas para a estimativa da pegada de carbono na cajucultura brasileira, considerando tanto inventários de ciclo de vida baseados em equações empíricas quanto a dinâmica do carbono na biomassa e no solo ao longo da vida útil dos pomares. Inicialmente, foram avaliados diferentes métodos de quantificação de GEE em um sistema convencional de produção de caju. As metodologias Nemecek-Calc, WFLDB, IPCC-Calc, BR-Calc e Agri-footprint foram comparadas conforme as normas ISO 14067. Os resultados evidenciaram variações de até 24,5% entre os métodos, sendo o N_2O o principal contribuinte das emissões. Com base em critérios de clareza metodológica, robustez científica e adequação aos dados regionais, os métodos WFLDB, IPCC-Calc e BR-Calc apresentaram melhor desempenho. Em uma segunda etapa, a pegada de carbono foi integrada à quantificação do carbono estocado na biomassa e à modelagem do carbono orgânico do solo (COS) ao longo do ciclo produtivo do cajueiro, considerando uma vida útil de 25 anos. Foram avaliados cinco sistemas de produção, em áreas experimentais e comerciais, incluindo sistemas monocultivo e consorciados. A biomassa foi quantificada por meio de equações alométricas específicas, e o COS (0–20 cm) foi estimado utilizando o modelo RothC. Os resultados demonstraram maior acúmulo de carbono na biomassa e no solo em sistemas diversificados, refletindo menores valores de pegada de carbono em comparação aos sistemas convencionais. Conclui-se que a escolha metodológica e o sistema de manejo influenciam significativamente os resultados da pegada de carbono na cajucultura, evidenciando o potencial de sistemas produtivos diversificados como estratégia de mitigação das mudanças climáticas e apoio à sustentabilidade do setor.

Palavras-chave: *Anacardium occidentale*; avaliação do ciclo de vida; mudanças climáticas; semiárido.

ABSTRACT

In the face of the climate crisis, food supply chains are increasingly seeking to implement sustainable production practices; for example, studies focused on the fruit sector. Cashew farming plays an important socioeconomic role in agriculture in Brazil, especially in the Northeast region. Thus, the objective was to evaluate, compare, and integrate methodological approaches for estimating the carbon footprint in Brazilian cashew farming, considering both life cycle inventories based on empirical equations and the dynamics of carbon in biomass and soil throughout the useful life of the orchards. Initially, different methods for quantifying GHGs in a conventional cashew production system were evaluated. The Nemecek-Calc, WFLDB, IPCC-Calc, BR-Calc, and Agri-footprint methodologies were compared according to ISO 14067 standard. The results showed variations of up to 24.5% between the methods, with N_2O being the main contributor to emissions. Based on criteria of methodological clarity, scientific robustness, and suitability to regional data, the WFLDB, IPCC-Calc, and BR-Calc methods showed the best performance. In a second stage, the carbon footprint was integrated with the quantification of carbon stored in biomass and the modeling of soil organic carbon (SOC) throughout the cashew tree's production cycle, considering a lifespan of 25 years. Five production systems were evaluated in experimental and commercial areas, including monoculture and intercropping systems. Biomass was quantified using specific allometric equations, and the SOC (0–20 cm) was estimated using the RothC model. The results demonstrated greater carbon accumulation in biomass and soil in diversified systems, reflecting lower carbon footprint values compared to conventional systems. It is concluded that the methodological choice and management system significantly influence the carbon footprint results in cashew farming, highlighting the potential of diversified production systems as a strategy for mitigating climate change and supporting the sustainability of the sector.

Keywords: *Anacardium occidentale*; life cycle assessment; climate changes; semi-arid.

SUMÁRIO

1 INTRODUÇÃO

Diante da crescente atenção às questões ambientais observadas nos últimos anos, as cadeias de suprimento de alimentos internacionais estão cada vez mais focadas na sustentabilidade e na redução do impacto ambiental. Nesse contexto, dados sobre a pegada ambiental de produtos agrícolas tornaram-se instrumentos essenciais para avaliar e melhorar a eficiência dessas cadeias, pois englobam importantes indicadores de impacto ambiental, como as mudanças climáticas e a escassez de água (SAMPAIO et al., 2021).

A redução das pegadas ambientais atribuídas à produção agrícola facilita atingir metas internacionalmente estabelecidas para combater às mudanças climáticas a partir da redução das emissões de gases do efeito estufa (GEE), principalmente quando esses estudos seguem os padrões estabelecidos pela International Standard Organization (ISO).

Uma opção para motivar os setores de produção a diminuir sua pegada de carbono surgiu por meio da organização das nações unidas (ONU) com a implementação do Protocolo de Kyoto, atualmente reconhecida como crédito de carbono (HARTL, 2019). O financiamento de carbono apresenta-se como uma abordagem economicamente viável para reduzir as emissões de GEE nas atividades produtivas, contribuindo para alcançar os objetivos de desenvolvimento sustentável (ONU, 2015; XU et al., 2023).

O governo brasileiro lançou os planos ABC (2010-2020) e ABC+ (2020-2030), plano setorial de mitigação e de adaptação às mudanças climáticas para a consolidação de uma economia de baixa emissão de carbono na agricultura (BRASIL, 2012), que incentivam o uso de boas práticas agrícolas, visando colaborar para que o Brasil possa alcançar às metas de redução de GEE entre 36,1% a 38,9% até 2020, e 43% até 2030 (BRASIL, 2012; 2021).

Os planos são fundamentados em ações como: 1) Recuperação de Pastagens Degradadas; 2) Integração Lavoura-Pecuária-Floresta (ILPF) e Sistemas Agroflorestais (SAFs); 3) Sistema de Plantio Direto (SPD); 4) Fixação Biológica do Nitrogênio (FBN); 5) Florestas Plantadas; 6) Tratamento de Dejetos Animais; e, 7) Adaptação à Mudanças Climáticas.

Nesse contexto, estudos buscando a aplicação de práticas sustentáveis de produção visando a promoção da agricultura de baixo carbono já vem sendo realizados para culturas como melão e manga. Barros et al. (2019) avaliaram diferentes consórcios entre leguminosas e gramíneas, visando a produção do melão em sistemas de plantio direto e em sistema de incorporação da biomassa produzida. Além disso, Dias et al (2020), avaliaram o consorcio da cultura da manga com espécies leguminosas. Esses estudos mostraram o potencial de estoque de carbono no solo em região semiárida, utilizando-se práticas de rotação de culturas (melão com gramíneas) e consorcio de plantas perenes com temporárias (manga com coquetéis vegetais).

Contudo, na literatura há falta de dados sobre práticas de cultivo comprovadamente redutoras da pegada de carbono cultura do caju produzido na região semiárida brasileira. A adoção dessas práticas de cultivo é de grande importância para vencer as barreiras comerciais não-tarifárias internacionais relacionadas à declaração ambiental de produto, contribuir para determinar às emissões do sistema de produção, identificar os pontos críticos para reduzir os percentuais das emissões de GEE estabelecidos nas metas nacionais e aumentar a eficiência do uso da água e outros insumos na cajucultura.

A cajucultura no Brasil concentra-se no Nordeste e é de grande importância socioeconômica na região, pois gera emprego e renda no período mais seco do ano (BRAINER; VIDAL, 2018). O seu cultivo e comercialização vêm ganhando espaço cada vez maior, devido à sua boa adaptabilidade às condições edafoclimáticas dessa região, bem como ao elevado número de produtos que podem ser obtidos da sua matéria-prima (ALENCAR et al., 2018). Por outro lado, na década (2011 a 2021), enquanto os principais produtores mundiais de castanha de caju aumentaram suas produções, com destaque para o crescimento de Costa do Marfim (113,2%) e Filipinas (91,8%), o Brasil caminhou em sentido oposto, perdendo 51,8% de sua produção (FAOSTAT, 2024; IBGE, 2024).

Os problemas na cadeia produtiva do caju são decorrentes de vários fatores, como: perda de áreas produtivas, infraestrutura deficiente na maioria das áreas cultivadas, secas cíclicas nas principais regiões produtoras e, baixa produtividade dos pomares, o que se deve, em parte, ao fato de uma grande parte dele ser formada por cajueiros gigantes, em fase de queda natural da produção. Além disso, a remuneração do produtor tem sido insuficiente para cobrir os custos de adoção de práticas culturais que aumentam a produtividade (OLIVEIRA, 2008; BRAINER, 2021).

Diante deste cenário, é necessário definir como modernizar os sistemas de produção do cajueiro, visto que a modernização da agricultura e aumento dos benefícios decorrentes da mesma, é que torna possível a prosperidade rural (ARTUZO et al., 2018). No caso da cadeia do caju, com a introdução do cajueiro-anão, o sistema de produção baseado no emprego de clones melhorados, cultivo adensado, aplicação de fertilizantes, irrigação e controle fitossanitário tem evoluído significativamente (OLIVEIRA, 2008; MELO, VIDAL NETO, BARROS, 2016).

É importante frisar que o uso indiscriminado de pacotes tecnológicos de fertilizantes sintéticos e produtos fitossanitários, podem estar em descompasso com os objetivos do desenvolvimento sustentável (ODS) indicados pela ONU (2015), tais como: fome zero e agricultura sustentável (ODS 2); consumo e produção responsáveis (ODS 12) e o combate às mudanças climáticas (ODS 13).

Estratégias de sequestro de carbono e redução de emissões de GEE em áreas agrícolas vem sendo bastante estudadas. Nesse sentido, a agricultura de baixo carbono tem usado práticas conservacionistas, como plantio direto, consórcios e a rotação de culturas, contribuindo para redução da pegada de carbono (PC). A utilização de práticas de manejo que visam armazenar carbono no solo para compensar as emissões de GEE tem sido implementada como uma estratégia essencial para mitigação das mudanças climáticas e produção sustentável de alimentos (SCHLEIFER; SUN, 2020), de maneira alinhada aos ODS 2, 12 e 13.

A utilização de sistemas de produção integrados como: lavoura-pecuária, lavoura-floresta e lavoura-pecuária-floresta contribuem de forma positiva para a mudança de C em diferentes profundidades de solo. Os sistemas integrados representam uma estratégia adequada para a intensificação sustentável da agricultura, aumentando a produção de alimentos e mitigando o aquecimento global pelo sequestro de C no solo (OLIVEIRA et al., 2023).

Outra estratégia promissora no combate às mudanças climáticas é o cultivo agroflorestal. Os sistemas agroflorestais representam uma estratégia viável em termos de acúmulo de carbono nas camadas mais superficiais do solo e na biomassa das árvores, o que contribui para a remoção do dióxido de carbono atmosférico e mitigação das mudanças climáticas (BOSSIO et al., 2020; MATOS et al., 2023). Assim, sistemas convencionais de monocultivo estão sendo repensados, como é o caso da produção de caju.

Diversas metodologias foram desenvolvidas e podem ser utilizadas com a finalidade de se calcular as emissões de GEE relacionadas as cadeias de produção agrícolas. Os estudos sobre avaliação do ciclo de vida (ACV), focados nas pegadas de carbono e hídrica, abrangem categorias de impacto de interesse global e local, como mudanças climáticas e escassez de água (FIGUEIRÊDO et al., 2016; SAMPAIO et al., 2021).

A avaliação de ciclo de vida (ACV) é uma metodologia utilizada para averiguar os potenciais impactos ambientais proporcionados a partir da produção de um produto ou serviço. A ISO 14067 (ISO, 2013) detalha os procedimentos metodológicos para conduzir o estudo da pegada de carbono (PC), enquanto a ISO 14046 (ISO, 2014), para estudos de pegada hídrica (PH). Ambos os padrões são baseados na ACV e permitem identificar a origem dos principais impactos de um produto, possibilitando desta forma, o desenvolvimento de atividades agrícolas com maior sustentabilidade ambiental.

Estudos sobre ACV aplicada na cultura do caju foram reportados por Krishnappa et al. (2023) em que, a avaliação de fluxo de energia indicou que a produção de caju é relativamente menos eficiente em termos de energia e é amplamente dependente de energia não renovável. A atual produção de caju na Índia é atribuída principalmente ao manejo de nutrientes (fertilizantes), seguida da energia proveniente do óleo diesel, máquinas, produtos químicos e gasolina. Figueirêdo et al. (2016) concluíram em seu estudo que as pegadas de carbono e hídrica são incrementadas quando se utiliza grandes quantidades de fertilizantes e pesticidas sintéticos, sendo necessário realizar um manejo otimizado para melhorar o desempenho ambiental da produção.

2 REVISÃO DE LITERATURA

2.1 A cultura do caju

2.1.1 Aspectos gerais da cultura do cajueiro

A cultura do caju (*Anacardium occidentale L.*) pertence à família Anacardiaceae, que inclui árvores e arbustos tropicais e subtropicais. Essa espécie é originária da América Tropical, encontrando-se dispersa numa extensa faixa compreendida entre os paralelos de 27º N, no sudeste da Flórida, e 28º S, na África do Sul (OLIVEIRA, 2008).

Do cultivo do cajueiro, podem ser extraídos um conjunto de produtos, tais como: castanha, pedúnculo, líquido da casca da castanha, goma, resina e a madeira. Dentre estes produtos, o mais importante é a castanha de caju, de onde é extraída a amêndoa, utilizada de diversas formas na alimentação humana (FIGUEIRÊDO et al., 2006).

Conforme elucidam Serrano & Pessoa (2016), no Brasil, a cultura do cajueiro se concentra na região Nordeste, expressando tolerância ao estresse hídrico e considerável adaptabilidade a solos de baixa fertilidade e elevados índices de temperaturas do ar. Essas características fazem do cajueiro uma importante fonte de renda para os agricultores da região.

Essa atividade agrícola apresenta alta relevância socioeconômica por ser responsável pela geração de emprego e de renda em períodos mais secos do ano. Importantes atores contribuem para o desenvolvimento da atividade, como produtores, associações, comerciantes, fornecedores de insumos, além das indústrias beneficiadoras de castanha que são geradoras de empregos diretos e indiretos (BRAINER & VIDAL, 2020).

A cultura do caju tem sua variabilidade genética dividida em dois grandes grupos, o tipo comum ou gigante e o anão, classificados de acordo com o porte da planta e a precocidade de produção. O grupo com maior área de cultivo é o tipo comum, natural do Brasil. A capacidade produtiva desse grupo é inferior ao tipo anão, podendo registrar valores de até 180 kg/ha de castanha por safra (OLIVEIRA, 2008).

O tipo anão apresenta baixo porte (< 3 metros), e precocidade de produção que inicia entre 6 e 18 meses. Conforme elucidaram Melo; Vidal Neto & Barros (2016) foram desenvolvidos diversos clones deste grupo, que vêm sendo bastante cultivados, sendo eles: o ‘CCP 06’ e o ‘CCP 76’ que apresentam produtividades médias de castanha em cultivo sequeiro de 600 e 700 kg/ha, respectivamente. O clone ‘BRS 226’, é recomendado para agricultura de sequeiro em ambientes de clima quente, baixa pluviosidade, solos arenosos e profundos, apresentando uma produtividade média de 1200 kg/ha (SERRANO et al., 2016).

2.1.2 Importância socioeconômica do cajueiro

A área mundial colhida de castanha de caju é de 6,81 milhões de hectares, com maior concentração em Costa do Marfim (28,1%), Índia (16,2%) e Tanzânia (14,4%). Estes três países foram responsáveis pelo aumento de 1,5 milhão de hectares nos últimos dez anos (2011-2021), crescendo a uma taxa anual de 6,3% e contribuindo para um incremento mundial na área cultivada de caju em 2,4% a.a. (FAOSTAT, 2021).

O cultivo do caju no Brasil é mais concentrado na região Nordeste e tem grande importância socioeconômica para a região, principalmente, nas áreas de clima semiárido, pois gera emprego e renda no período mais seco do ano. Vale ressaltar também o papel fundamental na geração direta ou mesmo indireta de empregos, com maior intensidade no segundo semestre do ano, sendo 25 mil diretos e 75 mil indiretos e, consequentemente, na geração de renda para os indivíduos e para a região (BRAINER; VIDAL, 2018; IBGE, 2023).

Segundo o Instituto Brasileiro de Geografia e Estatística (IBGE, 2021), a área total de produção da cultura do caju no Brasil é de 428,831 mil hectares, sendo que 99,5% dessa área se encontra no Nordeste (427,551 mil ha). Na região, os principais estados produtores são Ceará (271,061 mil ha), Piauí (71,080 mil ha) e o Rio Grande do Norte (51,516 mil ha).

Diante da importância desta cultura para a região Nordeste, Brainer & Vidal (2018) relatam que a substituição de áreas de cajueiro gigante por cajueiro do tipo anão é fundamental quando se pensa em revitalização da cajucultura nordestina. Contudo, segundo os autores, somente a adoção de clones melhorados não assegura o incremento nos rendimentos da castanha por unidade de área, afinal, grande parte dos produtores da cultura do caju não apresentam recursos para adoção do pacote tecnológico que é exigido pelas variedades melhoradas.

2.2 Mudanças climáticas e o impacto na agricultura

Segundo as Nações Unidas, a mudança climática é definida como a mudança no clima que resulta direta ou indiretamente da atividade humana que altera a composição da atmosfera global e somada a variabilidade natural do clima observada em períodos comparáveis

(BRASIL, 2004). De acordo com dados do Painel Intergovernamental sobre Mudanças Climáticas (IPCC, 2015) às mudanças climáticas constituem um fenômeno multifacetado que exerce influência nos sistemas de produção alimentares globalmente.

As mudanças climáticas promovem um impacto significativo nos regimes pluviométricos, em que, elevadas temperaturas proporcionam incrementos nas taxas de evapotranspiração, o que afeta a demanda de água pelas culturas, indicando que as mudanças climáticas aumentarão o uso diário de água para irrigação, afetando o nível das águas subterrâneas (GONDIM et al., 2018). Essa problemática torna-se mais preocupante para a agricultura de sequeiro, uma vez que o aumento da variabilidade da precipitação pluviométrica afeta diretamente a agricultura que engloba a maior parte das terras cultivadas.

O aquecimento global é causado, principalmente, pelo aumento da concentração de GEEs, destacando-se o dióxido de carbono (CO_2), o gás metano (CH_4) e os óxidos nitrosos (NOx), configurando-se desta forma, um dos problemas mais importantes do mundo contemporâneo. A queima de combustíveis fósseis e o desmatamento são as principais fontes de emissões antropogênicas de gás carbônico, enquanto a agricultura e pecuária intensiva geram quantidades significativas de CH_4 e N_2O (NOBRE, 2011; DMUCHOWSKI et al., 2022).

De acordo com dados do IPCC (SHUKLA et al., 2019), de 2007 a 2016, as emissões líquidas globais de GEEs do setor de agricultura, silvicultura e outros usos da terra representaram 23% (12,0 ± 3,0 Gt CO_2 eq ano^{-1}) do total de emissões antrópicas. No Brasil, em 2020, os setores de floresta, agropecuária e energia tiveram participação de 38,0, 28,5 e 23,2% nas emissões totais de GEEs, respectivamente. Sendo 13,7% maiores quando comparadas às emissões de 2016 (BRASIL, 2022).

A FAO e o Conselho Mundial da Água (2015) alertaram que até 2050, apesar da crescente população global, haverá água suficiente para produzir alimentos necessários. No entanto, o consumo excessivo, a manipulação e as mudanças climáticas reduzirão a disponibilidade de água, especialmente em países em desenvolvimento. Concomitante, o aquecimento global, as projeções globais indicam que a demanda e conflitos por água e energia tendem a aumentar significativamente nos próximos anos, em função dos cenários de mudanças climáticas, que representam risco para a agricultura global (IPCC, 2022).

Se os cenários previstos de mudança climática e escassez hídrica forem confirmados, a produção agrícola mundial sofrerá porque as culturas são sensíveis a diferentes temperaturas, níveis de dióxido de carbono e redução na disponibilidade hídrica. O aumento da temperatura também promove a intensificação de estresses: hídrico e salinidade, bem como o surgimento de fitomoléstias levando a declínios na produtividade vegetal, colocando em risco a sustentabilidade da agricultura (CUADRA et al., 2018; CINTRA et al., 2020).

Portanto, torna-se necessário realizar avaliações ambientais e agronômicas que averiguem o impacto ambiental da produção agrícola nas mudanças climáticas e na água (quantidade e qualidade). Nesse contexto, os estudos sobre a ACV, com foco nas pegadas de carbono e hídrica, são de imprescindível importância (CUI et al., 2022).

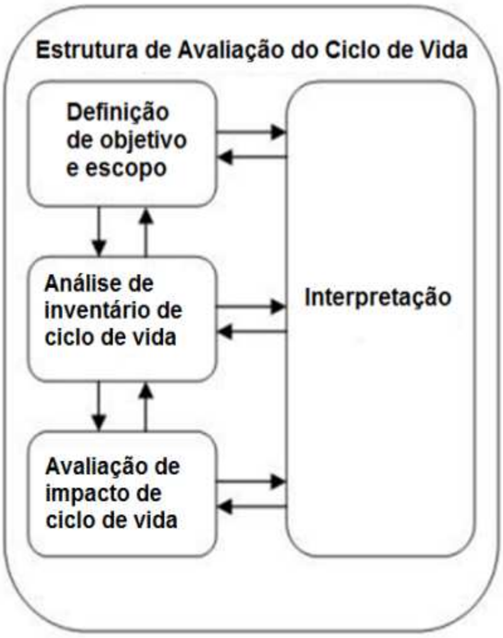
2.3 Avaliação do ciclo de vida (ACV)

A ACV é uma ferramenta útil para avaliar os impactos ambientais potenciais de da produção de um determinado produto ou serviço, contabilizando todos os recursos consumidos, todos os resíduos gerados e todas as emissões ao meio ambiente ao longo de seu ciclo de vida (GÜERECA et al., 2022).

Muitas empresas incorporaram essa ferramenta em seus processos produtivos com o objetivo de identificar pontos críticos e inserir modificações na cadeia produtiva com vistas a reduzir impactos ambientais, custos operacionais e manter ou melhorar a qualidade do produto. As aplicações da metodologia ACV são numerosas, incluindo o desenvolvimento e melhoria de produtos e processos, planejamento estratégico, marketing e elaboração de políticas ambientais (CHEHEBE, 1997).

A ACV aplicada no estudo de sistemas de produção agrícolas busca identificar pontos críticos e oportunidades de melhoria, auxiliando na identificação das melhores soluções ambientais (SAMPAIO et al., 2021). O estudo de ACV é dividido em quatro etapas, de acordo com a norma ISO 14040, conforme apresentado na Figura 1. A seguir, cada uma dessas etapas é detalhada.

Figura 1. Etapas da ACV segundo a ISO 14040:2006



Fonte: ISO (2006)

2.3.1 Definição de objetivos e escopo

A primeira etapa da ACV, tem como finalidade definir o objetivo e o escopo do trabalho. Ao formular o objetivo, deve-se levar em consideração questões como qual a aplicação pretendida, as razões para a realização do estudo, público interessado, se os resultados serão utilizados em estudos comparativos e se serão divulgados ao público.

A definição do escopo estabelece quais processos da cadeia produtiva serão incluídos no estudo, as fronteiras e os limites do sistema (berço ao portão ou berço ao túmulo etc.), os fluxos de referência e quais características dos produtos ou processos serão consideradas e como essa avaliação deve ocorrer (ISSO 14040, 2006^{a}; BJORN et al., 2018).

O fluxo de referência é a quantidade de produto necessária para fornecer a função definida. Todos os outros fluxos de entrada e saída na análise estão quantitativamente relacionados a ela. O fluxo de referência pode ser expresso em relação direta com a unidade funcional ou de uma forma mais orientada para o produto (ZAMPORI; PANT, 2019).

