Sustainable Production and Consumption 49 (2024) 163–178

Contents lists available at ScienceDirect

Sustainable Production and Consumption

journal homepage: www.elsevier.com/locate/spc

Using miscanthus and biochar as sustainable substrates in horticulture: An economic and carbon footprint assessment of their primary and cascading value chains

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ARTICLE INFO

Editor: Dr. Cecile Chéron-Bessou

Keywords:
Life cycle assessment
Life cycle costing
Horticultural substrates
Carbon removal
Biochar
Cascading value chains

ABSTRACT

Conventional substrates like peat, stone wool and coconut coir are responsible for high greenhouse gas emissions in the horticultural sector, necessitating low-emission and cost-efficient alternatives. Herein, using miscanthus and biochar as substrate components as well as in cascading substrate application can be alternative practices in a sustainable bioeconomy. However, the carbon footprint and economic impacts of these practices in relation to crop yields have not yet been investigated. Hence, we combined life cycle carbon footprint assessment and costing to analyze the Global Warming Potential and value chain costs of horticultural substrates in tomato cultivation in North-Rhine Westphalia. We conducted a comparison between conventional substrates (peat, stone wool, and coconut coir) and single use and cascading miscanthus-based substrates with and without 1–2 % biochar addition of the miscanthus mass. Also, a subsequent scenario analysis was carried out to examine alterations in inputs and costs.

Our results demonstrate that miscanthus-based substrates are climate-friendly and low-cost alternatives to the conventional practices. Switching to miscanthus-based substrates results in more emission savings than other input scenarios investigated. Additionally, incorporating biochar and adopting cascading methods contribute to lower emissions. Notably, biochar has the most significant impact, as its amount correlates with higher emission reductions. Additionally, costs for cascading miscanthus-based substrates are lower compared to conventional substrates. Overall, there is only a slight variance in costs between conventional and miscanthus-based substrates. However, with the introduction of carbon emission pricing and carbon removal certificates, miscanthus-based and biochar-containing substrates may emerge as more cost-efficient alternatives. Thus, by advancing financial instruments on carbon emissions and removal, introducing cascade use within and beyond the horticulture sector, and supporting cultivation of sustainable biomasses, miscanthus and biochar can effectively contribute to the development of a sustainable bioeconomy.

1. Introduction

The European horticultural substrate industry represents a large industry with an annual turnover of 1.3 billion Euros (GME, 2023). In Europe, 34.6 million cubic meters horticultural substrates are used every year, 75.1 % of which are peat-based. Herein, Germany is the largest peat producer in Europe (Hirschler et al., 2022), contributing almost a quarter to European substrate production (IVG and GGS, 2022).

Conventional horticultural substrates (i.e., peat, stone wool, and coconut coir) are relatively cheap (Maher et al., 2008), but often emit large amounts of greenhouse gas (GHG) emissions, leading to a high Global Warming Potential (GWP) (Peano et al., 2012; Stucki et al., 2019; Vinci and Rapa, 2019). Comparing commonly used horticultural substrates, peat-based substrates exhibit the highest GWP (Peano et al., 2012). The extraction of peat is closely linked to climate change (Cleary et al., 2005), resulting in approximately 12 million tons CO_2 eq emissions per year in the EU (UNFCCC, 2021). Other conventional substrates, such as coconut coir and stone wool, are also associated with high GWP. For coconut coir, long-distance transport and processing coconut husks can lead to large GHG emissions (Paoli et al., 2022). Also, the manufacture and recycling of stone wool, which entails melting limestone, cokes, and diabase at 1500 °C (Grunert et al., 2016), contribute

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https://doi.org/10.1016/j.spc.2024.06.016
Received 8 March 2024; Received in revised form 11 June 2024; Accepted 13 June 2024
Available online 19 June 2024

substantially to GHG emissions due to the considerable consumption of fossil energy (Nerlich and Dannehl, 2021).

Given this context, the regulations within the horticultural sector are poised to become more stringent. On the European level, net GHG-neutrality is required by 2035 in the agriculture, forestry, and land use sector (Hirschler et al., 2022). Hence, the German government has decided to include peat extraction in their mitigation targets, including a 100 % peat reduction in the hobby market by 2026 and a large reduction in the commercial market by 2030 (Hirschler et al., 2022). Therefore, the potential and the need are high for climate change mitigation in the German horticultural sector to realize a carbon-neutral or -negative bioeconomy.