Nesta etapa também são definidas a função de um produto e a sua utilidade para o consumidor, bem como a unidade funcional que será utilizada para quantificar a principal função identificada do produto. As principais funções e unidades funcionais em ACV de processos e produtos agrícolas, com escopo do berço ao portão da fazenda, são elucidadas por Nemecek et al. (2005) e estão dispostas a seguir:

- A função de gestão da terra descreve o cultivo da terra de forma a minimizar os impactos ambientais por área e unidade de tempo com a unidade funcional avaliada por área produzida no ano (isso/ano);
- Função financeira: Para o produtor, a renda é a principal motivação para a produção agrícola. O objetivo é minimizar os impactos ambientais por unidade monetária, de forma a maximizar a ecoeficiência, cujo a unidade de medida é renda obtida com a produção em uma área por ano (R$/isso.ano);
- A função produtiva reflete o objetivo de produção de um determinado produto. Representa principalmente a perspectiva dos consumidores. O objetivo é minimizar os impactos ambientais por unidade de produto. A função produtiva é quantificada por unidades físicas anuais, tais como: tonelada (t/ano), quilograma (kg/ano) e litros (L/ano).

Numa abordagem do berço ao túmulo, pode-se utilizar a função nutricional do alimento, de acordo com Heller; Keoleian (2003). Considerar a qualidade dos alimentos, aqui definida como o conteúdo e a composição dos nutrientes, é fundamental para melhorar a compreensão do nexo alimento-ambiente (HELLER et al., 2013).

Na definição do escopo, também são apontadas as categorias de impactos ambientais a serem analisadas e os métodos de avaliação a serem empregados (ISSO 14040, 2006ª). Exemplificando, um estudo pode focar na avaliação do impacto de um produto apenas nas mudanças climáticas, utilizando fatores relacionados ao potencial de aquecimento global dos GEE, estabelecidos pelo IPCC. Nesse caso, o foco desse estudo é a avaliação da PC do produto.

2.3.2 Análise de inventário

O objetivo da análise de inventário é determinar e medir os insumos (ex: agroquímicos, água e energia), produtos e resíduos (emissões para o ar, água e solo) dos processos que integram o escopo de um estudo (CRUZ-DILONÉ, 2014). Esta etapa começa com a coleta e processamento de dados, cálculo de emissões e validação, além da análise de sensibilidade.

Podem ser citados como exemplos de entradas da natureza: água, energia solar, carbono absorvido pelas plantas e minérios. As saídas na forma de emissões são: os GEE, compostos de N e P e outros compostos possuem capacidade de alterar a qualidade dos ecossistemas ou afetar a saúde humana (UGAYA, 2013).

Em um inventário de processo agrícola, a quantificação das entradas e saídas requer a coleta de dados sobre matéria-prima (ex: mudas ou sementes), insumos (ex: agroquímicos, mudas, água e energia) e produção advindos dos responsáveis pelas etapas de produção (dados primários). Os inventários de produção dos insumos utilizados na produção agrícola são usualmente oriundos de bases de dados de inventários (dados secundários) comerciais, como ecoinvent, Agri-footprint e World Food Database.

Na tabela 1 são abordadas as principais emissões de GEE advindas da mudança do uso da terra (MUT) em diferentes etapas de produção agrícola.

Após a coleta de dados, os cálculos sobre a validação dos dados coletados são realizados. Em seguida, os valores são então associados a cada processo no sistema de produção e finalmente vinculados aos fluxos de referência e unidades funcionais definidas na etapa anterior para criar o inventário final do sistema (ISSO 14040, 2006ª).

Os cálculos das emissões oriundas da MUT, realizada no início da instalação de áreas agrícolas, e das atividades agrícolas, também devem ser realizados. Os cálculos das emissões de GEE provenientes dos processos de produção em campo são realizados de acordo com a metodologia proposta pelo IPCC (2006; 2019) e MCTI (2010).

O mesmo processo de produção pode gerar vários produtos, caso em que o impacto ambiental desse processo é distribuído entre os produtos envolvidos. Essa distribuição é chamada de alocação de fluxo (GNANSOUNAU, 2009). A alocação pode ser realizada considerando os critérios de massa e/ou econômico. Isso significa que o impacto ambiental do sistema é atribuído a cada produto de acordo com determinados critérios baseados em suas propriedades físicas ou econômicas (ISSO 14044, 2013).

Recentemente, a Embrapa Meio Ambiente disponibilizou a ICVCalc, ferramenta para construção de inventários agrícolas para estudos de Avaliação de Ciclo de Vida (MATSUURA et al., 2022). Esta ferramenta é composta por um conjunto de planilhas, que estimam emissões para o ar, água e solo por meio de diferentes protocolos, e assim geram inventários de processo completos. As metodologias utilizadas pela ICVCalc também são reconhecidas internacionalmente, como: Nemecek; Schnetzer, (2012); WFLDB (Nemecek et al., 2015); Agri-footprint (Van Paassen et al., 2019); IPCC (Calvo-Buendía, 2019); Agribalyse (Koch; Salou, 2020) e a BR-Calc (EMBRAPA, 2022).

2.3.3 Avaliação de impactos

Segundo a norma ISO 14040 (2006a), a fase de avaliação de impactos pode ser dividida em duas etapas: obrigatória e não obrigatória. A primeira fase contempla a identificação das categorias de impacto e sua classificação e caracterização. As fases não essenciais têm recursos opcionais que permitem a realização de normalização, ponderação e análise de qualidade de dados.

A fase de classificação tem por objetivo correlacionar os resultados obtidos do inventário de ciclo de vida (ICV) às categorias de impacto ambiental que foram selecionadas. Já a etapa de caracterização, tem por finalidade a realização da conversão dos resultados do ICV para unidades comuns, por meio da utilização de fatores de caracterização, ou seja, fatores que mostram o potencial dos recursos naturais extraídos ou emissões geradas em causar determinados impactos ambientais (ISO 14040 2006a).

A normalização tem por finalidade principal identificar a contribuição de forma isolada dos indicadores de cada categoria de impacto em uma escala de impacto total. A etapa de ponderação tem como objetivo mostrar a importância de cada categoria em um índice final de impacto.

Na análise de qualidade de dados, informações adicionais podem ser requeridas com o intuito de melhorar a compreensão, a significância, incerteza e sensibilidades dos resultados obtidos em pesquisas com a metodologia da ACV. Possibilitando a identificação de diferenças significativas presentes no estudo.

Tem-se a disponibilidade de uma série de métodos de caracterização, cada um utiliza parâmetros de causa e efeito ambiental. Os modelos podem ocorrer em dois níveis de impacto: midpoint e endpoint. O primeiro é respectivo ao transporte das substâncias e a acumulação no meio ambiente. Já o segundo considera os danos finais causados pela acumulação de substâncias, ou seja, danos à saúde humana, recursos naturais e aos ecossistemas (UGAYA, 2013).

2.3.4 Interpretação dos resultados

A etapa de interpretação dos dados é dividida em três fases: identificar as questões ambientais relevantes com base nos resultados obtidos na análise do inventário; avaliar a integridade, sensibilidade e a consistência do estudo, e fornecer conclusões, as limitações do estudo e possíveis recomendações (ISO 14044, 2006b).

Ao final desta etapa apresentam-se as limitações e conclusões finais do estudo ACV, no qual as recomendações devem se basear e se relacionar com as aplicações pretendidas inicialmente (ISO 14044, 2006b; UGAYA, 2013).

A análise de incerteza dos dados, é realizada com o intuito de avaliar possíveis efeitos nos resultados devido à variação e incerteza dos dados de entrada e saída dos inventários, além das variações nos fatores de caracterização. A incerteza dos dados de inventário pode ser calculada empregando o método de Monte Carlos, a partir da definição do valor médio, desvio padrão e função de distribuição estatística para cada variável de entrada. O valor médio de cada variável é oriundo do inventário ambiental, enquanto o desvio padrão de cada variável pode ser calculado utilizando a matriz pedigree. Essa matriz analisa os indicadores de qualidade dos dados (de confiabilidade, completude, correlação temporal geográfica e tecnológica e tamanho da amostra) em distribuições de probabilidade lognormal (FRISCHKNECHT et al., 2007).

A simulação por Monte Carlo pode ser aplicada em problemas de tomada de decisão a qual envolva incerteza, ou seja, situações nas quais o comportamento das variáveis envolvidas com o problema não é de natureza determinística (SARAIVA JÚNIOR; TABOSA; COSTA, 2011), sendo uma metodologia amplamente utilizada em estudos de ACV (GREGORY et al., 2013).

De acordo com a ISO 14044 (2006b), a análise de sensibilidade tem por finalidade avaliar a confiabilidade dos resultados e conclusões, determinando de que forma eles são afetados por mudanças nos dados de entrada, critério de alocação, método de cálculo de emissões, unidade funcional ou modelo de caracterização empregado.

2.4 Pegada de carbono (PC) de produtos

Nos últimos anos, estudos sobre as pegadas de carbono e hídrica baseados na metodologia da ACV têm sido utilizados no estudo de diversos bens e/ou serviços (CUI et al., 2022). A PC é avalia o impacto potencial das emissões de GEE no aquecimento global (PATTARA et al., 2022). Assim, o cálculo da PC, dentro requer as quantificações das emissões diretas e indiretas dos gases do efeito estufa durante o ciclo de vida de um processo, produto ou serviço, fornecendo uma medida intuitiva da resposta dos sistemas naturais às emissões de carbono provenientes das atividades humanas (WEIDEMA et al., 2008; WIEDMANN & MINX, 2008).

O indicador da PC é o Potencial de Aquecimento Global (PAG), que mostra o potencial de cada GEE em relação ao gás CO_2. Assim, essa pegada é medida em CO_2 equivalente (SILVA; SILVA, 2022).

Na literatura científica, existem diversos estudos sobre a PC de frutíferas sob climas semelhantes ao do Brasil, como é o caso das culturas da manga (CARNEIRO et al., 2019), banana (COLTRO & KARASKI, 2019), caju (FIGUEIRÊDO et al., 2015), coco (SAMPAIO et al., 2021), laranja e morango (MORDINI et al., 2009). Esses trabalhos, tiveram como propósito central a avaliação ambiental dos sistemas convencionais de produção da fruticultura.

2.4.1 Protocolos para cálculo da PC

Existem diversos protocolos metodológicos que podem ser utilizados para a avaliação da PC tais como: a metodologia padrão sugerida pela ISO (14067, 2013), o Publicly Available Specification (PAS) 2050 publicado pela British Standards Institution (BSI, 2011) e o GHG Protocol Product Standard (GHG Protocol) produzido pelo World Resources Institute e pelo World Business Council for Sustainable Development (WRI; WBCSD, 2011).

O PAS 2050 foi o primeiro protocolo criado para a contabilização da PC de produtos. O GHG Protocol foi estabelecido com base nos padrões ISO que regem a ACV e na primeira versão do PAS 2050. Mais recentemente, foi desenvolvida a ISO 14067 (2013), que se refere ao cálculo da PC elaborada com base em normas internacionais sobre a ACV.

Esses três protocolos são baseados na metodologia da ACV conforme a ISO 14040 (2006a) e a ISO 14044 (2006b), e recomendam a utilização da metodologia elaborada pelo Painel Intergovernamental de Mudanças Climáticas (IPCC, 2007) para a quantificação da PC, incluindo as emissões decorrentes de mudanças no uso da terra.

Como principais semelhanças metodológicas, todos os protocolos expressam o resultado da pegada em termos de massa de CO_2-equivalente, considerando o potencial de aquecimento global dos GEE em um período de 100 anos. Associam os resultados da PC a uma unidade funcional de referência e requerem uma consideração das fontes de incerteza nos resultados.

Os três protocolos atendem ao princípio de qualidade de dados especificado na ISO 14044. Os dados são divididos em dois tipos, de acordo com suas fontes: primários e secundários. Os dados primários vêm de medições diretas do ciclo de vida, enquanto os dados secundários são usados para entradas onde os dados primários não estão disponíveis.

Com o intuito de facilitar o trabalho para o cálculo das emissões supracitadas e para avaliação da PC de produtos agrícolas, estão sendo desenvolvidas em todo o mundo, ferramentas operacionais baseadas em diferentes procedimentos metodológicos e/ou modelos de caracterização.

O Programa Brasileiro GHG Protocol é responsável pelo desenvolvimento de ferramentas de cálculo para estimativas de emissões de gases do efeito estufa. Foi desenvolvido pelo Centro de Estudos em Sustentabilidade da Fundação Getúlio Vargas e WRI. Os métodos de cálculo e/ou os fatores de emissão contidos na ferramenta são baseados em referências reconhecidas nacional e internacionalmente como, relatórios técnicos do Ministério de Minas e Energia, Ministério de Ciência, Tecnologia e Informação, da Agência Nacional do Petróleo, Gás e Biocombustíveis, do IPCC, Department for Environment Food and Rural Affairs (MONZONI et al., 2008).

2.4.2 Mudança de uso da terra (MUT)

Com a finalidade de investigar o impacto da MUT ocasionada por atividades agrícolas, quantificações de assimilação e acúmulo de carbono na biomassa das plantas e no solo são de fundamental importância, especialmente, quando a vegetação natural do ambiente é substituída por uma cultura agrícola intensiva, como é o caso do cajueiro.

A MUT acarreta emissões pela substituição da vegetação nativa de uma área para a produção agrícola principalmente, emissão ou estoque de gás carbônico. A quantificação das emissões relacionadas com a MUT e o impacto dessa mudança nas mudanças climáticas é de fundamental importância.

As florestas, como é o caso da caatinga, são reservatórios importantes de carbono no solo e na biomassa (por meio do processo de fotossíntese). A quantidade e o tempo de residência do carbono armazenado variam com o porte e o ciclo de vida da planta (SILVA et al., 2021). Contudo, com o desmatamento, queima e a substituição da flora natural por espécies agrícolas, além do preparo e revolvimento do solo, o carbono estocado nesses ambientes é liberado para a atmosfera, podendo causar impactos ambientais, como é o caso do aumento aquecimento global.

2.5 Estudos de PC de castanhas e frutas

Nos últimos 10 anos, em todo o mundo, estudos que investigam e quantificam as pegadas de carbono de frutas (ex: melão, banana, manga, limão etc.) e castanhas (ex: caju, castanheira-portuguesa etc.) tem sido cada vez mais frequentes na literatura científica. A avaliação ambiental desses produtos emprega escopo e métodos diferentes de avaliação dificultando a comparação dos resultados obtidos. Na tabela 3 estão apresentados trabalhos que tratam da avaliação ambiental de frutas e castanhas por meio da análise da PC.

Tabela 1. Resumo de trabalhos científicos que retratam a pegada ambiental de diferentes culturas agrícolas

Origem	**Referências**	**Título**	**Cultura**	**Objetivo**	**Escopo/Limite do sistema**	**Unidade Funcional/ Alocação**	**Método/ Categorias de impacto**	**Recomendações**
Brasil	Olegário et al., 2022	Water scarcity footprint of cocoa irrigation in Bahia	Cacau	Simular a pegada de escassez de água da irrigação do cacau em municípios considerados aptos para a cultura do cacau no estado da Bahia.	• Agricultura • Berço ao portão	• 1 kg • Não se aplica.	• Aware • Escassez hídrica	Necessidade hídrica deve ser reduzida.
Argentina	Ferrero et al., 2021	Water footprint assessment of lemon and its derivatives in Argentina: a case study in the province of Tucumán	Limão	Estimar o perfil de PH de limões e produtos derivados de limão em Tucumán, na Argentina.	• Agricultura; Pré-seleção; Embalagem e Industria. • Berço ao portão.	• 1 t Mássica e econômica.	• Aware; ReCiPe; USEtox 2.0. • Escassez hídrica e Pegada hídrica.	Reduzir a quantidade de irrigação, fertilização e uso de pesticidas.
Brasil	Figueirêdo et al., 2016	"Environmental assessment of tropical perennial crops: the case of the	Caju	Realizar a avaliação ambiental da cultura do caju cultivada no Brasil em área com diferentes aportes tecnológicos.	• Agricultura • Berço ao portão	• 1 kg Mássica e econômico.	• IPCC e Nemecek and Schnetzer. ReCiPe. • Mudanças climáticas. Pegada hídrica.	A produção e uso de fertilizantes e pesticidas sintéticos é responsável pelos maiores impactos ambientais.

Espanha	Banales et al., 2021	Using multiregional environmentally extended input-output assessment to quantify the carbon footprint of peach production	Pêssego	Analisar a validade da metodologia input-output multirregional para quantificar a pegada de carbono da produção de pêssego.	• Produção agrícola. • Berço ao túmulo.	• 1 kg Mássica e econômica.	• PCR for fruits and nuts. • Mudanças climáticas.	Reduzir a quantidade de fertilizantes sintéticos e de pesticidas.
Mexico	Bonales-Revuelta et al., 2022	Evaluating the environmental performance of orange production in Veracruz, Mexico: A life cycle assessment approach	Laranja	Avaliar o desempenho ambiental da cultura da laranja produzida em Veracruz, México.	• Produção de insumos, cultivo e colheita. • Berço ao portão.	• 1 t • Não se aplica.	• CML-IA baseline EU25 v3.03. • Mudanças climáticas. Pegada hídrica.	A produção e uso de fertilizantes e pesticidas são os principais focos de impactos na produção de laranja.
Brasil	Barros et al., 2018	Agronomic and environmental performance of melon produced in the brazilian semiarid region	Melão	Avaliar o desempenho agronômico e ambiental de melão, utilizando métodos convencionais e alternativos de cultivo baseados na rotação de melão com culturas de adubação verde.	• Produção e transporte de insumos, produção agrícola e transporte. • Berço ao tumulo.	• 1 t • Não se aplica.	• IPCC. • Mudanças climáticas.	O cultivo convencional aumenta a PC da cultura do melão, contudo, a utilização de adubação verde promoveu redução na PC..
Espanha	Núnes-Cárdenas et al., 2022	Environmental LCA of Precision Agriculture for Stone Fruit Production	Nectarina	Avaliar o desempenho ambiental e econômico de práticas de agricultura de precisão na produção de nectarina.	• Produção de insumos, estabelecimento e produção da cultura. • Berço ao portão.	• 1 kg • Não se aplica.	• IPCC; PCR for fruits and nuts e Environment Footprint 3.0. • Mudanças climáticas. Pegada hídrica.	A aplicação de práticas de agricultura de precisão baseadas na aplicação variável de insumos de cultivo (fertilizantes, pesticidas e água) promove redução na PC da cultura da nectarina.
Brasil	Sampaio et al., 2021	Reducing the carbon and water footprints of Brazilian green coconut	Coco	Analisar as pegadas de carbono e hídrica do coco verde, investigando oportunidades para redução dessas pegadas.	• Produção agrícola e colheita. • Berço ao portão.	• 1 t • Não se aplica.	• IPCC; Aware; ILCD. • Escassez hídrica;	É possível reduzir a PC e a PH, ajustando a fertilização e a irrigação às necessidades das culturas e aumentando a vida útil dos

							Mudanças climáticas.	pomares, ao mesmo tempo que aumenta o rendimento.
Equador	Roibás et al., 2016	Carbon footprint along the Ecuadorian banana supply chain: Methodological improvements and calculation tool	Banana	Realizar uma avaliação detalhada da PC do início ao fim da cadeia de valor da banana equatoriana.	• Produção e transporte de insumos, produção agrícola, transporte e consumo. • Berço ao túmulo.	• 1 t • Não se aplica.	• PAS 2050; IPCC. • Mudanças climáticas.	Modificação dos fatores de emissão utilizados nos países tropicais, por isso a utilização dos valores aqui propostos, adaptados aos climas tropicais e também às diferentes características do solo, é incentivada no futuro.
Brasil	Hernandes et al., 2022	Carbon footprint of Brazilian cocoa produced in Pará state	Cacau	Calcular a PC, com base em dados coletados durante o cultivo, fermentação e secagem do cacau, bem como o potencial que cada tipo de sistema de cultivo contribui para a redução da PC.	• Colheita, fermentação e secagem. • Portão ao portão.	• 1 kg • Não se aplica.	• GHG Protocol, IPCC. • Mudanças climáticas.	Um método de compostagem planejado que substitui o procedimento de descarte de casca como fertilizante reduz a emissão de metano e o efeito estufa. A não utilização de fertilizantes nitrogenados pode contribuir para a redução dos impactos ambientais.
Estados Unidos	Tabatabaie; Murthy, 2016	Cradle to farm gate life cycle assessment of strawberry production in the United States	Morango	Realizar ACV para a produção de morango usando o método de plasticultura. Propor métricas simples, amigáveis ao produtor/consumidor, que indiquem a eficiência geral do nitrogênio, fósforo e energia fóssil.	• Preparo do solo, plantio, irrigação, adubação, uso de agrotóxicos, operações mecanizadas e colheita. • Berço ao portão.	• 1 kg • Não se aplica.	• IPCC, Trace 2.1. • Mudanças climáticas. Pegada hídrica.	A incorporação de fatores de caracterização de produtos químicos agrícolas nos métodos existentes de avaliação do impacto do ciclo de vida é necessária para realizar uma AICV objetiva para produtos agrícolas.
Brasil	Carneiro et al., 2018	Carbon and water footprints of	Manga	Apresentar a avaliação da PC e da PH da manga.	• Produção e transporte de	• 1 kg	• PAS 2050; IPCC,	Para reduzir a PC da manga, a melhor opção é

		Brazilian mango produced in the semiarid region		Fornecer uma abordagem de modelagem para identificar os processos críticos e oportunidades para melhorias no sistema de cultivo convencional na região.	insumos, produção agrícola e embalagem. • Berço ao portão.	• Não se aplica	Aware, ReCiPe, UseTox. • Mudanças climáticas; Pegada hídrica. Escassez hídrica.	localizar novos pomares em áreas já desmatadas ou ocupadas com culturas anuais e investir em práticas precisas de irrigação e fertilização, ao longo de cada mês e fases de produção da cultura.
Espanha	Martin-Gorriz et al., 2020	Life cycle assessment of fruit and vegetable production in the Region of Murcia (south-east Spain) and evaluation of impact mitigation practices	Melão	Apresentar a quantificação dos impactos ambientais dos sistemas de produção de frutas e vegetais nesta região através da ACV.	• Produção e transporte de insumos, produção agrícola e transporte. • Berço ao portão.	• 1 kg • Não se aplica.	• CML; IPCC. • Mudanças climáticas. Pegada hídrica.	A substituição de fertilizantes sintéticos por estrume oferece uma mitigação substancial do impacto. A irrigação deficitária regulamentada aumenta a sustentabilidade.
Brasil	Coltro; Karaski, 2019	Environmental indicators of banana production in Brazil: Cavendish and Prata varieties.	Banana	Avaliar indicadores ambientais da produção de banana no Brasil por meio de ACV.	• Produção e transporte de insumos, produção agrícola e transporte. • Berço ao portão.	• 1 kg • Não se aplica.	• CML; IPCC; GHG protocol. • Mudanças climáticas. • Pegada hídrica.	Os indicadores ambientais podem ser alterados caso sejam feitas melhorias na fase de cultivo, através das reduções no uso de fertilizantes nitrogenados, de pesticidas à base de carbofurano e/ou uso de menores quantidades de pesticida.
Brasil	Santos et al., 2018	Cleaner fruit production with green manure: the case of Brazilian melons	Melão	Avaliar os impactos ambientais e os lucros resultantes do melão brasileiro, comercializado no Brasil.	• Produção e transporte de insumos, produção agrícola e transporte. • Berço ao portão.	• 1 kg • Não se aplica.	• IPCC; Nemecek and Schnetzer; ReCiPe; UseTox. • Mudanças climáticas; Pegada hídrica.	Os impactos podem ser diminuídos quando o transporte marítimo e terrestre do melão for combinado e o uso de fertilizantes sintéticos na for reduzido.

Ressalta-se que as fronteiras do sistema da grande maioria das pesquisas foram do berço ao portão. Levaram em consideração as etapas de produção e transporte de insumos; preparo do solo, produção agrícola (uso de adubação, pesticidas, irrigação, mecanização etc.); colheita e transporte dos produtos. (TABATABAIE; MURTHY, 2016; CARNEIRO et al., 2018; SAMPAIO et al., 2021).

Diversos protocolos foram utilizados para a realização destas pesquisas, tais como: a ISO 14067; GHG Protocol e a PAS 2050, para a avaliação da PC. As equações e fatores de emissão mais utilizados foram os propostos pelo IPCC (2006; 2019) e Nemecek e Schnetzer (2012) para a contabilização da emissão de compostos para o ar, solo e água. É constatado também a utilização de manuais como o ILCD (2011) e o CML 2001 para a avaliação de categorias de impacto relacionadas ao perfil da PH.

Como forma de mitigar os impactos ambientais, a ampla maioria das pesquisas sugeriram ações de reduções no uso de fertilizante sintéticos, pesticidas e a não abertura de novas áreas agrícolas. Também foram propostas a utilização de fontes alternativas de adubos, sistemas de irrigação mais eficientes e o menor revolvimento do solo.

3 OBJETIVO GERAL

Avaliar, comparar e integrar abordagens metodológicas para a estimativa da pegada de carbono na cajucultura brasileira, considerando tanto inventários de ciclo de vida baseados em equações empíricas quanto a dinâmica do carbono na biomassa e no solo ao longo da vida útil dos pomares.

3.1 Objetivos específicos

Comparar diferentes metodologias de quantificação de emissões de GEE em sistema convencional de produção de caju anão no semiárido brasileiro (Capítulo I);

Avaliar os métodos de cálculo de emissões segundo critérios de clareza metodológica, robustez científica e adequação aos dados regionais (Capítulo I);

Modelar a dinâmica do carbono orgânico do solo (COS) ao longo do ciclo produtivo do cajueiro utilizando o modelo RothC em diferentes sistemas de produção (Capítulo II);

Quantificar o carbono acumulado na biomassa do cajueiro desde o estágio de muda até árvores adultas, desenvolvendo equações alométricas específicas (Capítulo II);

Comparar a pegada de carbono de cinco sistemas de produção de caju (monocultivo convencional, sistemas com biochar/composto orgânico, e sistemas consorciados) ao longo de 25 anos de vida útil do pomar (Capítulo II);

Identificar estratégias de mitigação das mudanças climáticas na cajucultura através da análise integrada da pegada de carbono, estoques de carbono no solo e na biomassa.

4 CHAPTER I - QUANTIFICATION OF GHG EMISSIONS USING DIFFERENT METHODOLOGIES IN TROPICAL CONVENTIONAL CASHEW CULTIVATION

Abstract: Quantifying GHG emissions from cashew cultivation, especially in Brazil, is essential to assess the environmental impact and promote the sustainable development of this activity. The objective of this study is to evaluate and compare methods for quantifying GHG emissions based on empirical equations for life cycle inventories, using the conventional cashew production system in Brazil as a case study. The scope of the study encompasses, from gate to gate in a dwarf cashew production system, considering the production of one ton of cashew as a functional unit. GHG emissions were assessed and compared using the following methodologies: Nemecek-Calc, WFLDB, IPCC-Calc, BR-Calc, and Agri-footprint. The environmental assessment followed ISO standards (14040, 14044, and 14067). The results showed that the carbon footprint varied among the evaluated methodologies, with a difference of 24.5% between the highest value (129.5 kg CO2eq IPCC-Calc and BR-Calc) and the lowest (104 kg CO2 eq-Nemecek-Calc) per ton of cashew. N2O was the main contributor to emissions, accounting for up to 75.9%, while CO2 represented up to 25.8%. Based on the analysis criteria, WFLDB, IPCC-Calc, and BR-Calc are the most recommended methodologies, balancing clarity, scientific robustness, and regional adaptation. The choice of methodology is fundamental, as it directly influences the results and interpretation of the carbon footprint in cashew farming, impacting the sustainability of this agricultural activity.

Keywords: *Anacardium occidentale* L; carbon footprint; life cycle assessment; sustainability.

4.1 Introduction

Given climate change and attention to environmental issues observed in recent years, international food supply chains are increasingly focused on sustainability and reducing environmental impact. In this context, calculating greenhouse gas (GHG) emissions in agricultural production systems and determining possible mitigation points for these gases is paramount (Poore and Nemecek, 2018).

Therefore, there is a need to mitigate the environmental impact of products and make food production more sustainable (Giongo et al., 2025). Studies on the environmental footprints of agricultural products have become essential tools to assess and improve the efficiency of these chains, as they encompass important environmental impact indicators such as the carbon footprint (CF) (Sampaio et al., 2021).

The reduction of CF is attributed to agriculture, which facilitates reaching internationally established targets to combat climate change by reducing GHG emissions, especially when these studies follow international standards established by the International Standard Organization (ISO), the Intergovernmental Panel on Climate Change (IPCC) and sustainable development goals (SDGs).

Several methodologies have been developed and can be used to calculate GHG emissions related to agricultural production chains. Life cycle assessment (LCA) studies focused on CF cover impact categories of global interest, such as climate change (Figueirêdo et al., 2016; Barros et al., 2019). LCA is a methodology used to investigate the potential environmental impacts of producing a product or service according to ISO 14040, 14044 (ISO, 2006a, 2006b). ISO 14067 (ISO, 2018) details the methodological procedures for conducting CF studies. These studies allow identifying the origin of a product’s main impacts, thus enabling the development of agricultural activities with greater environmental sustainability.

Thus, it is essential to use methodologies for quantifying direct GHG emissions from agricultural production. To improve the efficiency of calculating the emissions mentioned above and consequently, the evaluation of the CF of agricultural products, operational tools based on different methodological procedures, and/or characterization models are being developed worldwide.

Recently, in Brazil, Embrapa Environment released ICVCalc, a tool designed for building agricultural inventories for LCA studies (Matsuura et al., 2022). This tool consists of a set of spreadsheets that estimate emissions using various methodological protocols, thereby generating comprehensive process inventories. The methodologies used are internationally recognized, such as Nemecek-Calc (Nemecek et al., 2012), World Food LCA Database (WFLDB) (Nemecek et al., 2019), IPCC-Calc (IPCC, 2019), BR-Calc (Matsuura et al., 2022), and Agri-footprint (Blonk et al., 2023).

Thus, the BR-Calc methodology is an initiative aimed at addressing the need to develop tools that use characterization factors adapted to the reality of tropical climate countries, enabling more accurate estimates of GHG emissions under these conditions. Comparison with international methods can help identify areas for improvement in BR-Calc, such as incorporating best practices from other methodologies or adjusting to better reflect Brazilian conditions. Since concerns about climate change and sustainability are global, emission estimation methodologies must be internationally comparable.

However, studies evaluating and comparing the estimation of GHG emissions and the impact on the CF of agricultural products are incipient in the literature, especially when it comes to studies conducted for tropical climate regions and crops, such as Brazil and the cashew crop.

Additionally, while various methodologies are available, few studies provide a systematic comparison of their applicability to tropical conditions (Basset-Mens et al., 2022). As a result, there is still a limited understanding of how different empirical equation-based methods perform in estimating GHG emissions for cashew production in Brazil, considering regional data availability, scientific robustness, and methodological transparency. This gap in the literature justifies the need for a comprehensive assessment of different GHG quantification methods applied to cashew production, ensuring that the chosen approach accurately represents the environmental impacts in this specific context.

The novelty of this manuscript lies in its focus on providing a comprehensive comparison of different methodologies for GHG emissions estimation, specifically applied to a tropical agricultural system. By considering regionally adapted approaches and a crop that has great economic importance in Brazil, this study fills a crucial gap in the literature, offering insights that are directly relevant to decision-making for sustainable agricultural practices.

Thus, the objective of this study was to evaluate and compare methods for quantifying GHG emissions based on empirical equations for life cycle inventories, using the conventional cashew production system in Brazil as a case study.

4.2 Material and methods

4.2.1 Quantification of GHG from crop production

The following methodologies were applied for estimating direct emissions of CO_2, N_2O, and CH_4: Nemecek-Calc (Nemecek et al., 2012), World Food LCA Database (WFLDB) (Nemecek et al., 2019), IPCC-Calc (IPCC, 2019), BR-Calc (Matsuura et al., 2022), and Agri-footprint (Blonk et al., 2023). The ICVCalc tool v1.1 (Matsuura et al., 2022), was used to calculate GHG emissions by the chosen methods. It is emphasized that the indirect emissions of NOx, NH_3, and NO_3, which contribute to N_2O emissions, were considered for calculation purposes following the methods suggested by each GHG methodology. However, these emissions are not a focus of evaluation in the present study.

For the evaluation of the carbon footprint of cashew production years, the global warming potentials of GHGs in the horizon of 100 years were used, according to (IPCC, 2021), for evaluation. Each methodology’s input data and emissions were evaluated using the software Simapro® version 9.5.0.0.

4.2.2 Criteria for evaluating methodologies

To systematically evaluate GHG emission quantification methods used in this study, five key criteria were defined: clarity, scientific robustness, consideration of regional data, calculation transparency, and data accessibility. These criteria ensure a comprehensive assessment of each method, considering both its scientific credibility and practical applicability. Each criterion was scored on a scale from 1 (Low) to 3 (High), where a higher score indicates better performance in that category. Clarity criterion evaluates how well documented and understandable the methodology is. Scientific robustness considers the method’s foundation in scientific literature and whether it has undergone peer review. Consideration of regional data assesses the extent to which the method incorporates Brazilian specific emission factors and agricultural conditions. Calculation transparency examines the level of detail provided in the equations and emission factor sources. Lastly, data accessibility measures how easily the necessary data can be obtained.

The scoring process was conducted based on a critical analysis of each methodology, leading to a consensus among all authors. This approach ensured a balanced and well-founded evaluation, considering both methodological documentation and its applicability to the study context. The scoring system applied to each criterion is detailed in Table 1.

Table 1. Criteria for evaluating GHG emissions quantification methodologies.

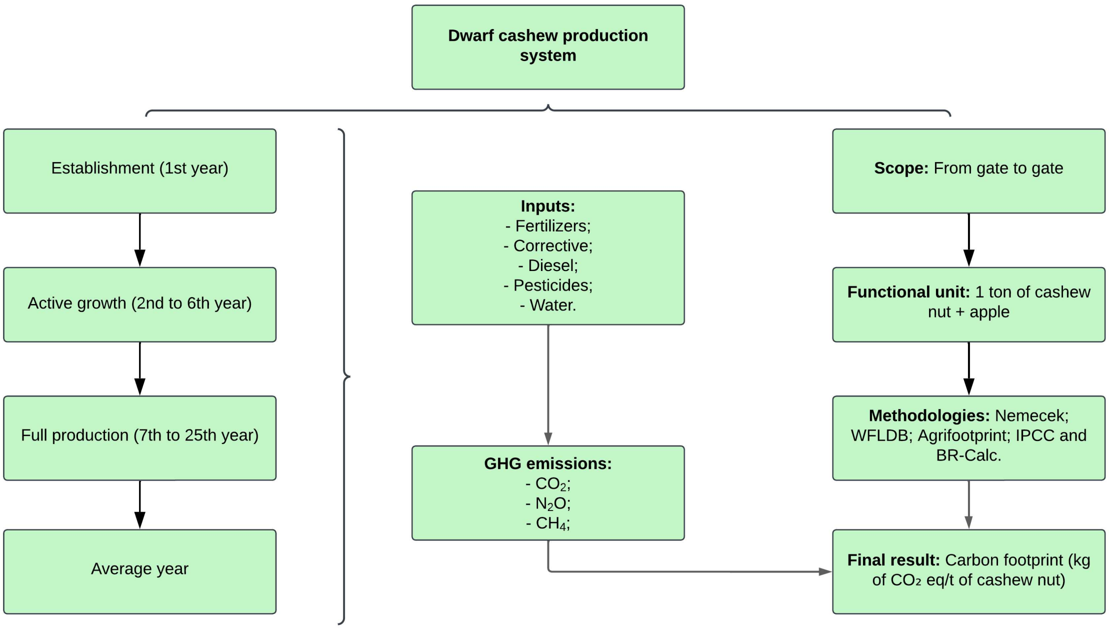
Criterion	Description	Score 1 (low)	Score 2 (medium)	Score 3 (high)
Clarity	Level of understanding of the methodology and available documentation	Technical documentation is complex and difficult to understand	Clear documentation, but requires specific prior knowledge	Well-documented, easy to interpret for different audiences
Scientific robustness	Scientific basis and acceptance of the method in the literature, including peer review	Based on few studies or poorly referenced; not peer-reviewed	Based on recognized references but with some limitations; partially peer-reviewed	Highly validated in scientific literature, widely used, and peer-reviewed
Consideration of regional data	Use of specific emission factors and parameters for tropical regions	Based exclusively on global or non-regional data	Allows partial adaptation to the context of tropical regions	Uses or has been calibrated with data from tropical regions
Calculation transparency	Availability and detail of equations and emission factors	Equations are poorly explained or contain difficult-to-access factors	Equations are available but with some limitations in replicability	Well-described equations, with sources and detailed explanations
Data accessibility	Ease of obtaining emission factors and necessary parameters	Restricted data or requires a paid subscription	Data is available but scattered or difficult to access	Publicly available data or easily accessible in well-known databases

4.2.3 Emissions from cashew production

The production of one ton of cashew nut + apple was considered a functional unit, corresponding to the cultivation of one hectare of the Embrapa dwarf cashew production system, evaluated over 25 years of cultivation. This period represents the typical lifespan of a dwarf cashew orchard, including the following production stages: establishment (including soil preparation and seedling transplantation during the 1st year), active growth (from the 2th to the 5th year) and full production (from the 6th to the 25th year). The seedling production stage was not considered due to its insignificant contribution to the results, as noted by (Figueirêdo et al., 2016). The assessment was based on the average annual performance of the orchard.

Primary and experimental data were used to develop an inventory of GHG emissions for the conventional dwarf cashew crop production in Brazil (Figure 1), made available by Embrapa Tropical Agroindustry and complemented by (Serrano, 2016).

Figure 1. Flowchart of the system limits for the functional unit under study.



4.2.4 Description of the conventional production system of the dwarf cashew tree

The information taken into consideration for the preparation of the inventory of the Embrapa dwarf cashew production system was based on experimental data (considering a field experiment, 13 years old). The BRS 226 clone, recommended for dryland cultivation in environments with hot climate conditions, low rainfall and deep, sandy soils, was considered as the genetic material evaluated (Melo et al., 2016). The study covers the following steps:

Establishment (Year 1): After cleaning the area, soil preparation begins by harrowing, correcting soil acidity with limestone and digging planting holes measuring 40 x 40 x 40 cm. At this time, fertilization is carried out with fertilizers containing macro and micronutrients. 30 days after preparing the holes, the grafted cashew seedlings are transplanted, spaced 8 x 6 m apart, corresponding to a stand of 208 plants per ha. Irrigation is only used at this stage and is intended to save the seedlings during the dry season (6 months).

Active growth (Years 2–5): Dwarf cashew plants grow actively until the sixth year, with slow development in the rainy season and intense development in the dry season. At this stage, formation fertilization begins, fertilizing with nitrogen (urea), phosphate (simple superphosphate) and potassium fertilizers (potassium chloride) and micronutrients (FTE BR-12). During this period begins formation pruning, aiming to form a compact, well-lit and airy crown. Pest, disease and weed management is carried out simultaneously.

Full Production (Years 6–25): In full production, the cashew tree cultivated in the Embrapa system reaches up to 4 m in height, with an estimated average productivity of 2500 kg/ha/year of nuts. At this stage, the use of mineral fertilization with macro and micronutrients is carried out intensively. Similarly, annual cleaning and maintenance pruning, as well as the application of phytosanitary products and mechanized weddings, are carried out.

4.3 Results and discussion

4.3.1 Comparison of methodologies

The results presented in Table 2, calculated from the scores established in Table 1 indicate that the WFLDB, IPCC-Calc, and BR-Calc methods achieved the highest overall scores (14 points each), suggesting superior performance across the evaluated criteria. Agri-footprint obtained an intermediate score (12 points), while Nemecek-Calc had the lowest overall performance (10 points), primarily due to lower transparency in the calculations.

Among the evaluated criteria (Table 2), clarity was rated highest for WFLDB, IPCC-Calc, and BR-Calc, indicating well-documented methodologies that are easy to interpret, whereas Nemecek-Calc and Agri-footprint had lower scores, suggesting greater complexity. Scientific robustness, assessed based on peer-reviewed validation, was strongest for WFLDB and IPCC-Calc, while BR-Calc scored slightly lower, likely due to a smaller number of studies applying its approach. Consideration of regional data was best addressed by BR-Calc, reflecting its adaptation to specific conditions such as those in Brazil, whereas the other methods demonstrated more generalized applicability. Calculation transparency was a limiting factor for Nemecek-Calc, which had the lowest rating in this category, whereas the remaining methods scored highly, ensuring better traceability of calculations. Data accessibility was consistently high across all methodologies, highlighting the availability of input data for researchers and practitioners. These findings reinforce the need to balance clarity, scientific robustness, and regional adaptation when selecting an appropriate methodology for GHG emission assessments.

Table 2. Comparative evaluation of GHG emission quantification methodologies based on key assessment criteria.

Criterion	Nemecek-Calc	WFLDB	IPCC-Calc	BR-Calc	Agrifootprint
Clarity	2	3	3	3	2
Scientific robustness	2	3	3	2	2
Consideration of regional data	2	2	2	3	2
Calculation transparency	1	3	3	3	3
Data accessibility	3	3	3	3	3
Total	10	14	14	14	12

4.3.2 Inventory by cashew production stage

From the inventory of input of the Embrapa system of production of dwarf cashew (Table 3), the phases of full production and active growth were the ones that most used inputs (fertilizers, pesticides, and fuel) per hectare of cashew cultivation. In these phases, macronutrients, agricultural pesticides, and agricultural operations are used more intensively than in the stage of crop establishment.

Table 3. Inputs in one ha of dwarf cashew orchard for 25 years in the dwarf cashew production system.

Inventory	Unit	Dwarf cashew production system			
		Establishment (year 1)	Active growth (years 2-5)	Full production (years 6-25)	Average year
Products					
Cashew nut	t	0	2.131	47.312	1.978
Cashew apple	t	0	10.655	236.56	9.889
Inputs					
Limestone	kg	1.500	800	3.000	212
Seedling	p	260	0	0	10.4
Macronutrients					
Urea (N)	kg	20.8	395.2	4347.2	190.5
Simple superphosphate (P)	kg	208	1112.8	4576	235.9
Potassium chloride (K)	kg	18.72	239.2	1497.6	70.2
Micronutrients					
Boron	kg	0.3744	1.123	7.114	0.34
Copper	kg	0.1644	0.4992	3.162	0.15
Manganese	kg	0.416	1.248	7.904	0.38
Zinc	kg	1.872	5.616	35.568	1.72

Pesticides					
Deltamethrin	kg	0.015	0.075	0.285	0.015
Spinetoram	kg	0	0.1	0.95	0.042
Acetamiprid	kg	0.451	2.255	8.567	0.42
Etofenprox	kg	0.81	4.05	15.39	0.81
Sulfur	kg	0	2.376	22.572	0.99
Glyphosate	kg	1.44	7.2	27.36	1.44
Other products					
Water	L	124.800,00	0	0	4992
Diesel	L	177	285	1107	62.8

In absolute terms, the full production stage presents the highest production of cashews, contributing 95.7% of the total production estimated for 25 years of orchard life. However, it is also at this stage that the highest amounts of limestone, urea, and diesel are used in field production, which will lead to GHG emissions.

It can be seen from the data corresponding to the average year of the useful life cycle of the cashew orchard that the main inputs used in these production systems that directly contribute to GHG emissions and consequently to the increase in the carbon footprint were as follows: limestone (212 kg per ha) emitting mainly CO_2; urea (190.5 kg per ha) emitting CO_2 and N_2O; and diesel (62.8 L per ha) used in agricultural operations, which through its combustion produces emissions of CO_2, N_2O, and CH_4.

The quantification of carbon dioxide (CO_2) emissions assessed by different methodologies presented variable results (Table 4). IPCC-Calc and BR-Calc generated the same and highest results (397 kg of CO_2/ha), while the Nemecek-Calc and Agri-footprint methodologies were, respectively, 24.7 and 41.3% lower when comparing both situations.

Table 4. Quantification of CO_2 emissions to air in dwarf cashew production system.

CO_2 emissions to air	Unit	Dwarf cashew production system
		Average year
Nemecek-Calc	kg	299
WFLDB	kg	392
IPCC-Calc	kg	397
BR-Calc	kg	397
Agri-footprint	kg	233

Table 5 presents the results for nitrous oxide (N_2O) emissions, highlighting notable variations among the methodologies. The highest absolute emissions were observed in the IPCC-Calc and BR-Calc methodologies, both yielding 4.17 kg of N_2O per ha. In comparison, the Agri-footprint methodology showed a slight decrease of 1.44%, while WFLDB and Nemecek-Calc exhibited more substantial reductions of 9.4% and 17.5%, respectively.

Table 5. Quantification of N_2O emissions to air in dwarf cashew production system.

N_2O emissions to air	Unit	Dwarf cashew production system
		Average year
Nemecek-Calc	kg	3.44
WFLDB	kg	3.78
IPCC-Calc	kg	4.17
BR-Calc	kg	4.17
Agri-footprint	kg	4.11

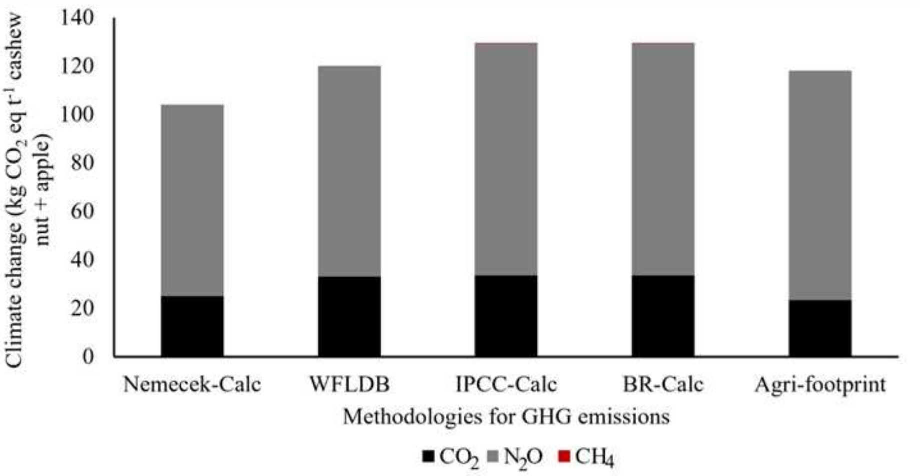
Emissions of methane gas (CH_4) (Table 6) were quantified by only two of the five methodologies evaluated. Since only the IPCC-Calc and BR-Calc methodologies account for emissions from diesel combustion, a pattern is noted in the CH_4 emissions results, in which both methodologies presented the same result (0.01 kg of CH_4/ha).

Table 6. Quantification of CH_4 emissions to air in dwarf cashew production system.

CH_4 emissions to air	Unit	Dwarf cashew production system
		Average year
Nemecek-Calc	kg	Not applicable
WFLDB	kg	Not applicable
IPCC-Calc	kg	0.01
BR-Calc	kg	0.01
Agri-footprint	kg	Not applicable

Figure 2 illustrates the impact of GHG emissions on climate change as calculated using different methodologies. The IPCC-Calc and BR-Calc methodologies presented the highest cumulative values (129.5 kg CO_2 eq per t of cashew nut + apple). In contrast, Agri-footprint and Nemecek-Calc presented the lowest, 114 and 104 kg CO_2 eq per t of cashew nuts, respectively. The WFLDB methodology presented intermediate results (120 kg CO_2 eq per t of cashew nut + apple). It was found that, for all the evaluated methodologies, the largest contributions to climate change resulted from the global warming potential of N_2O, reaching up to 75.9%, while CO_2 emissions contributed up to 25.8% of the impact on climate change.

Figure 2. Impact of GHG emissions methodologies on climate change.



The evaluation of GHG emissions quantification methodologies based on criteria analysis revealed significant differences between the methods analyzed, reflecting variations in clarity, scientific robustness, and consideration of regional data. The IPCC-Calc, BR-Calc, and WFLDB methods achieved the highest scores due to a balance between these criteria, while Agri-footprint obtained an intermediate score and Nemecek-Calc presented the lowest overall performance.

IPCC-Calc (IPCC, 2019) stood out for its high clarity, as its guidelines are well-established and extensively documented. In addition, its scientific robustness is widely recognized, being one of the most widely used methods for national emissions inventories. However, its consideration of regional data is limited, since the emission factors are global and require calibration for local conditions, which may compromise its accuracy for tropical systems such as cashew cultivation in Brazil.

BR-Calc (Matsuura et al., 2022; Giongo et al., 2025), presented an equally high score, standing out mainly in the consideration of regional data, as it was developed specifically for edaphoclimatic conditions in Brazil. Its clarity was also well evaluated, being a potentially more accessible model for the national context. In addition, its scientific robustness was considered high, as it is based on local data and specific adaptations for the Brazilian agricultural reality, making it a relevant option for analyses in tropical conditions. In addition, this methodology has been reviewed by experts in the field.

WFLDB (Nemecek et al., 2019) also obtained a high score due to its detailed documentation, which ensures satisfactory clarity. Its scientific robustness was evaluated as high since it is widely used in LCA of agri-food production. However, its consideration of regional data is only average, since, although it has broader information than Nemecek-Calc

(Nemecek et al., 2012), it is not fully adjusted to tropical conditions, requiring additional adaptations.

Agri-footprint (Blonk et al., 2023) obtained an intermediate performance, being a method used in agri-food LCA and with good scientific robustness. However, its clarity was evaluated as average, since the documentation can vary depending on the version used. Furthermore, its consideration of regional data was also intermediate, like the WFLDB, indicating the need for adjustments to better represent agricultural conditions in Brazil.

On the other hand, Nemecek-Calc (Nemecek et al., 2012), had the lowest overall score, mainly due to its low transparency in calculations. Despite being one of the most reliable databases in LCA and having high scientific robustness, its clarity was considered only average, as its methodologies and emission factors are unclear. Furthermore, its consideration of regional data is limited, as the emission factors are based on temperate conditions, requiring significant adjustments to be applied in tropical regions.

Thus, the results reinforce that the choice of the most appropriate method should consider a balance between clarity, scientific robustness, and regional adaptation. While IPCC-Calc, BR-Calc, and WFLDB proved to be the most recommended options, Agri-footprint can be useful depending on the context of the analysis, and Nemecek-Calc requires greater caution due to its limitations in transparency and adaptation to tropical conditions.

The comparison highlights substantial variations in emission estimates produced by each methodology. These discrepancies underscore the influence of methodological choices on the results obtained, consequently affecting the projected impact of emissions on climate change. This emphasizes the importance of selecting appropriate methods for accurate assessments.

Furthermore, these limitations may impact the assessment of the carbon footprint of the analyzed system. Methods with less transparency in calculations, such as Nemecek-Calc, may hinder the traceability of estimates, generating uncertainty in the quantification of emissions, and compromising the reliability of the LCA. Although they do not adequately consider regional data in their standard approach and use global emission factors that do not reflect the particularities of the cashew production system in Brazil, IPCC-Calc (IPCC, 2019) and WFLDB (Nemecek et al., 2019) presented satisfactory results in terms of carbon footprint. These are like those obtained in BR-Calc, which, although it has regionalized factors for Brazil, for this study, there was no significant influence from them.

Thus, the choice of methodology directly influences decision-making, reinforcing the need to select approaches that offer greater data representativeness, transparency in calculations, and adaptation to the context analyzed.

To explain differences in results, we compared equations and emission factors adopted in each methodology (Table 7 and 8).

Table 7. Equations and emission of factors used for GHG emissions calculations by different methodologies.

GHGs	**Methodologies**	**Equations**	**EF**	**EF1**	**EF2**	**EFi**
		Emissions from the use of fertilizers and correctives				
CO_2	Nemecek-Calc	Urea = 44/12 * (M_{urea} * EF)	0.43	-	-	-
	WFLDB	Urea = 44/12 * ((M_{urea} * EF) + Lime = ($M_{limestone}$ * EF1) + ($M_{dolomite}$ * EF2))	0.43	0.12	0.13	-
	IPCC-Calc	Urea = 44/12 * ((M_{urea} * EF) + Lime = ($M_{limestone}$ * EF1) + ($M_{dolomite}$ * EF2))	0.20	0.12	0.13	-
	BR-Calc	Urea = 44/12 * ((M_{urea} * EF) + Lime = ($M_{limestone}$ * EF1) + ($M_{dolomite}$ * EF2))	0.20	0.12	0.13	-
	Agrifootprint	Urea = 44/12 * ((M_{urea} * EF) + Lime = ($M_{limestone}$ * EF1) + ($M_{dolomite}$ * EF2))	0.20	0.12	0.13	-
		Emissions from burning fossil fuels (diesel)				
CO_2	Nemecek-Calc	Not applicable	-	-	-	-
	WFLDB	Not applicable	-	-	-	-
	IPCC-Calc	Emission of CO_2 = V * d * NCV * Efi	-	-	-	74100
	BR-Calc	Emission of CO_2 = V * d * NCV * Efi	-	-	-	74100
	Agrifootprint	Not applicable	-	-	-	-
N_2O	Nemecek-Calc	Not applicable	-	-	-	-
	WFLDB	Not applicable	-	-	-	-
	IPCC-Calc	Emission of N_2O = V * d * NCV * Efi	-	-	-	28.6
	BR-Calc	Emission of N_2O = V * d * NCV * Efi	-	-	-	28.6
	Agrifootprint	Not applicable	-	-	-	-
CH_4	Nemecek-Calc	Not applicable	-	-	-	-
	WFLDB	Not applicable	-	-	-	-
	IPCC-Calc	Emission of CH_4 = V * d * NCV * Efi	-	-	-	4.15
	BR-Calc	Emission of CH_4 = V * d * NCV * Efi	-	-	-	4.15
	Agrifootprint	Not applicable	-	-	-	-

M_{urea} = amount of urea (kg); EF = emission factor; $M_{limestone}$ = amount of limestone (kg); EF1 = emission factor; $M_{dolomite}$ = amount of dolomite (kg); EF2 = emission factor. V = fuel volume (L); D = fuel density (kg L^{-1}); NCV = net calorie value (TJ kg^{-1}); EFi = emission factor to GHG (kg TJ^{-1}).

Table 8. Equations and emission of factors used for N_2O emissions calculations by different methodologies.

GHGs	Methodologies	Equations	EF1	EF4	EF5
		Emissions from the use of fertilizers and the mineralization of soil organic matter and crop residues			
N_2O total	Nemecek-Calc	$N_2O = 44/28 * (EF1 * (N_{tot} + N_{cr}) + (EF1 * 14/17 * NH_3) + (EF5 * 14/62 * NO_3)$	0.01	-	0.075
	WFLDB	$N_2O = 44/28 * (EF1 * (Ntot + Ncr + Nsom) + (14/17 * NH_3) + (14/46 * NO_x) + (EF5 * 14/62 * NO_3))$	0.01	-	0.075
N_2O total	IPCC-Calc	$N_2O_{direct} = 44/28 * ((F_{SN} + F_{ON} + F_{CR} + F_{SOM}) * EF1 + N_2O_{indirect} (N_2O_{(ATD)} + N_2O_{(L)}))$	0.01	-	-
	BR-Calc	$N_2O_{direct} = 44/28 * ((F_{SN} + F_{ON} + F_{CR} + F_{SOM}) * EF1)$	0.01	-	-
	Agrifootprint	$N_2O_{indirect} = N_2O_{(ATD)} = ((F_{SN} * Frac_{GASF}) + (F_{ON} + F_{PRP}) * Frac_{GASM}) * EF4 + N_2O_{(L)} = ((F_{SN} + F_{ON} + F_{PRP} + F_{CR} + F_{SOM}) * Frac_{LEACH-(H)}) * EF5$	-	0.01	0.011

EF1 = emission factor for N_2O emissions from N inputs; EF4 = emission factor from atmospheric deposition of N on soils and water surfaces; EF5 = emission factor for N_2O emissions from N leaching and runoff; $Frac_{GASF}$ = fraction of synthetic fertilizer N that volatilizes as NH_3 and NOx (0.11); $Frac_{GASM}$ = fraction of applied organic F_{ON} and F_{PRP} that volatilizes as NH_3 and NOx (0.21); $Frac_{LEACH-(H)}$ = fraction of all N added to/mineralized in managed soils in regions where leaching/runoff occurs (0.24); NH_3 = ammonia emission; NO_3 = nitrate emission; NOx = nitrogen oxides emission; N_{TOT} = total nitrogen in mineral and organic fertilizers (kg); $N_{CR} = F_{CR}$: amount of N (kg) in crop residues (above-ground and below-ground); $N_{SOM} = F_{SOM}$: amount of N in mineral soils that is mineralized (kg); F_{SN}: amount of synthetic fertilizer N applied to soils (kg); F_{ON} = amount of animal manure and organic compost (kg); F_{PRP} = amount of urine and dung N deposited by grazing animals on pasture, range and paddock (kg); $N_2O_{(ATD)}$ = amount of N_2O produced from atmospheric deposition of N volatilized from managed soils; $N_2O_{(L)}$ = from leaching and runoff of N additions to managed soils in regions where leaching/runoff occurs.

CO_2 emissions (Table 4) are related to the use of urea, limestone ($CaCO_3$) and dolomite ($(CaMg)CO_3$). Urea application leads to the release of CO_2 previously fixed in the fertilizer molecule. This occurs due to urea hydrolysis, where the carbon in its structure is converted into CO_2. Since approximately 20% of urea's mass consists of carbon, applying the stoichiometric conversion to CO_2 (44/12) results in an estimated emission of CO_2 per kg of urea. On the other hand, the carbonates in limestone and dolomite decompose in the soil, releasing CO_2. In the case of limestone, about 12% of its mass is carbon, while in dolomite, this proportion is approximately 13%.

The IPCC-Calc (IPCC, 2019) and BR-Calc (Matsuura et al., 2022) methodologies produced identical results as they accounted for urea and limestone emissions, using the same emission factors (0.12 for limestone and 0.20 for urea) and additionally included emissions from fossil fuel (diesel) combustion. The Nemecek-Calc (Nemecek et al., 2012) estimated lower emissions because it did not consider limestone and dolomite emissions, whereas the

WFLDB (Nemecek et al., 2019) reported higher values due to the full accounting of carbon emissions from these inputs. The Agri-footprint methodology (Blonk et al., 2023), despite using the same emission factors for urea and limestone, did not include diesel combustion emissions (Table 7), leading to different results from those of IPCC-Calc and BR-Calc. Consequently, the inclusion of diesel emissions in IPCC-Calc and BR-Calc significantly increased CO_2 emissions and, therefore, the carbon footprint (Figure 2).

N_2O emissions were estimated in all methodologies considering direct and indirect emissions, as proposed by based on (IPCC, 2006). Direct N_2O emissions are from the use of mineral and organic fertilizers, decomposition of crop residues and mineralization associated with loss of soil organic matter resulting from change of land use or management of mineral soils.

Indirect emissions regard the conversion of NH_3, NOx and NO_3^- into N_2O). However, differences were found in the methodologies regarding emission sources and factors. The lowest emission of N_2O was obtained using the methodology of Nemecek-Calc due to disregarding the mineralization of soil organic matter (Nsom) and the indirect emission from NOx. WFLDB adopts equations with modifications and factors considering direct emissions from fertilizer applications (mineral and organic), crop residues and decomposition of soil organic matter, as well as indirect emissions from NH_3 volatilization, NO_3 leaching and NOx emissions. On the other hand, the highest N_2O values were from IPCC-Calc and BR-Calc, justified by the greater specificity of the equation (Tier 2) for N_2O emissions and by the lack of both considering nitrous oxide emissions from diesel combustion.

Considering the carbon footprint results obtained from each methodology, IPCC-Calc and BR-Calc showed the highest impacts. This is because, in addition to fossil CO_2 and N_2O emissions, these methodologies account for additional GHG emissions resulting from diesel combustion, a criterion not evaluated by the other methodologies. Even without evaluating emissions from burning diesel, the WFLDB methodology showed a lower level of only 9.8% in relation to the greater impact, justifying the fact that this method uses a greater emission factor for urea, directly contributing to the impact on climate change.

Nitrogen fertilization directly contributes to the increase in the carbon footprint, where urea, the main fertilizer source of N, increases CO_2 emissions due to its synthesis from ammonia and CO_2, increasing GHG emissions by about 40% due to its high carbon content (Galusnyak et al., 2023).

BR-Calc (Matsuura et al., 2022) is inserted as a regional alternative adapted to Brazilian conditions, seeking to fill gaps left by global methodologies such as the IPCC (IPCC,

2019) and more detailed models, such as the WFLDB (Nemecek et al., 2019), incorporating emission factors and parameters adjusted to climatic, soil, and agricultural management particularities in Brazil, making it especially relevant for local and regional studies (Giongo et al., 2025). It is also noteworthy that BR-Calc also calculates emissions other than GHG-related ones, such as heavy metals and phosphate emissions.

When the methodologies of Nemecek-Calc and Agri-footprint were used for the quantification of GHGs, lower values of environmental impact were obtained in the climate change category. This result occurred mainly due to the simplification of calculation present in these methodologies, especially in Nemecek-Calc, which presented underestimated results for most of the quantified emissions (Figure 2).

Currently, the most frequently used methodologies for estimating GHG emissions from agricultural systems in LCA studies are those adopted by the IPCC-Calc (IPCC, 2019) and the WFLDB (Nemecek et al., 2019), especially the joint use of both, according to Lima et al., 2024; Subedi et al., 2024.

It is important to stress that more specific models such as BR-Calc (Matsuura et al., 2022) and Agri-footprint (Blonk et al., 2023), although they allow the estimation of emissions within a limited time and with a small financial budget, require knowledge of local ecosystems to calibrate specific variables for the correct modeling (Figueirêdo et al., 2016).

Based on the IPCC Guidelines (IPCC, 2019), the IPCC-Calc quantifies only greenhouse gas emissions, considering N_2O from fertilizers and crop residues and CO_2 from limestone and urea application. However, this methodology has limitations that may affect comparisons with other methods, as it does not include the indirect formation of NO_2, the radiative forcing of NO_x, water vapor, and sulfates, nor the indirect effects proposed by the IPCC, which may underestimate climate impacts. Additionally, it does not account for the conversion of CO-to-CO_2, a relevant factor under certain agricultural conditions (Fernández-Coppel et al., 2018).

The BR-Calc (Matsuura et al., 2022) corresponds to a protocol developed by Embrapa Environment, which compiles methods consolidated in the literature for estimating emissions from agricultural activities, selected for better representing tropical conditions. Additionally, the tool includes a climate and soil database specific to Brazil, allowing users to choose the most suitable geographical scale for their study. However, this protocol uses the same equations and emission factors as the IPCC-Calc for GHG emission quantification, resulting in little mathematical differentiation between the methods. Therefore, future studies should focus on developing GHG emission factors adapted to Brazil's edaphoclimatic conditions to improve estimation accuracy.

In the Nemecek-Calc (Nemecek et al., 2012) methodology, a significant underestimation of GHG emissions is observed, mainly due to the absence of accounting for fossil CO_2 from limestone use, nitrogen mineralization in mineral soils, and the exclusion of indirect emissions of (NOx) which, according to the authors, correspond to 21% of N_2O emissions. Additionally, this methodology features poorly explained equations and factors that are difficult to understand, compromising the clarity and transparency of the calculations.

The WFLDB (Nemecek et al., 2019) methodology is an update of the method by Nemecek and Schnetzer (2012), correcting most of the issues of its predecessor by providing greater data transparency and enhanced scientific robustness. However, in both methodologies, GHG emissions from fossil fuel combustion are not accounted for, which limits the accuracy of the estimates.

In the literature, it is observed that most of the studies that evaluate GHG emissions resulting from agricultural production in tropical climate conditions use the IPCC-Calc and WFLDB methodologies together, especially when evaluating the emission of gases that indirectly contribute to the greenhouse effect (NOx, NH_3, and NO_3), as reported in coconut (Sampaio et al., 2021), cashew (Figueirêdo et al., 2016), melon (Barros et al., 2019) macauba (Fernández-Coppel et al., 2018), and soybean (Lucas et al., 2023) crops.

More recently, in the context of Brazilian agriculture, the integrated use of the BR-Calc methodology with the methods mentioned above has been observed, as evidenced by wheat (Giongo et al., 2025) and banana (Lima et al., 2024) crops. However, although all these studies use more than one methodology to assess emissions, they do not compare the different results that each method provides.

Table 9 presents summaries of the main advantages and limitations of all methodologies evaluated in this study, providing a direct comparison between the methods and offering insights into their applicability in different contexts.

Table 9. Summary of the main advantages and limitations of the evaluated methodologies

Source	Methodology	Advantages	Limitations
Nemecek and Schnetzer (2012)	Nemecek-Calc	Robust methodology based on ecoinvent data for assessing emissions in agricultural crops.	Accuracy may be limited by the generalizability of the data. It does not always reflect regional soil and climate specificities.
Nemecek et al. (2019)	WFLDB	Represents agricultural products and food in a global context, useful for eco-design projects and Environmental Product Declarations. Comprehensive globally traded agricultural products.	Application at local scale may be limited by the lack of specific regional data. It may not capture detailed local agricultural practices.
Calvo-Buendía et al. (2019)	IPCC-Calc	Globally accepted methodology for estimating national GHG inventories. Provides a sound scientific basis for national and regional estimates.	Less suitable for specific ICVs due to generalization for national use. Not very detailed for local agricultural practices.
Embrapa (2022)	BR-Calc	Adjusted for Brazilian agricultural conditions, including specific soil and climate parameters for the country's 137 agricultural mesoregions. Useful for accurate estimates in tropical systems.	The methodology may not be recognized internationally. Although there are regionalized parameters for Brazil, these have little direct impact on the calculation of GHGs.
Blonk et al. (2023)	Agri-footprint	Comprehensive, industry-specific database for the food and agriculture sector with over 11,000 products. Accepted by the industry and scientific community and useful for LCA.	Focuses on global practices, requiring adjustment of data to reflect specific local conditions.

The results of this study can guide public policies and sustainable agricultural practices in cashew cultivation. Methods such as IPCC-Calc and BR-Calc, which provide more accurate estimates, allow the search for more effective actions to reduce GHG emissions from cashew cultivation in tropical environments.

For farmers, it is recommended to optimize the use of fertilizers (Poore et al., 2018), adopt organic and green fertilizers (Figueirêdo et al., 2016; Bansal et al., 2022), and implement agroforestry systems (Ménard et al., 2023), reducing N_2O emissions and improving the carbon balance in the soil. For policymakers, it is essential to encourage methodologies and emission factors adapted to the Brazilian reality, in addition to promoting research and technologies to strengthen low-carbon agriculture, according to the ABC+ plan (Brasil, 2021).

These strategies are aligned with SDGs (ONU, 2016), 2 (zero hunger and sustainable agriculture), 12 (responsible consumption and production), and 13 (climate change mitigation). Thus, the study not only improves the quantification of GHG emissions but also offers guidelines to make cashew production more sustainable.

4.4 Conclusion

This study contributes to the advancement of LCA and CF in tropical regions by addressing the gap in methodological comparisons highlighted in the work. By evaluating different approaches to quantifying GHG in a tropical agricultural system, our results highlight the importance of choosing methodologies that can be adapted to different agricultural scenarios.

The choice methodology for estimating GHG emissions is a critical factor, as it directly influences the interpretation of agricultural carbon footprints. In this study, the IPCC-Calc and BR-Calc methodologies yielded the highest emission estimates for cashew production under tropical conditions, leading to the largest carbon footprints. In contrast, the Nemecek-Calc methodology reported the lowest values, highlighting the variability among methods and the need for regionally adapted approaches.

Based on the analysis criteria, the WFLDB, IPCC-Calc, and BR-Calc methodologies were the most recommended, balancing clarity, scientific robustness, and regional adaptation. BR-Calc stood out for its consideration of regional data, while WFLDB and IPCC-Calc demonstrated greater scientific robustness. In contrast, Nemecek-Calc showed limitations in transparency, and Agri-footprint had an intermediate performance, proving useful depending on the analysis objective.

Therefore, it is suggested that BR-Calc should be used for evaluations in national contexts, especially in situations where factors such as the use of limestone, urea, and local agricultural practices have a significant impact on GHG emissions. This approach can improve the representativeness of the results and provide more precise support for decision-making aimed at mitigating emissions in Brazilian agricultural production.

Furthermore, future studies should consider the integration of primary data and direct measurements to validate the estimates obtained through different methodologies, reducing uncertainties and enhancing the applicability of models in tropical agricultural systems. The adoption of hybrid approaches, combining empirical equations with process-based modeling, could represent a promising alternative to increase the accuracy of estimates and assist in the development of more effective policies for mitigating GHG emissions in agriculture.

5 CHAPTER II - PROSPECTIVE ASSESSMENT OF THE CARBON FOOTPRINT OF CASHEW PRODUCTION IN THE BRAZILIAN SEMIARID BASED ON CARBON DYNAMICS MODELING

Abstract: Prospecting the carbon footprint (CF) of production systems is essential for guiding sustainable decision-making in fruit orchards. However, few assessments of fruit cropping systems integrate soil organic carbon (SOC) dynamics throughout the entire orchard lifespan, particularly of novel non-monoculture experimental systems. This study innovates by combining SOC modeling for orchard lifespan and biomass carbon measurements with CF assessment in cashew production, enabling a prospective analysis of the sustainability of cashew cropping systems in the Brazilian semiarid region. Five cashew systems were evaluated, encompassing orchards aged 6 to 13 years, in experimental (E) and commercial (C) areas. The CF of 1 kg of cashew (nut and apple) was assessed according to ISO 14067 and the GHG Protocol. Cashew trees were assumed to have a lifespan of 25 years. Biomass carbon was measured from the seedling stage to adult trees. Emissions were calculated using the ICVCalc tool. SOC (0–20 cm) for different orchard years was estimated using the RothC model. Results showed biomass carbon increased from 0.0014 to 27.63 Mg ha^{-1} over the years, allowing the development of a cashew-specific allometric equation. The highest predicted SOC stock occurred in the system intercropped with forage, whereas the lowest was found in the commercial monoculture. The lowest CF (0.046 kg CO_2eq kg^{-1}) was observed in the E3 intercropping system. The integration of SOC and biomass carbon modeling with CF assessment proved effective for forward-looking projections, underscoring the potential of diversified systems to meet sustainability certification criteria and support climate change mitigation.

Keywords: *Anacardium occidentale*; climate change; life cycle assessment; soil organic carbon.

5.1 Introduction

Carbon footprint (CF) is one of the main indicators of environmental sustainability in agriculture, allowing the quantification of greenhouse gas (GHG) emissions throughout the crop life cycle (ISO, 2018). In recent years, CF studies of agricultural products have expanded to cover tropical fruits such as melon (Barros et al., 2019), mango (Carneiro et al., 2019), and banana (Lima et al., 2024). These studies have consistently identified agricultural practices with reduced impacts, supporting decarbonization goals and strategies for a more efficient use of resources.

CF assessments also support global environmental policies, such as the European Green Deal and the European Union's Common Agricultural Policy (European Commission, 2024), as well as the Brazilian program ABC+ (Brazil, 2021), which promote the adoption of low carbon cropping systems. Moreover, major fruit retailers such as Tesco and Walmart started to requere fruits CF data from producers around the world (Bhutta et al., 2021), making the absence of these data a non-tariff barrier in international trade.

However, most studies addressing CF focus on conventional systems or historical data (Subedi et al., 2024). Few studies have assessed the CF of experimental fruit-growing systems, such as cashew (Figueirêdo et al., 2016), melon (Barros et al., 2019), and mango (Dias et al., 2020) orchards. However, these studies did not account for the SOC and biomass carbon dynamics in orchards over years, which is important in prospective studies. In view of these limitations, this study sought to advance in this matter by integrating the quantification of biomass and soil carbon across different scenarios of cashew production, providing a more comprehensive view of their climate-mitigation potential.

The cashew tree (*Anacardium occidentale* L.) is native to the Brazilian semiarid region, which accounts for 99.5% of the country's cultivated area (451,424 ha) (IBGE, 2025). Most of the production is carried out on small and medium-sized farms, which collectively generate about 100 thousand jobs (Brainer and Vidal, 2020). Globally, Africa (Ivory Coast, Benin, Tanzania, Mozambique, Ghana, and Nigeria) and Asia (India, Vietnam, Indonesia, and the Philippines) cultivate approximately 6 million hectares of cashew (FAO, 2024). Adapted to hot weather, dry regions, the cashew tree has a low water requirement (800–1200 mm year^{-1}) and a productive lifespan of more than 25 years. These characteristics favor carbon accumulation in biomass. Commercial crops rely predominantly on monoculture systems established on sandy soils that are poor in organic matter, with low carbon stocks (Serrano, 2016).

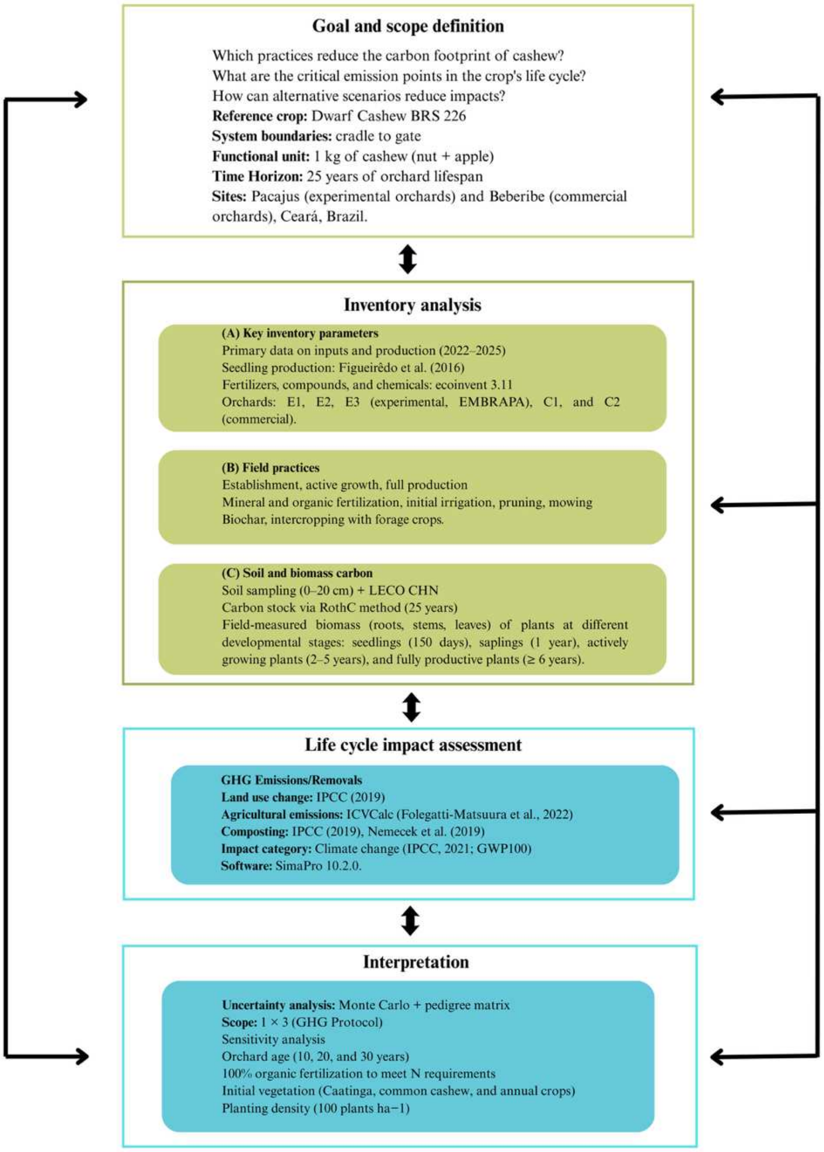
Few studies have evaluated the environmental impacts of cashew production. Previous studies focused on monocropping systems and identified land use changes (LUC), chemical fertilization, and the consumption of fossil fuels as the primary sources of GHG emissions (Figueirêdo et al., 2016; Krishnappa et al., 2023; Sales et al., 2025). To date, no study has integrated the modeling of soil carbon and biomass dynamics into a prospective assessment of the cashew CF across different cropping systems, such as intercropping. Integrated systems are assumed to provide higher carbon inputs to the soil and reduce net CF compared with conventional monocropping.

In this context, this study assessed the CF of cashew production using primary data from five commercial (C) and experimental (E) systems with orchard ages ranging from 6 to 13 years: i) experimental conventional monoculture (E1); ii) experimental monoculture amended with biochar and organic compost (E2); iii) experimental system intercropped with perennial forage (E3); iv) commercial monoculture amended with organic inputs (C1); and a commercial system intercropped with annual crops (C2). This assessment aimed to support farmers' decision about which cropping system is best when pursuing carbon credit projects or low carbon certification schemes.

5.2 Material and methods

CF analysis followed ISO 14067 (2018). The approach adopted in the study is illustrated in Figure 1 and described in detail in the following sections.

Figure. 1. Flowchart detailing the steps in the life cycle assessment of dwarf cashew BRS 226 production in the Brazilian Semiarid.



Goal and scope definition

Which practices reduce the carbon footprint of cashew?
What are the critical emission points in the crop's life cycle?
How can alternative scenarios reduce impacts?
Reference crop: Dwarf Cashew BRS 226
System boundaries: cradle to gate
Functional unit: 1 kg of cashew (nut + apple)
Time Horizon: 25 years of orchard lifespan
Sites: Pacajus (experimental orchards) and Beberibe (commercial orchards), Ceará, Brazil.

Inventory analysis

(A) Key inventory parameters
Primary data on inputs and production (2022–2025)
Seedling production: Figueirêdo et al. (2016)
Fertilizers, compounds, and chemicals: ecoinvent 3.11
Orchards: E1, E2, E3 (experimental, EMBRAPA), C1, and C2 (commercial).

(B) Field practices
Establishment, active growth, full production
Mineral and organic fertilization, initial irrigation, pruning, mowing
Biochar, intercropping with forage crops.

(C) Soil and biomass carbon
Soil sampling (0–20 cm) + LECO CHN
Carbon stock via RothC method (25 years)
Field-measured biomass (roots, stems, leaves) of plants at different developmental stages: seedlings (150 days), saplings (1 year), actively growing plants (2–5 years), and fully productive plants (≥ 6 years).

Life cycle impact assessment

GHG Emissions/Removals
Land use change: IPCC (2019)
Agricultural emissions: ICVCalc (Folegatti-Matsuura et al., 2022)
Composting: IPCC (2019), Nemecek et al. (2019)
Impact category: Climate change (IPCC, 2021; GWP100)
Software: SimaPro 10.2.0.

Interpretation

Uncertainty analysis: Monte Carlo + pedigree matrix
Scope: 1 × 3 (GHG Protocol)
Sensitivity analysis
Orchard age (10, 20, and 30 years)
100% organic fertilization to meet N requirements
Initial vegetation (Caatinga, common cashew, and annual crops)
Planting density (100 plants ha−1)

5.2.1 *Study purpose and scope*

The purpose of this study was to identify field practices that reduce the CF of cashew production across different production systems by pinpointing critical emission hotspots and evaluating possible improvement scenarios. The assessment adopted a cradle-to-gate scope, encompassing LUC, input production and transportation, and the cultivation of dwarf cashew BRS 226. This clone was selected due to its adaptability to high temperature (32-40 °C), low rainfall (600-800 mm year^{-1}), and sandy (50%), deep soils (<1.5 m), conditions typically encountered in Brazil's main cashew-producing regions (Serrano, 2016).

Five production systems were evaluated (Table 1): i) experimental conventional monoculture (E1); ii) experimental monoculture amended with biochar and organic compost (E2); iii) experimental system intercropped with perennial forage (E3); iv) commercial monoculture amended with organic inputs (C1); v) commercial system intercropped with annual crops (C2).

All orchards were rainfed and aged 6 to 13 years. Most crops were placed in areas previously occupied with Caatinga vegetation, a type of savanna, endemic to Brazil.

Table 1. Description of the studied cashew production systems in the Brazilian semiarid region

System	Crops	Cashew tree spacing	Plants ha^{-1}	Year of establishment	Previous land use	Soil class
E1	Cashew	8 × 6 m	208	2011	Caatinga vegetation	Red-Yellow Argisol
E2	Cashew	8 × 6 m	208	2017	Caatinga vegetation	Red-Yellow Argisol
E3	Cashew + *Brachiaria brizantha*	8 × 6 m	208	2018	Caatinga vegetation	Red-Yellow Argisol
C1	Cashew	9 × 9 m	123	2019	Coconut palms	Quartzarenic Neosol
C2	Cashew + maize/sorghum/pearl millet	7 × 21 m	68	2019	Caatinga vegetation	Quartzarenic Neosol

The functional unit was 1 kg of cashew (nut + apple), considering an orchard lifespan of 25 years in the reference situation. Moreover, the CF was also calculated to 1kg of cashew nut to allow comparison with other nuts in the discussion section. Mass and economic allocation criteria were used to this aim (Table 2).

Table 2. Yield and revenue of the studied cashew production systems in the Brazilian semiarid region.

System	Products	Price (US\$ kg^{-1})	25-year production (kg ha^{-1})	25-year revenue (US\$ ha^{-1})	Mass allocation (%)	Economic allocation (%)
E1	Nut	0.735	49,450	36,360.29	10	47
	Apple	0.092	445,050	40,905.33	90	53
E2	Nut	0.735	66,613	48,980.15	10	47
	Apple	0.092	599,519	55,102.85	90	53
E3	Nut	0.735	43,865	32,240.76	5.6	37.9
	Apple	0.092	394,787	36,320.40	49.5	42.7
	Biomass*	0.046	358,107	16,457.12	44.9	19.4
C1	Nut	0.735	25,800	18,970.59	10	47
	Apple	0.092	232,200	21,341.91	90	53
C2	Nut	0.735	24,475	17,996.32	3.6	30.8
	Apple	0.092	220,275	20,245.86	32.2	34.7
	Biomass**	0.046	438,892	20,189.03	64.2	34.5

* Biomass production of dwarf cashew intercropped with *Brachiaria brizantha*.

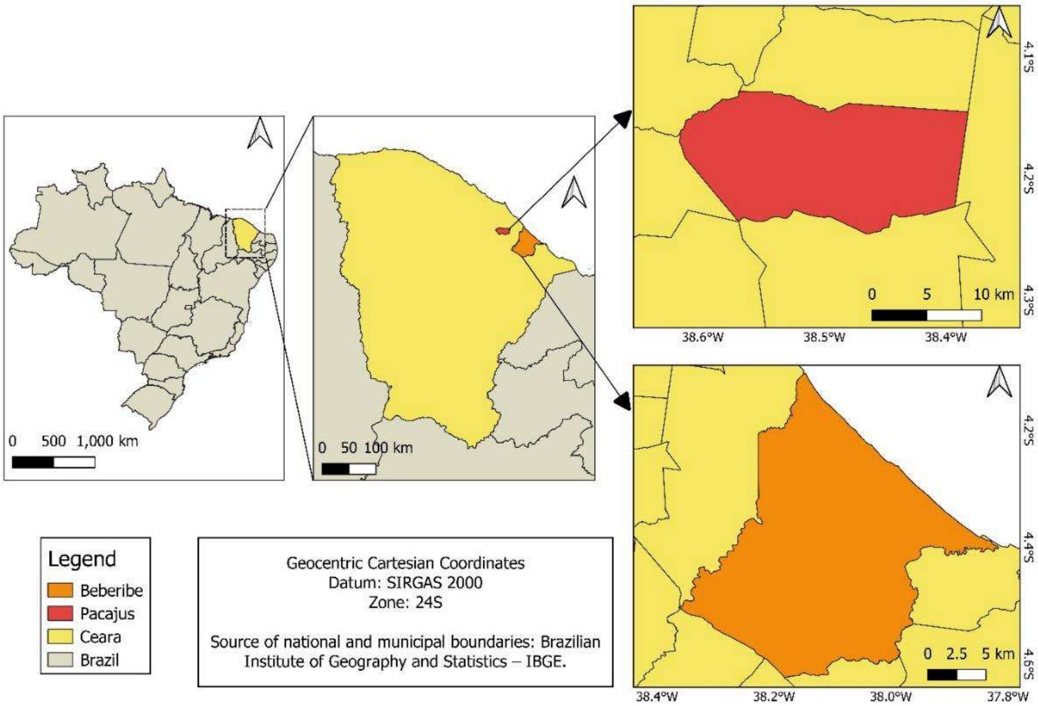
** Biomass production of dwarf cashew intercropped with maize, sorghum, and millet.

5.2.2 Environmental inventory

Cashew production systems were evaluated based on primary data on input use and production at each cropping system, collected with researchers and farmers between 2022 and 2025. Data were obtained from Figueirêdo et al. (2016) for seedling production and from Roesch et al., (2025) for biochar production. Information on the production and transportation of agrochemicals and composting was sourced from the ecoinvent® v3.9.1 database (Supplementary Material-SM, Annex I).

The studied production systems were located at Embrapa experimental station in Pacajus (E) and at a commercial farm (C) in Beberibe, both in Ceará State, Brazil (Figure 2).

Figure 2. Location map of the studied cashew production systems in Brazil.



The climate in Pacajus and Beberibe is tropical semiarid, with average temperatures of 26 to 28 °C and irregular rainfall concentrated between January and May (IPECE, 2020). The average annual rainfall is 791.4 mm in Pacajus and 914.1 mm in Beberibe. The cropping systems were evaluated had different ages and land use histories (Table 1).

Primary data on input use and production were collected for the following stages of orchard development, assuming a 25-year lifespan:

- Establishment (year 1): After initial clearing, the soil is prepared by harrowing, and acidity is corrected by liming. Planting pits measuring 40 × 40 × 40 cm are opened and fertilized with macro- and micronutrient sources. At 30 days after pit preparation and liming, grafted dwarf cashew seedlings are planted. Irrigation is used only during this early stage to ensure seedling survival during the dry season, which may last up to 6 months.
- Active growth (years 2–5): From the second to the fifth year, cashew plants undergo continuous growth. During this stage, early fertilization is performed using mineral fertilizers and organic amendments. Formation pruning is also initiated to develop a dense, well-ventilated canopy with adequate light penetration. Disease, pest, and weed management is carried out concurrently.
- Full production (years 6–25): Beginning in the sixth year, dwarf cashew trees enter their adult phase, reaching high yields and growing up to 4 m in height. Fertilization with macro- and micronutrients from organic and inorganic sources is intensified to maintain

productive performance. Because the orchards had different ages, input use and yield were assumed to remain constant during the full-production years.

The main types of pruning carried out in cashew orchards are formation pruning, cleaning pruning, and maintenance pruning. Formation pruning is performed annually and manually in all production systems during the establishment and early-growth phases (years 1–5). Maintenance and cleaning pruning both remove unwanted branches. In adult cashew trees, maintenance pruning prevents branch overcrowding and ground-directed growth, while cleaning pruning eliminates suckers and diseased or pest-infested branches, and should be carried out about one month after harvest. Mechanized pruning is conducted annually during the production phase (years 6–25), and the resulting pruned material is incorporated into the soil. Biomass and carbon from pruning waste were measured and included in the prospective soil carbon modeling (Section 2.3).

Mechanized mowing is conducted annually between cashew rows to control weeds in monoculture systems and to collect biomass from intercrops in intercropping systems. All systems received mechanized applications of protection agents annually, according to crop-specific needs.

An organic amendment composed of a mixture of sawdust, cattle manure, and millet straw is applied throughout the 25-year orchard life in all systems, except E1. Additionally, biochar is added to the planting pits in E2. The biochar is produced from the pruning waste of evergreen trees by sun-drying, followed by carbonization in a rudimentary brick kiln under low-oxygen conditions (Gondim et al., 2024).

Table 3 presents the input inventory for the studied orchards over their 25-year lifespan.

Table 3. Environmental inventory of the studied cashew orchards (25-year lifespan) in the Brazilian semiarid region.

Item	**Unit**	**Cashew orchard**				
		E1	**E2**	**E3**	**C1**	**C2**
Transformed area (from caatinga to orchard)	ha	1.0	1.0	1.0	1.0	1.0
Product						
Cashew	kg	494,500	666,132	438,653	258,000	244,750

Inputs						
Limestone	kg	5300	5300	5300	13,365.4	32,913.5
Gypsum	kg	-	-	-	4900.0	19,898.1
Seedlings	kg	260	260	260	265	141
NPK fertilizer	kg	-	4347.2	-	1141.9	4389.9
Urea	kg	4763.2	5553.6	3512.9	-	2500.0
Monoammonium phosphate	kg	-	-	-	-	1143.1
Single superphosphate	kg	5896.8	-	7280.0	-	-
Potassium chloride	kg	1755.2	784.2	2674.5	-	2500.0
Organic compost	kg	-	128,000.1	128,000.1	124,000.0	238,235.3
Poultry litter	kg	-	-	-	4000.0	50,000.0
Biochar	kg	-	416	-	-	-
Acetamiprid	kg	0	34.4	0	16.7	22.3
Atrazine	kg	-	-	-	-	22.5
Deltamethrin	kg	7.8	7.8	7.8	9.2	6.8
Dimethoate	kg	-	-	-	92.8	71.1
Glyphosate	kg	24.9	24.9	24.9	26.3	51.2
Copper oxychloride	kg	206.1	206.1	206.1	-	-
Pyraclostrobin	kg	-	-	-	34.4	90.5

5.2.3 Determination of soil organic carbon (SOC)

SOC stock was measured before orchard establishment and in the following years up to 2025. For the initial stocks, soil samples with preserved structure were collected prior to the installation of each production system and in native vegetation preserved sites near the orchards.

The contribution of biomass carbon from cashew pruning to the soil was included in the assessment. Pruning biomass was quantified by directly weighing the fresh material on three spots, while its carbon content was estimated using the mean carbon fraction of the dry matter (45 percent of the dry weight). Formation pruning was disregarded as it occurs only in the early years of orchard establishment and represents a small fraction of the total biomass added throughout the production cycle.

Soil samples were collected at depths of 0–5, 5–10, and 10–20 cm. Samples were air-dried in the shade for 72 h, gently disaggregated with a wooden rolling pin, and sieved through a 2 mm mesh sieve to obtain the fine air-dried fraction. Soil bulk density was determined using the volumetric ring method, using undisturbed samples collected in cylinders of known volume, following standard procedures.

Soil carbon content was determined by dry combustion using a LECO CHN 600 elemental analyzer. SOC stock (Mg C ha^{-1}) was calculated from carbon content, soil bulk density, and the thickness of each sampled layer, following the procedures described by Giongo et al. (2020).

SOC dynamics over the orchard lifespan of each cropping system were assessed using the RothC model (Coleman et al., 2014). This model is widely used to simulate SOC dynamics under different land use, climate, and management conditions.

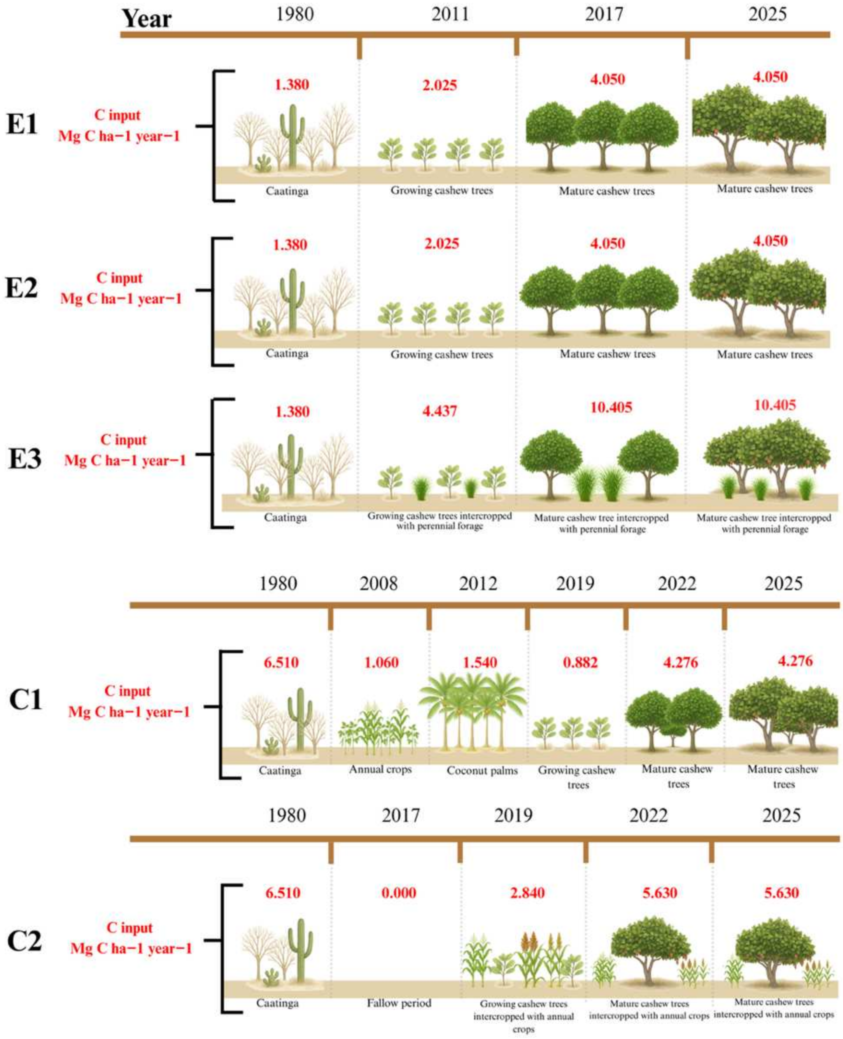
Monthly temperature, rainfall, and evapotranspiration data were included to obtain realistic simulations of soil moisture and carbon turnover (SM, Annex II). Model execution followed the procedures and calibration described by Giongo et al. (2020) for semiarid, mango-producing areas in Petrolina, Pernambuco, Brazil.

Model calibration to the study conditions was performed using measurements of soil organic matter in the 0–20 cm layer collected between 2010 and 2025 obtained from Gondim et al. (2024), Taniguchi et al. (2024) and Martins et al. (2025) and personal communication with these authors. A conversion factor of 1.72 was applied to transform soil organic matter into organic carbon, equivalent to an organic carbon content of 58% in organic matter (Nelson and Sommers, 1996).

RothC assumes that soil carbon inputs originate from all forms of organic matter added to the soil. The annual carbon input from caatinga vegetation was estimated by running RothC in reverse mode to identify the input required to match the initial SOC stock (Giongo et al., 2020). A ratio of 0.67 of decomposable to resistant plant material was adopted, following recommended values for vegetation from savanna formations, which are structurally similar to caatinga (Coleman et al., 2014).

The model was then executed for each production system according to its specific land-use chronosequence and carbon input trajectory (Figure 3). Data on total SOC stocks and carbon contributions from above- and belowground plant matter were tested for normality of residuals using the Shapiro–Wilk test ($p > 0.05$). Homoscedasticity was evaluated using Bartlett's test ($p > 0.05$). Model performance was assessed by comparing simulated and observed values for each production system, and by calculating the root mean square error (RMSE), mean difference, and correlation coefficient.

Figure 3. Chronosequence of carbon input in the studied cashew orchards according to land use histories in the Brazilian semiarid region.



5.2.4 Determination of biomass carbon in dwarf cashew BRS 226

Biomass measurements were conducted by cutting and separating the roots, stems, and leaves of plants at different developmental stages: seedlings (150 days), saplings (1 year), actively growing plants (2–5 years), and fully productive plants (≥ 6 years). After cutting, fresh biomass was determined by weighing samples in the field. Subsequently, samples from each plant component were placed in labeled containers and dried in a forced-air oven at 65 °C until reaching constant weight to obtain the dry biomass.

The carbon content in cashew plant biomass was determined following the method described by Silva et al. (2009). From these data, carbon stocks were calculated on a hectare basis according to the planting density in each production system, thereby accounting for differences in plant number among the evaluated orchards. Results are expressed in Mg C ha^{-1}.

5.2.5 Calculation of GHG removals and emissions of LUC and cashew production

LUC-related GHG emissions and removals were calculated using IPCC (2019) equations, based on the balance between carbon accumulation in biomass and soil before orchard establishment and after 25 years of cashew cultivation.

CO_2, CH_4, and N_2O emissions associated with agricultural production were estimated using the ICVCalc tool (Matsuura et al., 2022), applying equations and emission factors provided by IPCC (2019). In systems where organic compost was applied, emissions from compost production and management were calculated using the emission factors reported by IPCC (2019). A detailed description of the equations, emission factors, and references used in these calculations is provided in the SM (Annex III).

5.2.6 CF assessment of cashew production

CF was assessed using the climate change impact category as defined by IPCC (2021), which expresses the global warming potential of GHGs over a 100-year time horizon. Analyses were performed using SimaPro 10.2.0, including two evaluation scopes (1 and 3) in accordance with the GHG Protocol (2026). Scope 1 encompassed direct GHG emissions and removals from LUC, agricultural operations (fuel combustion), and soil and fertilizer emissions, whereas scope 3 encompassed all direct and indirect emissions across the crop's life cycle, including the production, transportation, and processing of inputs used in cashew production.

5.2.7 Uncertainty and analysis in PC comparison of production systems

Uncertainty in the comparison of cultivation systems was evaluated using the Monte Carlo method, following Goedkoop et al. (2023), using 1000 simulations. The log-normal distribution was adopted for inputs and outputs, and their geometric standard deviations were determined using the Pedigree Matrix. The CF of a cropping system A was considered significantly lower that the CF of a system B when the CF of A – B < 0 in more than 95% of the simulations.

5.2.8. Sensitivity analyses

The reference situation of the evaluated production systems considered a 25-year useful life, caatinga as the initial vegetation, and fertilization, plant spacing, biochar amendment according to the cropping system with inventory data provided by researchers and farmers (Table 3). However, potential variations were explored in a sensitivity analysis considering the following scenarios: S1) orchards with 10, 20, and 30 years; S2) the common cashew variety as the vegetation before the installation of the dwarf cashew orchard; S3) annual crop (maize) as vegetation before orchard installation; S4) fertilization of cashew trees with 100% organic nitrogen sources, according to the total quantity reported by each system; and S5) a planting density of 100 cashew trees ha^{-1}. Data regarding fertilization amount and composition as well as biomass and soil carbon used in these scenarios are in the SM (Annex IV).

5.3 Results and discussion

5.3.1 Effect of LUC on SOC

For all experimental systems, SOC stocks increased relative to caatinga vegetation, with E3 showing the largest increase (99.5%). By contrast, C1 and C2 showed a tendency toward SOC reduction (44.6% and 22.9%, respectively) (Table 4).

Table 4. Mean annual carbon (C) inputs and final soil organic carbon (SOC) stocks in the studied cashew production systems.

System	C input (Mg C ha^{-1} year^{-1})	SOC stock (Mg C ha^{-1})
E1	3.18	12.69 ± 1.06
E2	3.23	14.18 ± 0.92
E3	5.64	16.12 ± 3.49
C1	1.79	19.71 ± 1.24
C2	3.17	27.39 ± 3.12
Caatinga*	1.38	8.08 ± 0.68
Caatinga**	6.51	36.06 ± 1.22

SOC stock results are presented as mean ± standard deviation.

* Caatinga area of experimental systems.

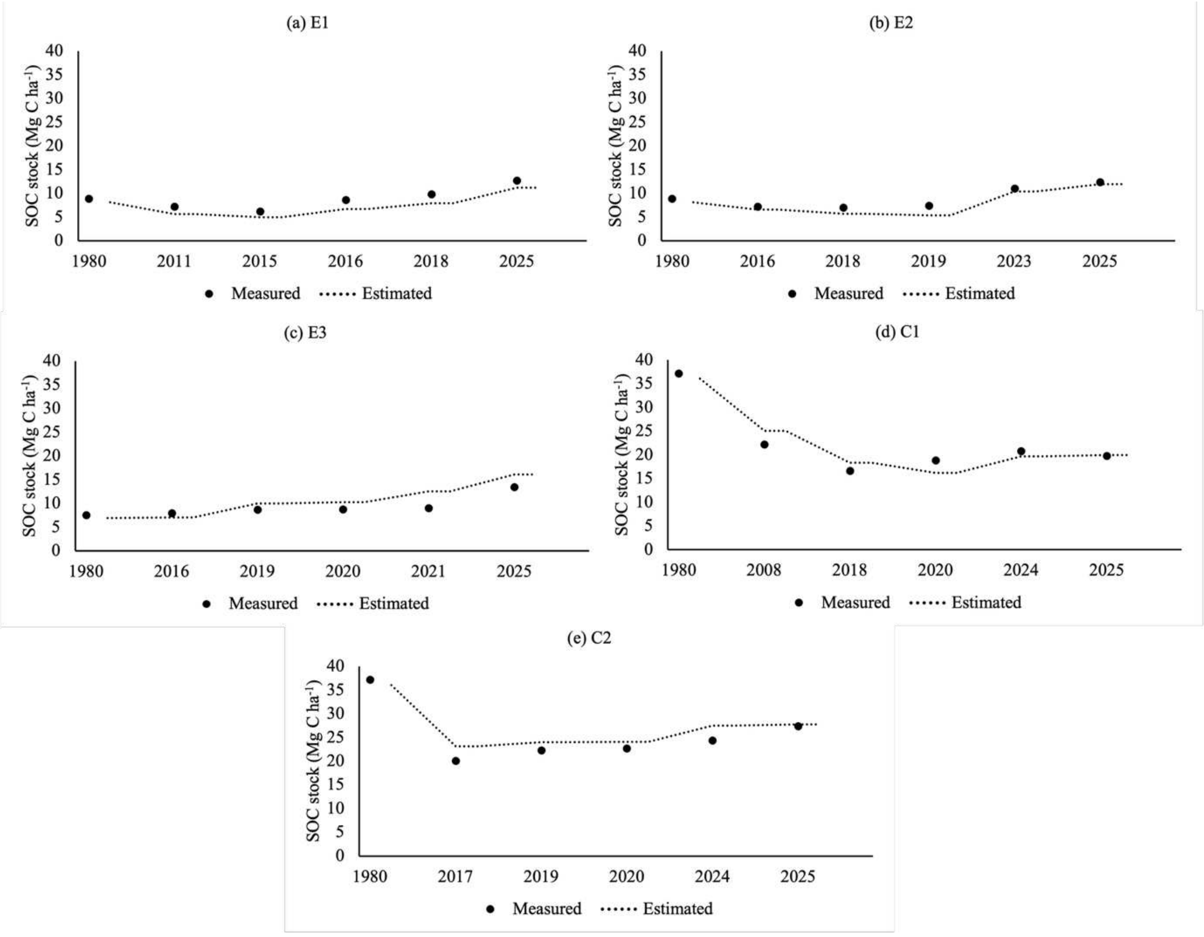
** Caatinga area of commercial systems.

The increase in SOC stocks observed in experimental systems is associated with the land use history of these areas, which were previously degraded and characterized by low levels of organic matter. By contrast, the commercial production systems were established on originally preserved caatinga vegetation, which had higher SOC stocks prior to conversion (36.06 Mg C ha^{-1}) than the degraded caatinga vegetation of experimental systems (6.51 Mg C ha^{-1}).

Regarding annual carbon inputs to the soil, the monocropping systems (E1, E2, and C1) received carbon primarily from cashew pruning residues incorporated into the soil, with a smaller contribution from roots and root exudates. In intercropping systems (E3 and C2), the main sources of carbon input were cover crops (≈50%), pruning residues (≈35%), and organic amendments (≈15%).

The performance of the RothC model was evaluated by comparing simulated SOC stocks with observed values across the different datasets. SOC dynamics were analyzed considering the various carbon input rates (Table 4), cultivation systems, and management types. The model was initially calibrated to estimate carbon inputs for the caatinga, ensuring that SOC stocks for the year 1980, prior to land use conversion to fruit production, were adequately reproduced (Figure 4).

Figure 4. Estimated and measured soil organic carbon (SOC) stocks in the 0 to 20 cm layer for the studied cashew production systems in the Brazilian semiarid region, as simulated using the RothC model.



The RothC model successfully predicted the proportional increases in measured SOC stocks in all evaluated production systems. However, a tendency to overestimate SOC was observed in the E3 system. The statistical performance of the model for each production system is presented in Table 5.

Table 5. Statistical performance of the RothC model for five cashew production systems in the Brazilian semiarid region.

Production system	*N*	RMSE (%)	MD (Mg C ha^{-1})	*r*
E1	6	15.32	1.45	0.98

E2	6	17.6	0.92	0.98
E3	6	19.95	1.76	0.94
C1	6	8.86	−0.02	0.96
C2	6	15.07	−1.41	0.98

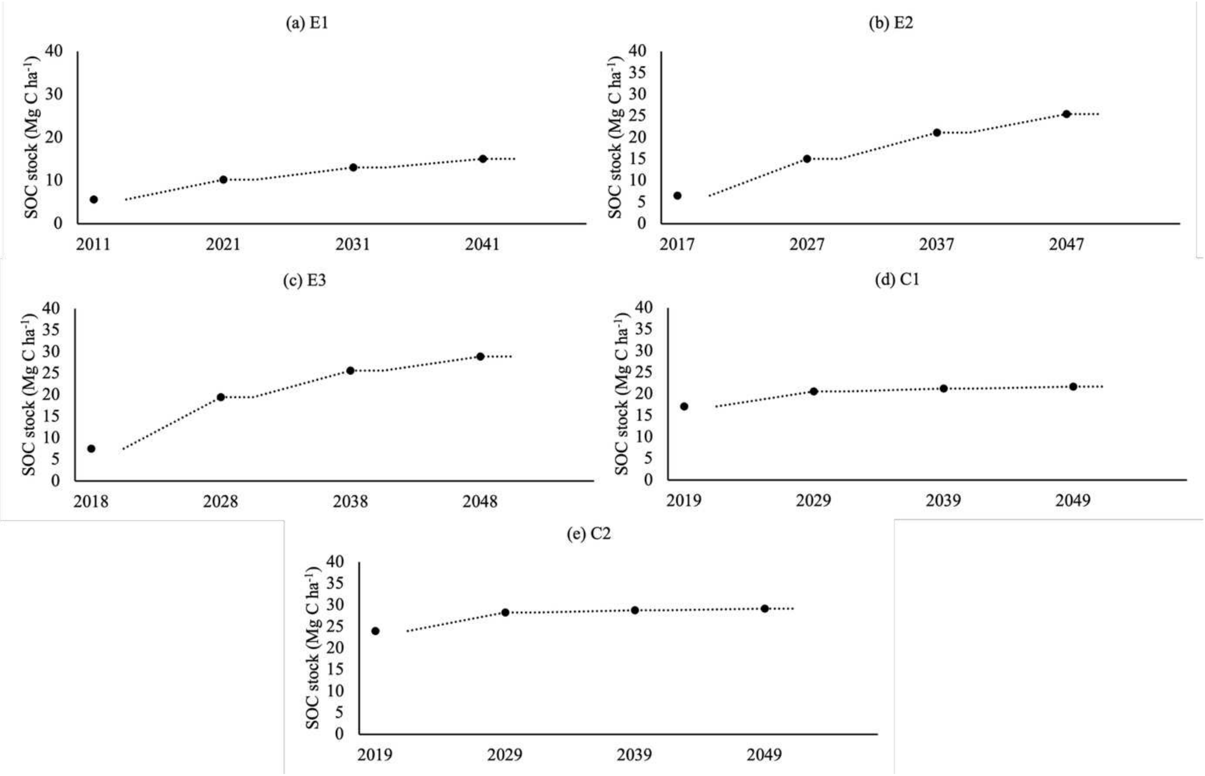
N, number of observations; RMSE, root mean square error; MD, mean difference; *r*, sample correlation coefficient.

Overall, the model satisfactorily described the change in SOC inventories. The RMSE was low, ranging from 8.86% to 19.95%, indicating low relative differences between observed and predicted SOC stocks. Mean differences (−1.41 to 1.76 Mg C ha^{-1}) and correlation coefficients (0.94 to 0.98) showed only minor variations ($p < 0.05$).

Following calibration of the RothC model for the studied conditions, SOC stocks were projected for additional orchard ages. An increase in SOC was observed in all production systems over the modeled time horizon. In the final projection (2041–2049), C2 had the highest SOC stock (29.2 Mg ha^{-1}), followed by E3 (28.3 Mg ha^{-1}) and E2 (26.1 Mg ha^{-1}), whereas E1 showed the lowest estimated value (15.1 Mg ha^{-1}).

In absolute terms, C2 accumulated an additional 7.5 Mg ha^{-1} relative to C1, representing a 34.5% increase. A similar pattern was observed between E3 and E1, with an increase of 13.2 Mg ha^{-1} (87.4%), demonstrating that integrated systems, which provide greater carbon inputs to the soil, have a higher carbon sequestration potential (Figure 5).

Figure 5. Future soil organic carbon (SOC) stock in the 0 to 20 cm layer in cashew production systems in the Brazilian semiarid region, as simulated with the RothC model. E1, experimental conventional monoculture.



Cashew production systems exhibited distinct trends under current climatic conditions, revealing differences in their soil carbon storage capacities. Integrated production systems (E3 and C2) showed the greatest potential for carbon storage in soil. These findings reinforce that management strategies promoting greater returns of plant residues to the soil are essential for increasing carbon accumulation and, consequently, mitigating net GHG emissions in long-term orchards.

5.3.2. Dynamics of carbon stock in cashew biomass

The relationship between cashew tree age and biomass carbon stock was described using a three-parameter logistic equation fitted to experimental data ($R^2 = 0.99$). Model parameters were statistically significant for b ($p = 0.0071$) and marginally significant for a and x_0 ($p = 0.0705$ and 0.0613, respectively), indicating satisfactory predictive performance. The fitted equation was as follows (Eq. 1):

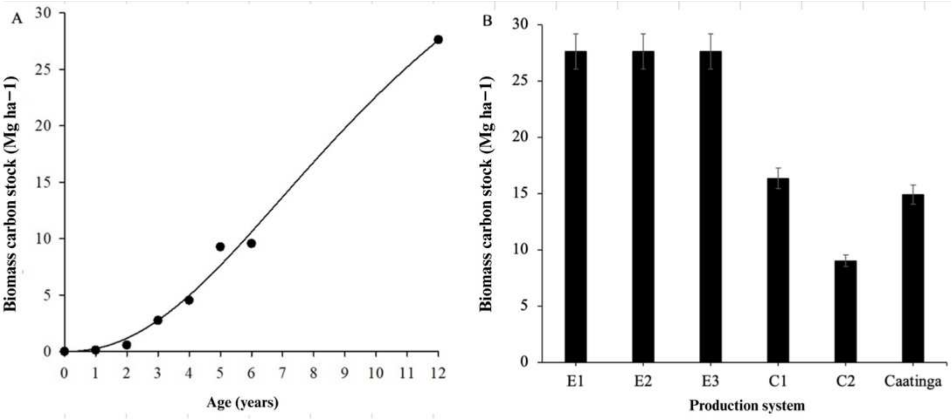
$$Y = \frac{49.89}{1+\left(\frac{x}{10.89}\right)^{-2.20}} \qquad (1)$$

where Y represents the biomass carbon stock (Mg ha^{-1}) and x represents the tree age (years).

Biomass carbon stock (Mg ha^{-1}) was modeled as a function of plant age (years), considering a density of 208 trees ha^{-1}. For other planting densities, the biomass carbon stock was calculated by multiplying the mean carbon stock per plant by the number of plants per hectare.

Carbon stock accumulation followed a sigmoidal pattern, with significant increases beginning in the third year and reaching approximately 90% of the asymptotic value by 10 years (Figure 6A). This pattern reflects the vegetative growth of the cashew tree, which exhibits rapid biomass accumulation during the juvenile phase, followed by stabilization as the orchard enters full production.

Figure 6. Biomass carbon stock of (A) cashew trees at different ages and (B) cashew production systems in the Brazilian semiarid region.



Carbon stocks in cashew biomass varied significantly among production systems. E1, E2, and E3 exhibited similar values (27.63 Mg C ha^{-1}), whereas C1 showed a lower value (16.34 Mg C ha^{-1}), and C2 had the lowest (9.03 Mg C ha^{-1}) (Figure 6B).

All experimental systems exhibited higher biomass carbon stocks (85.4%) compared with the mean carbon stock in caatinga vegetation (14.9 Mg C ha^{-1}) (MCTI, 2010). On the other hand, the biomass carbon stock of the C1 system was only 9.7% higher than that of caatinga vegetation, and C2 had a 39.4% lower stock. These differences are mainly attributable to orchard planting density (Table 1), which is 208 plants ha^{-1} in the experimental systems, 123 plants ha^{-1} in C1, and only 68 plants ha^{-1} in C2. Higher densities lead to greater soil cover and increased biomass accumulation per hectare, explaining the observed carbon stocks.

5.3.3 Inventory analysis of production systems

Overall, inventory results indicate that E2 and E3 have greater potential for carbon storage. By contrast, commercial systems, particularly the integrated C2 system, relied heavily on soil amendments (limestone) and fertilizers, as well as organic inputs (compost and poultry litter), resulting in higher GHG emissions, primarily CO_2 and N_2O.

Regarding GHG emissions from crop production, C2 had the highest input use, and C1 was the least intensive (Table 3), directly influencing CO_2 emissions among the evaluated systems. N_2O emissions were mainly from the use of fertilizers. C2 and E2 generated approximately 85% and 40% more emissions, respectively, than C1 due to the high application of inorganic and organic fertilizers (Table 6). CH_4 emissions were from burning of fossil fuels from agricultural operations, with higher values generated in systems C2 and C1 due to the use and production of composting

Regarding GHG emissions and removals from LUC, the integrated (E3) and monoculture (E2) experimental systems exhibited higher net CO_2 removals than C1, corresponding to 301.9 and 251.6% higher values, respectively, being due to the greater carbon sequestration in the biomass and soil of these orchards (Table 6).

Table 6. GHG balance of agricultural production in 25-year orchards, including emissions and removals associated with land use changes.

GHG emission from cashew production	**Unit**	**Production system**				
		E1	**E2**	**E3**	**C1**	**C2**
CO_2	kg ha^{-1}	7192.30	7982.70	5990.89	3847.20	11,850.50
N_2O	kg ha^{-1}	93.60	130.34	139.64	70.40	173.30
CH_4	kg ha^{-1}	0.43	0.49	0.47	0.55	0.64
LUC-related GHG removals and emissions						
CO_2	kg ha^{-1}	−806.30	−2834.84	−3241.07	4425.90	4006.60
N_2O	kg ha^{-1}	0.25	0.25	0.25	0.25	0.25
CH_4	kg ha^{-1}	2.76	2.76	2.76	2.76	2.76

N_2O and CH_4 emissions are attributed to biomass burning that occurs during LUC, where natural vegetation (Caatinga) is replaced by cashew cultivation, and are the same across all systems because the LUC process, type of vegetation removed, burning intensity, and emission factors, was identical for all areas assessed.

5.3.4. Comparison of cashew CF among production systems

In both scopes 1 and 3, experimental systems exhibited smaller CF values than commercial systems (Table 7). In scope 1, the CF of cashew reduced 25.5% when produced in E3 compared to C1 and 19.6%, to C2. Among commercial systems, C1 had the greatest climate impact, exceeding C2 by 16.1%. In scope 3, the cashew CF from E3 resulted in reductions of 111.7% compared to C1 and of 82.4% compared to C2.

Table 7. Carbon footprint of 1 kg of cashew produced in different production systems, under different accounting scopes.

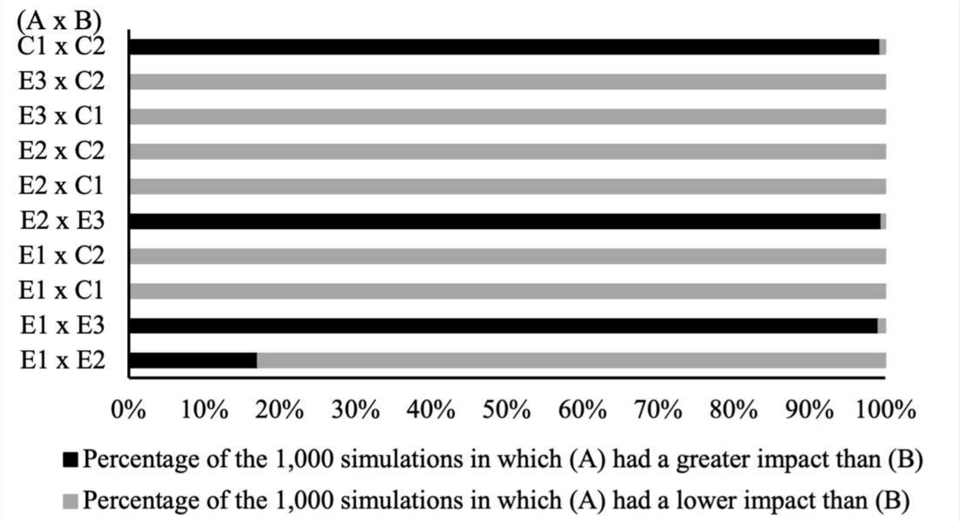
Production system	**Unit**	**Scope***	
		1	**3**
E1	kg CO_2eq kg^{-1} cashew	0.064	0.098
E2	kg CO_2eq kg^{-1} cashew	0.061	0.102
E3	kg CO_2eq kg^{-1} cashew	0.051	0.087
C1	kg CO_2eq kg^{-1} cashew	0.108	0.158
C2	kg CO_2eq kg^{-1} cashew	0.093	0.139

* Scope 1, direct GHG emissions from LUC, agricultural operations (fuel combustion), and soil and fertilizer emissions; scope 3, direct and indirect emissions across the crop's life cycle, including input production, transportation, and processing.

Scope 3 showed higher values than scope 1, due to the inclusion of indirect emissions from input production, transportation, and processing. This increase was 53.1% for E1, 67.2% for E2, 41.4% for E3, 46.3% for C1, and 49.5% for C2, indicating that indirect emissions contribute substantially to the total impact, particularly in commercial systems.

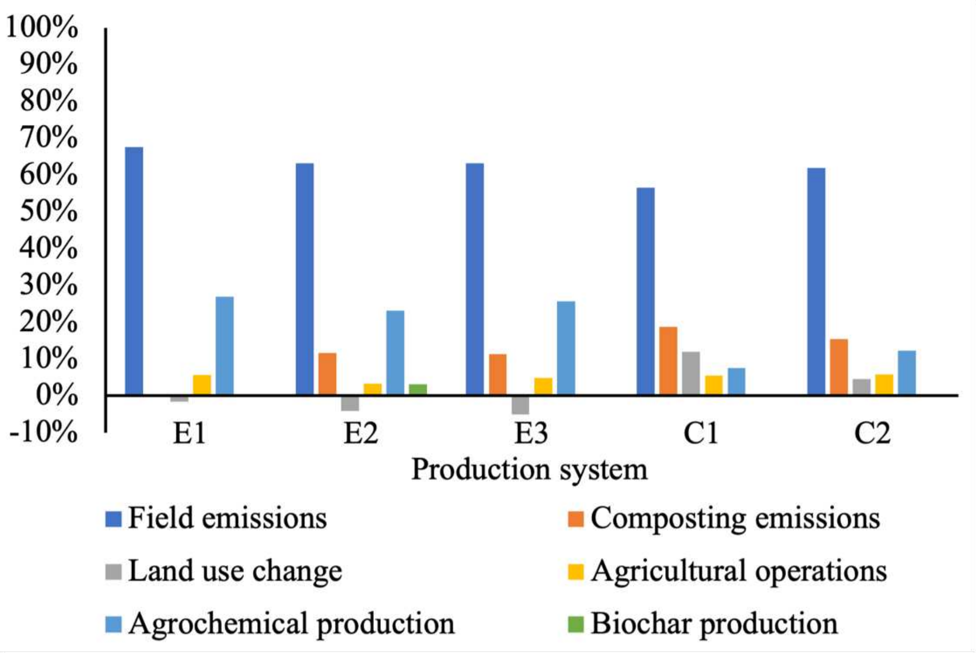
The comparison of cashew cropping systems under scope 3 showed that E3 consistently resulted in the smallest impact among all systems. In 100% of the 1,000 simulations, E3 had a lower impact than C1 and C2, and in more than 95–99% of the simulations, it also outperformed E1 and E2, according to the uncertainty analysis (Figure 7).

Figure 7. Uncertainty analysis in the comparisons of cashew cropping systems.



Contribution analysis revealed that field emissions accounted for the largest share of the CF in all cashew production systems. Input production was the second-largest contributor, primarily due to the production and processing of mineral fertilizers, particularly nitrogen-based fertilizers. Although LUC contributed negatively to CF in all experimental systems, especially in E3, it was insufficient to offset the GHG emissions from inputs production and agricultural operations (Figure 8).

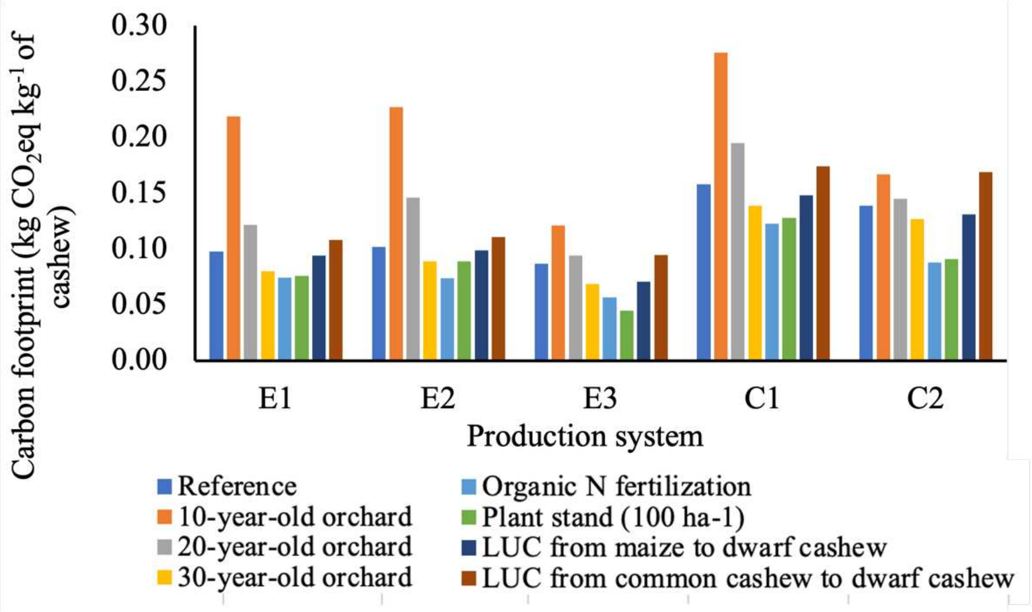
Figure 8. Contribution of processes and inputs to the carbon footprint of cashew production systems in the Brazilian semiarid region.



5.3.5. Sensitivity analysis

Regarding different orchard lifespans, the CF increased by reducing the orchard lifespan in all cashew systems. However, this reduction was smaller in C2 because the system has a lower plant density per hectare, resulting in reduced carbon accumulation and productivity. The CF of cashew from a 10-year-old orchard ranged from 0.121 in E3 to 0.276 kg CO_2eq kg^{-1} in C1 (Figure 9. By 30 years, CF decreased to 0.069 and 0.139 kg CO_2eq kg^{-1}, representing reductions of 42.9% (E3) and 49.6% (C1) compared to the 10-year-old orchard. These results demonstrate the positive effect of long-term orchard management on carbon sequestration efficiency (Figure 6A) and SOC stock (Figure 5).

Figure 9. Sensitivity analysis of the carbon footprint for 1 kg of cashew under different production and management systems.



The replacement of mineral fertilizer with 100% organic fertilizer led to significant reductions in CF across all systems compared to the reference scenario. In this scenario, E3 exhibited the smallest footprint (0.057 kg CO_2eq kg^{-1}), corresponding to reductions of 56.5% compared to C1 (0.131 kg CO_2eq kg^{-1}) and 40.6% compared to C2 (0.096 kg CO_2eq kg^{-1}). This is explained by the E3 system having undergone an update process in its fertilization recommendations, resulting in reduced nutritional demands compared to other systems, thus requiring less organic fertilizer.

A planting density of 100 plants ha^{-1} also reduced CF in all systems relative to the reference scenario, particularly in E3 and C2, because of fewer plants per hectare require less application of agrochemicals, especially fertilizers. Under this scenario, the E3 footprint was 50.5% lower than that of C1 and 76% lower than C2.

All evaluated systems showed a higher footprint in the scenario considering LUC from common cashew to dwarf cashew than in the reference situation (caatinga to dwarf cashew) due to the higher carbon losses from converting an existing cashew orchard. The lowest impact was in E3 (0.095 kg CO_2eq kg^{-1}) because this system makes a significant contribution to CO_2 sequestration and storage in the soil, offsetting carbon losses from biomass. Conversely, when the LUC was from maize to dwarf cashew, the footprint lower impact from all systems, particularly in E3 (0.071 kg CO_2eq kg^{-1}), with reductions of 52.0% and 45.8% relative to C1 and C2, respectively. These results underscore the importance of land use history in carbon footprint analysis.

SOC stocks in the surface layer (0–20 cm) under Caatinga vegetation (8.06 and 36.06 Mg C ha^{-1}) were adequately simulated by using the standard settings of the RothC (Figure 2). This initial calibration is crucial for the correct parameterization of the model, as it directly influences subsequent predictions (Giongo et al., 2020).

The soil classes of the cashew production systems evaluated in this study (Argisol and Quartzarenic Neosol) are naturally high in sand and low in clay. Under these conditions, carbon decomposition dynamics predicted by the RothC model are particularly sensitive to sandy textures (Coleman et al., 2014), as also noted by Mujuru and Hoosbeek (2016). Despite these challenges, the model reproduced the observed results satisfactorily (Table 3). RMSE values ranged from 5% to 18% and remained within expected limits, indicating only minor differences between observed and predicted SOC and yielding statistically reliable results (Senapati et al., 2014). Overall, statistical analyses indicated that the model exhibits low uncertainty, supporting its application in other regions with similar sandy soils and hot climates.

The study by Giongo et al. (2020) demonstrated the successful use of the RothC model to simulate soil carbon dynamics in a mango orchard established under semi-arid conditions in Northeast Brazil. After calibration, the model adequately reproduced the observed SOC stocks in the 0–20 cm layer, confirming its sensitivity to biomass inputs from the perennial system. The simulations showed that mango cultivation, when conducted under conservation practices, can promote significant annual increases in SOC.

Evaluating melon in the Brazilian semi-arid region, Silva et al. (2024) showed that RothC adequately represented the dynamics of SOC in irrigated dry climate systems. The model captured the increase in carbon stocks in scenarios with greater biomass input and the stability or slight reduction under conventional management. These results reinforce the applicability of RothC in semi-arid conditions.

The learnings from this study shows that to reduce the carbon footprint of cashew is important to install orchards in already deforested areas, opt for integrated cropping systems, use biochar, and efficient fertilization.

Regarding orchard installation site, this study showed that replacement of caatinga vegetation by cashew orchard, coupled with initial biomass removal and reduced organic matter inputs, led to SOC reductions, especially in monocropping systems (C1 and E1). Thus, orchards should be installed in already deforested areas. Moreover, many cashew producing areas in Northeast Brazil contain unproductive common (giant) cashew trees that need to be replaced by dwarf cashew trees, however, this practice promotes GHG emissions. Therefore, management strategies such as the use of green manures between cashew rows, the use of soil conditioners such as biochar, and the application of organic fertilizers according to the actual needs of the crop are necessary (Figueirêdo et al., 2016; Gondim et al., 2024; Giongo et al., 2025).

Regarding intercropping, this study showed that cashew systems integrated with integration with forage (*Brachiaria brizantha)* enhanced biomass accumulation and nutrient cycling, facilitating the gradual recovery of SOC stocks. Moreover, cashew integration with grasses (maize/sorghum/millet rotations) under organic amendments promoted gradual SOC accumulation over the simulated period. Integrated cropping systems enhance the continuous input of organic matter through forage or intercrop species, promoting SOC accumulation and offsetting part of the agricultural emissions, while also reducing the need for synthetic fertilizers and mechanized operations, thereby lowering direct and indirect emissions and ultimately resulting in lower net impacts and greater carbon sequestration potential compared with conventional monocultures (Cherubin et al., 2025; Santos et al., 2026).

Cerri et al. (2024) emphasized that conservation practices such as intercropping can storage large quantities of carbon, mitigating GHG emissions while improving soil health and resilience. This underscores the importance of practices that return organic residues to the soil, especially in sandy soils typical of semi-arid regions.

Regarding fertilization, significant contributions to CF from field emissions and input production in all cashew systems were mainly associated with CO_2 and N_2O emissions arising from the production and use of synthetic fertilizers, particularly nitrogen fertilizers, as well as excessive application of organic compounds and high rates of limestone (Figure 8). The production and application of synthetic mineral fertilizers and organic amendments are important sources of GHG emissions, primarily through CO_2 and N_2O release. Considering that the global warming potential of N_2O is 296 times higher than that of CO_2, it is essential to make judicious use of nitrogen fertilizers, including urea and organic amendments (Chopra et al., 2022; Feng et al., 2022).

Although organic fertilizers are often promoted as lower-impact alternatives to synthetic inputs, their use does not guarantee lower GHG emissions. Organic fertilizers also release CO_2 and N_2O during mineralization, and excessive or inefficient applications can substantially increase emissions, as observed in the C1 system, where the compost was used as the sole nutrient source but applied at rates disproportionate to the crop's demand. Therefore, the environmental benefits of organic fertilization depend on the application of inputs in agronomic appropriate doses and the adequacy of nutrient supply to the current needs of the cashew orchard, and not solely on the replacement of synthetic fertilizers (Ding et al., 2013).

Regarding biochar contribution for reducing the carbon footprint of crops, this study showed that its overall benefit depends on the amount used. The amount used in the only system applying it (E2) proved small for offsetting emissions in scope 1 accounting. However, biochar benefits go beyond carbon storage, improving water and nutrient slow release in soil, increasing yield and reducing GHG emissions after fertilization (Gondim et al., 2024; Han et al., 2025). Future studies should assess the benefits of increasing the amount of biochar used in cashew integrated systems, evaluating its effect in yield and CF.

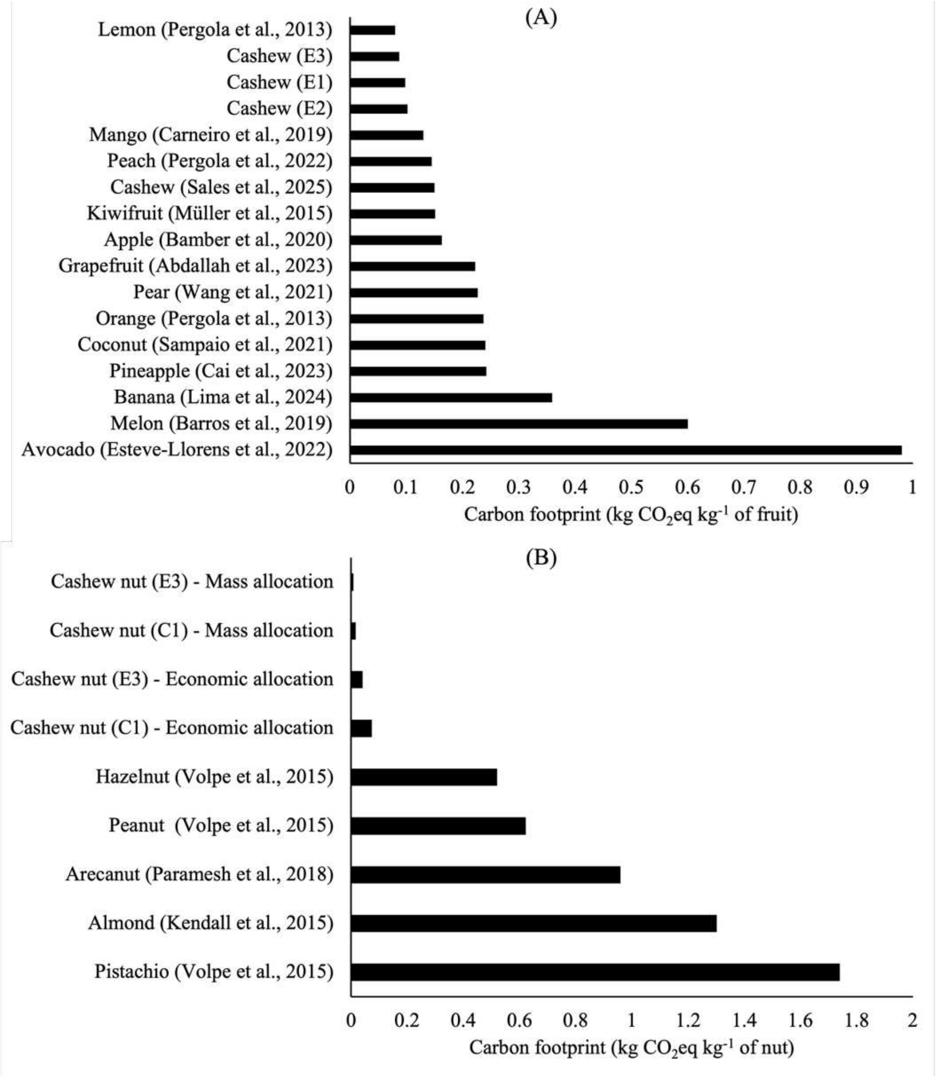
Another strategy to reduce the CF of cashew production is to increase carbon storage in plant biomass. Perennial crops such as cashew and mango can store more aboveground biomass than much of the native Caatinga vegetation, especially under proper management, as discussed by Subedi et al. (2024). Indeed, Carneiro et al. (2019) showed that mango orchard can accumulate up to 47.85 Mg ha^{-1} of carbon in biomass, contributing to CF reduction. However, despite this advantage, biomass accumulation alone is not sufficient to fully offset the emissions associated with agricultural production (Scope 1).

In the commercial orchards analyzed, LUC increased the CF (Table 6 and Figure 8), largely due to the low planting density, which limits the carbon stock in orchard biomass (Figure 5). Sampaio et al. (2021) reported that higher planting densities in coconut orchards substantially enhance carbon sequestration, helping to mitigate climate impacts associated with LUC. However, this raises an important question: what is the optimal balance between increasing tree density boosting biomass carbon stocks and maintaining enough inter row space for annual crops or other practices that also contribute to SOC gains?

In semi-arid rainfed systems, where resilience depends on both biomass and soil organic matter, achieving this balance is essential. Management should aim to maximize biomass carbon storage without compromising practices that increase SOC, since the latter plays a decisive role in offsetting net emissions and effectively reducing the CF.

Globally, several studies have evaluated CF associated with fruit and nut production. Based on data from Subedi et al. (2024) and Volpe et al. (2015), which synthesize results from multiple studies and consider a cradle-to-gate boundary, the mean CF of fruits is estimated at approximately 0.30 ± 0.21 kg CO_2eq kg^{-1} (Figure 10A), while for nuts (Figure 10B), is 1.11 ± 0.55 kg CO_2eq kg^{-1}.

Figure 10. Comparison of the mean values of carbon footprint of (A) fruits and (B) nuts produced in various countries, as reported in different studies.



The CF values of cashew observed in the current study across all production systems (Table 7) are below the mean value for fruits reported in the literature. Except for lemon (0.08 kg CO_2eq kg^{-1}), the CF of cashew from E3 (0.087 kg CO_2eq kg^{-1}) is lower than that of most other fruits. Regarding cashew nuts, both the best-performing system (E3) and the least efficient one (C1) showed substantially lower CF than that reported for other nuts, particularly when mass allocation was applied.

Moreover, the CF of cashew nuts in this study is lower than values reported by Figueirêdo et al. (2016), who estimated impacts of 4.19 and 8.94 kg CO_2eq kg^{-1} for systems with high and low input use, respectively, based on economic allocation. This discrepancy likely arises from differences in modeling approaches. Figueirêdo et al. (2016) assumed that cashew plants would be removed at the end of the orchard's useful life with all wood sold as a coproduct from the system, leading to significant GHG emissions from LUC, which accounted for up to 85% of the CF of cashew nuts.

Although the concept of prospective LCA, as defined by Arvidsson et al. (2024), was adopted, this study has limitations. Background inventories for future input production (inventories) were not used, nor were potential changes in climate conditions that could influence soil carbon dynamics, such as increased temperatures or altered rainfall patterns. Consequently, SOC stock projections were performed assuming that climatic conditions in the next decade will remain similar to current conditions and GHG predictions were based on current climatic conditions, which may under- or overestimate actual future impacts. The absence of these elements underscores a critical area for improvement in future studies, which should integrate future-oriented background inventories with future climate scenarios.

Furthermore, the good performance of the E3 system, although promising, requires extended temporal validation in experimental site. It is also necessary to assess the potential for reducing cashew fertilization due to nutrient supply from inter-row cover crops. Additionally, validation under commercial production conditions is important to confirm the system's effectiveness.

5.4 Conclusion

Prospective RothC modeling proved to be a promising and effective approach for estimating SOC stocks under different agricultural management practices, providing valuable information to enhance SOC accumulation and reduce LUC impacts. Field emissions and input production were the main contributors to GHG emissions in cashew production systems, primarily CO_2 and N_2O, with particularly significant impacts in commercial systems.

The system integrating cashew trees with intercropped forage (E3) showed a substantially lower CF than other systems, representing a notable advancement in the sustainability of cashew cultivation.

Several complementary strategies can support the decarbonization of cashew production. Integrating the orchard with forage or cover crops increases CO_2 capture in biomass and increases the input of organic matter into the soil, promoting the accumulation of SOC and reducing dependence on synthetic inputs. The use of organic compost can also contribute to the reduction of net emissions, if application rates correspond to the crop's demand. Establishing orchards in previously deforested areas further strengthens the carbon balance, avoiding emissions resulting from LUC.

6 CONSIDERAÇÕES FINAIS

Este trabalho contribui para o avanço da avaliação do ciclo de vida e da pegada de carbono em sistemas agrícolas tropicais ao abordar lacunas metodológicas relacionadas à comparação entre diferentes abordagens de quantificação de emissões de gases de efeito estufa. A avaliação de múltiplas metodologias aplicadas à cajucultura brasileira evidenciou que a escolha do método exerce influência direta sobre os resultados obtidos e, consequentemente, sobre a interpretação do desempenho ambiental dos sistemas produtivos.

Os resultados demonstraram elevada variabilidade entre as metodologias analisadas, com destaque para os maiores valores estimados pelos métodos IPCC-Calc e BR-Calc e para os menores valores obtidos pelo Nemecek-Calc. Essa discrepância reforça a necessidade de adoção de abordagens adaptadas às condições regionais, especialmente em sistemas agrícolas tropicais, nos quais fatores como práticas locais de manejo, uso de fertilizantes, corretivos e características edafoclimáticas influenciam de forma significativa as emissões de GEE.

A integração da avaliação da pegada de carbono com a quantificação do carbono na biomassa e a modelagem prospectiva do carbono orgânico do solo pelo modelo RothC ampliou a compreensão da dinâmica do carbono ao longo do ciclo de vida do cajueiro. Os resultados indicaram que as emissões de campo e a produção de insumos constituem as principais fontes de GEE, sobretudo de CO_2 e N_2O, com impactos mais pronunciados em sistemas comerciais. Por outro lado, sistemas diversificados apresentaram maior capacidade de sequestro de carbono na biomassa e no solo.

Destaca-se o desempenho superior do sistema consorciado com forrageira, que apresentou a menor pegada de carbono, evidenciando o potencial de sistemas integrados como estratégia efetiva de mitigação climática. Práticas complementares, como o uso de culturas de cobertura, aplicação racional de compostos orgânicos e a implantação de pomares em áreas previamente desmatadas, mostraram-se promissoras para a redução das emissões líquidas e o aumento do estoque de carbono orgânico.

Por fim, recomenda-se que estudos futuros integrem dados primários e medições diretas para validação dos modelos, bem como a adoção de abordagens híbridas, combinando equações empíricas e modelagem baseada em processos. Essas estratégias podem reduzir incertezas, aumentar a precisão das estimativas e subsidiar políticas públicas mais eficazes para a mitigação das emissões de GEE na agricultura tropical.

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APÊNDICE A — INVENTORIES FROM THE ECOINVENT DATABASE

Inputs	Inventories
Planting	Planting tree {GLO}| market for planting tree | Cut-off, U
Agricultural machinery	Agricultural machinery, unspecified {GLO}| market for agricultural machinery, unspecified | Cut-off, U
Diesel	Diesel, low-sulfur {BR}| market for diesel, low-sulfur | Cut-off, U
Fatty acid methyl ester	Fatty acid methyl ester {BR}| market for fatty acid methyl ester | Cut-off, U
Poultry manure	Poultry manure, fresh {GLO}| market for poultry manure, fresh | Cut-off, U
N	Inorganic nitrogen fertiliser, as N {RoW}| nutrient supply from urea | Cut-off, U
P	Inorganic phosphorus fertiliser, as P_2O_5 {RoW}| nutrient supply from single superphosphate | Cut-off, U
K	Inorganic potassium fertiliser, as K_2O {RoW}| nutrient supply from potassium chloride | Cut-off, U
Monoammonium phosphate	Monoammonium phosphate {RoW}| market for monoammonium phosphate | Cut-off, U
Potassium chloride	Potassium chloride {RoW}| market for potassium chloride | Cut-off, U
Urea	Urea {RoW}| market for urea | Cut-off, U
Fertilizing	Fertilizing, by broadcaster {BR}| fertilising, by broadcaster | Cut-off, U
Pesticide	Pesticide, unspecified {GLO}| market for pesticide, unspecified | Cut-off, U
Harvesting	Combine harvesting {BR}| combine harvesting | Cut-off, U
Limestone	Limestone, crushed, for mill {RoW}| market for limestone, crushed, for mill | Cut-off, U
Gypsum	Gypsum, mineral {RoW}| market for gypsum, mineral | Cut-off, U

APÊNDICE B — INPUT DATA FOR MODELING WITH ROTHC

E1: Cashew monoculture - Growing plants

Months	Temperature (º C)	Rain (mm)	Evaporarion (mm)	FYM (Mg C)	Plant residue (Mg C)	Cover	DPM/RPM
January	27.92	123.45	112.08	0.037	1.445	0.00	0.67
February	27.67	192.57	100.64	0.00	0.00	0.00	0.67
March	27.07	237.48	99.89	0.00	0.00	0.00	0.67
April	27.17	195.65	96.84	0.00	0.00	0.00	0.67
May	27.20	163.95	97.39	0.00	0.00	0.00	0.67
June	26.82	68.53	95.78	0.00	0.00	0.00	0.67
July	26.65	58.55	95.71	0.00	0.00	0.00	0.67
August	27.10	6.47	100.35	0.00	0.00	0.00	0.67
September	27.65	4.83	108.99	0.00	0.00	0.00	0.67
October	28.13	8.33	111.38	0.00	0.00	0.00	0.67
November	28.42	6.98	117.86	0.00	0.00	0.00	0.67
December	28.33	29.48	120.05	0.00	0.00	0.00	0.67

E1: Cashew monoculture - Adult plants

Months	Temperature (º C)	Rain (mm)	Evaporarion (mm)	FYM (Mg C)	Plant residue (Mg C)	Cover	DPM/RPM
January	27.95	162.05	118.65	0.56	6.89	1.00	0.67
February	27.55	165.00	96.68	0.00	0.00	1.00	0.67
March	27.35	253.55	100.35	0.00	0.00	1.00	0.67
April	27.25	159.70	92.25	0.00	0.00	1.00	0.67
May	27.70	171.95	93.23	0.00	0.00	1.00	0.67
June	27.70	51.20	91.20	0.00	0.00	1.00	0.67
July	27.85	197.40	90.38	0.00	0.00	1.00	0.67
August	27.90	21.00	99.15	0.00	0.00	1.00	0.67
September	28.25	5.40	106.73	0.00	0.00	1.00	0.67
October	28.50	6.30	112.80	0.00	0.00	1.00	0.67
November	28.60	3.30	117.83	0.00	0.00	1.00	0.67
December	28.35	197.30	123.83	0.00	0.00	1.00	0.67

E2: Cashew monoculture - Growing plants

Months	Temperature (º C)	Rain (mm)	Evaporarion (mm)	FYM (Mg C)	Plant residue (Mg C)	Cover	DPM/RPM
January	27.92	123.45	112.08	0.037	1.445	0	0.67
February	27.67	192.57	100.64	0	0	0	0.67
March	27.07	237.48	99.89	0	0	0	0.67
April	27.17	195.65	96.84	0	0	0	0.67
May	27.2	163.95	97.39	0	2.955	0	0.67
June	26.82	68.53	95.78	0	0	0	0.67
July	26.65	58.55	95.71	0	0	0	0.67
August	27.1	6.47	100.35	0	0	0	0.67
September	27.65	4.83	108.99	0	0	0	0.67
October	28.13	8.33	111.38	0	0	0	0.67
November	28.42	6.98	117.86	0	0	0	0.67
December	28.33	29.48	120.05	0	0	0	0.67

E2: Cashew monoculture - Adult plants

Months	Temperature (º C)	Rain (mm)	Evaporarion (mm)	FYM (Mg C)	Plant residue (Mg C)	Cover	DPM/RPM
January	27.95	162.05	118.65	0.56	6.89	1	0.67
February	27.55	165	96.675	0	0	1	0.67
March	27.35	253.55	100.35	0	0	1	0.67
April	27.25	159.7	92.25	0	0	1	0.67
May	27.7	171.95	93.225	0	0	1	0.67
June	27.7	51.2	91.2	0	0	1	0.67
July	27.85	197.4	90.375	0	2.955	1	0.67
August	27.9	21	99.15	0	0	1	0.67
September	28.25	5.4	106.725	0	0	1	0.67
October	28.5	6.3	112.8	0	0	1	0.67
November	28.6	3.3	117.825	0	0	1	0.67
December	28.35	197.3	123.825	0	0	1	0.67

C1: Annual crop							
Months	Temperature (º C)	Rain (mm)	Evaporarion (mm)	FYM (Mg C)	Plant residue (Mg C)	Cover	DPM/RPM
January	27.18	294.90	115.67	0.00	0.00	1.00	1.44
February	27.38	188.63	107.55	0.00	0.00	1.00	1.44
March	26.93	351.55	109.99	0.00	0.00	1.00	1.44
April	26.55	435.38	96.30	0.00	0.00	1.00	1.44
May	26.63	232.78	99.71	0.00	0.00	1.00	1.44
June	26.33	144.70	92.36	0.00	1.06	1.00	1.44
July	26.18	99.18	92.55	0.00	0.00	0.00	1.44
August	26.55	30.93	99.09	0.00	0.00	0.00	1.44
September	27.00	0.85	104.18	0.00	0.00	0.00	1.44
October	27.45	11.53	115.35	0.00	0.00	0.00	1.44
November	27.75	11.88	117.88	0.00	0.00	0.00	1.44
December	27.83	30.73	123.39	0.00	0.00	0.00	1.44

C1: Coconut palms							
Months	Temperature (º C)	Rain (mm)	Evaporarion (mm)	FYM (Mg C)	Plant residue (Mg C)	Cover	DPM/RPM
January	27.61	114.63	113.04	0.95	0.589	1.00	1.44
February	27.31	176.34	96.72	0.00	0.00	1.00	1.44
March	27.39	300.53	105.91	0.00	0.00	1.00	1.44
April	27.17	259.01	98.45	0.00	0.00	1.00	1.44
May	27.26	157.49	102.68	0.00	0.00	1.00	1.44
June	26.91	87.11	91.21	0.00	0.00	1.00	1.44
July	26.66	79.60	91.93	0.00	0.00	1.00	1.44
August	26.97	8.59	97.74	0.00	0.00	1.00	1.44
September	27.23	8.27	100.29	0.00	0.00	1.00	1.44
October	27.63	7.26	111.42	0.00	0.00	1.00	1.44
November	27.86	7.81	114.24	0.00	0.00	1.00	1.44
December	27.87	59.01	119.04	0.00	0.00	1.00	1.44

C1: Cashew monoculture - Growing plants							
Months	Temperature (º C)	Rain (mm)	Evaporarion (mm)	FYM (Mg C)	Plant residue (Mg C)	Cover	DPM/RPM
January	27.67	170.10	116.05	0.012	0.62	0.00	0.67
February	27.40	236.73	95.15	0.00	0.00	0.00	0.67
March	26.90	350.70	96.28	0.00	0.00	0.00	0.67
April	27.23	337.67	91.40	0.00	0.00	0.00	0.67
May	27.30	313.63	95.30	0.00	0.00	0.00	0.67
June	26.87	162.10	90.95	0.25	0.00	0.00	0.67
July	26.63	53.27	89.08	0.00	0.00	0.00	0.67
August	27.00	12.60	96.28	0.00	0.00	0.00	0.67
September	27.47	7.70	106.93	0.00	0.00	0.00	0.67
October	27.90	11.37	111.10	0.00	0.00	0.00	0.67
November	28.40	7.23	119.30	0.00	0.00	0.00	0.67
December	28.07	38.20	122.55	0.00	0.00	0.00	0.67

C1: Cashew monoculture - Adult plants							
Months	Temperature (º C)	Rain (mm)	Evaporarion (mm)	FYM (Mg C)	Plant residue (Mg C)	Cover	DPM/RPM
January	27.70	170.10	118.65	0.036	3.49	1.00	0.67
February	27.63	291.80	96.68	0.00	0.00	1.00	0.67
March	27.17	371.10	100.35	0.00	0.00	1.00	0.67
April	27.17	330.97	92.25	0.00	0.00	1.00	0.67
May	27.37	226.00	93.23	0.00	0.00	1.00	0.67
June	27.17	58.83	91.20	0.75	0.00	1.00	0.67
July	27.33	151.87	90.38	0.00	0.00	1.00	0.67
August	27.47	14.13	99.15	0.00	0.00	1.00	0.67
September	27.93	5.37	106.73	0.00	0.00	1.00	0.67
October	28.30	9.50	112.80	0.00	0.00	1.00	0.67
November	28.33	7.57	117.83	0.00	0.00	1.00	0.67
December	28.30	146.73	123.83	0.00	0.00	1.00	0.67

C2: Fellow period							
Months	Temperature (º C)	Rain (mm)	Evaporarion (mm)	FYM (Mg C)	Plant residue (Mg C)	Cover	DPM/RPM
January	27.65	129.20	114.04	0.00	0.00	0.00	0.67
February	27.10	228.45	91.28	0.00	0.00	0.00	0.67
March	27.10	377.65	102.45	0.00	0.00	0.00	0.67
April	27.05	265.90	96.11	0.00	0.00	0.00	0.67
May	27.20	176.90	100.50	0.00	0.00	0.00	0.67
June	27.00	49.60	95.14	0.00	0.00	0.00	0.67
July	26.50	137.75	88.24	0.00	0.00	0.00	0.67
August	26.95	11.25	97.05	0.00	0.00	0.00	0.67
September	27.25	6.40	101.33	0.00	0.00	0.00	0.67
October	27.70	8.50	114.08	0.00	0.00	0.00	0.67
November	28.00	6.40	118.91	0.00	0.00	0.00	0.67
December	27.85	109.00	119.96	0.00	0.00	0.00	0.67

C2: Cashew monoculture - Growing plants							
Months	Temperature (º C)	Rain (mm)	Evaporarion (mm)	FYM (Mg C)	Plant residue (Mg C)	Cover	DPM/RPM
January	27.67	170.10	116.05	0.15	0.39	1.00	0.67
February	27.40	236.73	95.15	0.00	0.00	1.00	0.67
March	26.90	350.70	96.28	0.00	0.00	1.00	0.67
April	27.23	337.67	91.40	0.00	0.00	1.00	0.67
May	27.30	313.63	95.30	0.00	0.00	1.00	0.67
June	26.87	162.10	90.95	0.48	1.82	1.00	0.67
July	26.63	53.27	89.08	0.00	0.00	1.00	0.67
August	27.00	12.60	96.28	0.00	0.00	1.00	0.67
September	27.47	7.70	106.93	0.00	0.00	1.00	0.67
October	27.90	11.37	111.10	0.00	0.00	1.00	0.67
November	28.40	7.23	119.30	0.00	0.00	1.00	0.67
December	28.07	38.20	122.55	0.00	0.00	1.00	0.67

C2: Cashew monoculture - Adult plants

Months	Temperature (º C)	Rain (mm)	Evaporarion (mm)	FYM (Mg C)	Plant residue (Mg C)	Cover	DPM/RPM
January	27.70	170.10	118.65	0.45	1.93	1.00	0.67
February	27.63	291.80	96.68	0.00	0.00	1.00	0.67
March	27.17	371.10	100.35	0.00	0.00	1.00	0.67
April	27.17	330.97	92.25	0.00	0.00	1.00	0.67
May	27.37	226.00	93.23	0.00	0.00	1.00	0.67
June	27.17	58.83	91.20	1.43	1.82	1.00	0.67
July	27.33	151.87	90.38	0.00	0.00	1.00	0.67
August	27.47	14.13	99.15	0.00	0.00	1.00	0.67
September	27.93	5.37	106.73	0.00	0.00	1.00	0.67
October	28.30	9.50	112.80	0.00	0.00	1.00	0.67
November	28.33	7.57	117.83	0.00	0.00	1.00	0.67
December	28.30	146.73	123.83	0.00	0.00	1.00	0.67

APÊNDICE C — EQUATIONS, EMISSION FACTORS, AND REFERENCES FOR CALCULATING EMISSIONS FROM AGRICULTURAL PRODUCTION IN THE CROPPING SYSTEMS UNDER STUDY

Land Use Change (LUC)

For the land use change emissions, it was assumed that 8% is harvested - not considered in the emissions - 20% is burned and 72% of the biomass suffers decay (Nemecek et al. 2016).

1.1 CO_2 emissions from biomass decay (IPCC 2019)

$$\boldsymbol{E = \frac{(A * (C - avAgri))}{20} * \frac{44}{12}}$$

Where:

- **E** - Carbon emission (t CO_2. ha^{-1});
- **A** - Area transformed (ha);
- **C** - Carbon stock in biomass and dead organic matter (t C. ha-1);
- **avAgri** - Carbon stock in the crop area (t C.ha-1).

1.2 Carbon in soil (IPCC 2019)

$$\boldsymbol{Es = (A * \Delta Csoil * \frac{44}{12})}$$

$$\boldsymbol{\Delta Csoil = Csoil * \frac{[fc(t_0) - fc(t_f)]}{20}}$$

$$\boldsymbol{fc\ (t) = fUT * fRG * fI}$$

Where:

- **Es** - net carbon emission (kg CO_2);
- **A** - area transformed (ha);
- **Csoil** - carbon stock in the soil (kg $C.ha^{-1}$);
- **fc (t)** - carbon stock change factor on a period *t* (dimensionless);
- ***fUT*** **-** stock change factor due to LUC (dimensionless);
- ***fRG*** - stock change fator associated with management practices (dimensionless);
- ***fI*** - stock change associated to input of organic matter (dimensionless).

1.3 CO_2, N_2O, CH_4, NO_X and CO emissions from biomass burning (IPCC 2019)

$$\boldsymbol{E\_burning = A * M_b * C_f * G_{ef}}$$

Where:

- **E_burning** - gas emission from biomass burning (kg gas ha^{-1});
- **A** - burned area (ha);

- **M_b** - mass of fuel available for combustion (ton.ha^{-1});
- **C_f** - combustion factor (dimensionless);
- **G_{ef}** - emission factor of the gas (g gas.kg fuel^{-1}).

1.4 N_2O from organic matter mineralization (IPCC 2019)

Direct emissions

$$\boldsymbol{Emission\_N - N_2O = \left((F_{SOM}) * EF1\right) * \frac{44}{28}}$$

$$\boldsymbol{F_{SOM} = [\left(\Delta C_{soil} * \frac{1}{R}\right) * 1000]}$$

Where:

- **Emission_N-N_2O** - Direct emissions from mineralization of organic matter (kg N_2O.ha^{-1})
- **F_{SOM}** - amount of N mineralized in soil because of change in land use (kg N. ha^{-1});
- **EF1** - emission factor for N_2O (dimensionless);
- **F_{SOM}** - amount of nitrogen mineralized from land use change (kg N);
- **ΔC_{soil}** - carbon stock change due LUC (kg C) (see topic 1.2)
- **A** - area transformed (ha)
- **R** - C:N - Carbon and Nitrogen ratio of soil organic matter (dimensionless).

Indirect emissions from leaching and runoff (IPCC 2019)

$$\boldsymbol{N - N_2O = \left((\ F_{SOM}) * Frac_{leach-(H)} * EF_5\right) * \frac{44}{28}}$$

Where:

- **N_2O-N** - amount of N2O emission from leaching and runoff of N additions to soils (kg N_2O.ha^{-1});
- **F_{SOM}** - amount of N mineralized because of land use changes (kg N.ha$^{=1}$);
- **$Frac_{Leach-(H)}$** - fraction of all N that is lost through leaching and run off (dimensionless);
- **EF_5** - emission factor (dimensionless).

1.5 NO_x emission to air due to organic matter mineralization (Nemecek and Schnetzer 2012)

$$\boldsymbol{NO_x = 0.21 * \ N_2O}$$

Where:

- **N_2O** - total amount of N_2O emitted (kg N_2O. ha^{-1});
- **NO_x** - amount of NO_x emitted to air (kg NO_x. ha^{-1}).

Crop production field emission

1.6 CO_2, CH_4 and N_2O emissions from fuel burning (IPCC, 2019)

$$\boldsymbol{Emission_i = V * d * NCV * EF_i}$$

Where:

- ***Emission$_i$*** - emission of i (t CO2.ha^{-1});
- ***i*** - GHG (CO_2, CH_4 e N_2O);
- ***V*** - fuel volume (L. ha^{-1});
- ***D*** - fuel density (Kg.L^{-1});
- ***NCV*** - Net calorie value (TJ.Kg^{-1});
- ***EFi*** - Emission factor to GHG i (kg.TJ^{-1}).

1.7 NOx emissions to air due fertilizer application (Nemecek et al. 2015)

$$\boldsymbol{NOx = 0.012 * N}$$

Where:

- **NOx** - nitrogen oxides emissions from nitrogen fertilizers use (kg NO_2.ha^{-1});
- **N** - total input of nitrogen from fertilizers (kg N.ha^{-1}).

1.8 NH_3 emissions to the air from applied mineral fertilizers (Nemecek & Schnetzer 2012)

$$\boldsymbol{NH_3 - N_{min} = \sum_{i=1}^{N} \left(m_{ferti_{i-j}} * EF_i\right) * \frac{17}{14}}$$

Where:

- $\boldsymbol{NH_3 - N_{min}}$ - amount of ammonia emitted from mineral fertilizer (kg NH3.ha^{-1});
- $\boldsymbol{m_{ferti_{i-j}}}$ - amount of mineral fertilizer (kg. ha^{-1});
- $\boldsymbol{EF_i}$ - Emission factor for NH_3;
- **i** - fertilizer type;
- **j** - region.

1.9 Emissions of N_2O to the air (IPCC 2019)

$$\mathbf{N2O = 44/28 * (0.01\ (N_{tot} + N_{cr}) + 0.01 * 14/17 * NH_3 + 0.0075 * 14/62 * NO_3^-)}$$

Where:

- **N_2O** - dinitrogen monoxide releases to air (kg N_2O/ha);
- **Ntot** - total nitrogen in mineral and organic fertilizers (kg N.ha^{-1});
- **Ncr** - nitrogen contained in the crop residues (kg N.ha^{-1});
- **NH_3** - losses of nitrogen in the form of ammonia (kg NH_3.ha^{-1}) – previous calculations – see *2.2.*
- **NO_3^-** - losses of nitrogen in the form of nitrate (kg NO_3^-.ha^{-1}) – previous calculations – see *2.3.*

1.10 Release of Fossil CO2 from lime applications (IPCC 2019)

$$\boldsymbol{CO2 - lime = m_{limestone} * EF1 + m_{dolomite} * EF2}$$

Where:

- **CO_2-lime** - emission of fossil CO_2 to air (kg CO_2.ha^{-1});

- $\boldsymbol{m_{limestone}}$ - amount of limestone input to soil (kg.ha^{-1});
- $\boldsymbol{EF1}$ - emission factor for limestone (kg CO_2-C/kg);
- $\boldsymbol{m_{dolomite}}$ - amount of dolomite input to soil (kg.ha^{-1});
- $\boldsymbol{EF2}$ - emission factor for dolomite (kg CO_2-C/kg).

1.11 CO_2 emissions from urea use (IPCC 2019)

$$\boldsymbol{Emiss\text{õ}es\ C - CO_2 = (M * EF) * \frac{44}{12}}$$

Where:

- **Emissões C- CO_2** - CO_2 emissions from urea application (kg CO_2.ha^{-1});
- **M** - amount of urea (kg N.ha^{-1});
- **EF** - emission factor for CO_2 from urea use (kg CO_2/kg N).

APÊNDICE D — INVENTORY OF CASHEW ORCHARDS STUDIED (LIFE CYCLE OF 10, 20 AND 30 YEARS)

		Production systems														
		E1			E2			E3			C1			C2		
Inventory	Unit	Ages of the orchards (Years)														
		10	20	30	10	20	30	10	20	30	10	20	30	10	20	3
Transformed area	ha	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Product																
Cashew	t	104.7	364.5	624.3	127.9	394.3	772.6	127.9	394.3	772.6	53.3	106.6	159.9	36.04	72.1	108
Inputs																
Limestone	kg	2900	4700	5900	2900	4700	5900	2900	4700	5900	5346.2	10692	16038.5	13165	26330	394
Gypsum	kg	-	-	-	-	-	-	-	-	-	1960	3920	5880	7959	15918	238
NPK	kg	-	-	-	915.2	3203.2	5491.2	-	-	-	456.8	913.5	1370.3	1755.9	3511.9	526
Urea	kg	1175.2	3567.2	5959.2	1497.6	4201.6	6905.6	1073.3	2146.6	3219.8	-	-	-	1000	2000	300
Monoammonium phosphate	kg	-	-	-	-	-	-	-	-	-	-	-	-	457.3	914.5	137
Simple superphosphate	kg	2151.8	4648.8	7144.8	-	-	-	1495.6	2991.1	4486.7	-	-	-	-	-	-
Potassium chloride	kg	507.5	1339.5	2171.5	368.7	645.7	922.7	414.6	984.2	1483.6	-	-	-	1000	2000	300
Composting	kg	-	-	-	51200	102400	153600	51200	102400	153600	49600	99200	148800	95294	190588	2858
Poultry litter	kg	-	-	-	-	-	-	-	-	-	1600	3200	4800	20000	40000	600
Pesticide	kg	121.3	242.6	363.8	121.3	242.6	363.8	121.3	242.6	363.8	126.9	253.9	380.9	166.3	332.6	498
Biochar	kg	-	-	-	104	104	104	104	104	104	-	-	-	-	-	-
Outputs																

GHG Emissions																
CO_2	kg	2531.7	5717.24	8638.7	2853.47	6351.64	9585.08	2429.17	4256.94	5899.29	1589.58	3094.57	4599.74	4790.78	9497.06	1420
N_2O	kg	29.46	74.88	112.32	52.14	114.37	156.41	33.42	94.81	148.78	28.16	52.84	89.14	38.85	94.57	211.
CH_4	kg	0.172	0.344	0.516	0.191	0.381	0.569	0.191	0.381	0.569	0.234	0.445	0.669	0.256	0.524	0.7