Besides the environmental concerns, future development of conventional substrates' availabilities and prices is uncertain (Blok et al., 2021; Toboso-Chavero et al., 2021). For instance, there are suggestions to include peat in carbon pricing schemes (Hirschler et al., 2022; Stepanyan et al., 2023), which could lead to a sharp increase in peat prices (27 €/m^3 peat increase if carbon price is 100 €/Mg CO_2 eq.) (Isermeyer et al., 2019). Additionally, global demand for substrates is anticipated to rise quickly due to the increased production of crops in soilless growing systems (Blok et al., 2021). In the case of coconut coir, increased demand for substrates in the Asian market and other competing applications may limit accessibility (Blok et al., 2021; Hirschler et al., 2022). Thus, decision makers and substrate producers are looking for alternative substrate management options (Blok et al., 2021; BMEL, 2022).

A significant contribution to a sustainable bioeconomy can be cascading resource use (BMBF, 2014; Fritsche et al., 2020), providing an opportunity to significantly reduce environmental impacts and growing costs (Montero et al., 2009). In this context, findings on yield response differ, with most studies reporting only minor deviations between new and reused substrates. Although some studies concluded dissimilar outcomes (Diara et al., 2012), more recent studies demonstrated that reusing organic substrates is possible (Vandecasteele et al., 2023, 2020). Cascading use displays economically and environmentally promising options beyond horticultural applications. Spent substrates can be reused as nutrient-rich soil amendments, improving soil properties and sequestering carbon (Vollmer et al., 2022). Alternatively, they can also be incinerated for energy generation (Kraska et al., 2018).

Next to cascading use, applying alternative substrates can present a sustainable practice. Herein, substrate alternatives should fulfill three requirements; reliable and consistent yield performance, affordability, and minimal environmental impacts (Barrett et al., 2016; Gruda, 2019; Schmilewski, 2017). Several studies indicate that miscanthus, as a horticultural substrate, yields similar crop production to conventional substrates, thus positioning it as a suitable alternative to peat, coconut coir, and stone wool (Kraska et al., 2018; Nguyen et al., 2022, 2021).

Miscanthus, a perennial rhizomatous C4 grass, originates from East Asia but demonstrates high productivity in temperate zones like Europe as well. Herein, its cultivation requires low agricultural inputs and exerts low environmental impacts (Clifton-Brown et al., 2004; Lewandowski et al., 2000). Additionally, miscanthus can be grown on ecological priority areas, for which farmers in the EU receive subsidies (Kreuzer et al., 2023). Miscanthus cultivation covered 4600 ha in Germany in 2020 (BMEL, 2020). From 2015 to 2023, the miscanthus cultivation area in North Rhine-Westphalia increased from 618 to 670 ha (LWK NRW, 2023a). Even though the cultivation area increased by 8.4 %, miscanthus still covers only a minor fraction of the total arable land in Germany (Statistisches Bundesamt, 2022),

Another means of promoting a sustainable bioeconomy is the utilization of biochar (Ok and Tsang, 2022). Biochar was found to be a suitable biomass carbon removal and sequestration technique, sequestering up to 3.3 Mg CO_2 eq./Mg biochar (Dees et al., 2023). Particularly when applied to poor and acidic soils, biochar can benefit yields and soil organic carbon (Xu et al., 2021). In terms of the production process, it is produced by heating biomass or waste materials in an oxygen-reduced process to retrieve a solid and carbon-rich material (i.e. pyrolysis) (Zhang et al., 2019). The common process for biochar production is slow pyrolysis, where biomass is heated to temperatures between 450 and 650 °C at heating rates between 0.01 and 2 °C/min (Sohi et al., 2009). Besides biochar as a main product, the co-products of the pyrolysis process offer high potentials to replace fossil resources and thus limit global warming to 1.5 degrees (Werner et al., 2018). The study of (Woolf et al., 2010) estimates that biochar can reduce more than one tenth of anthropogenic GHG emissions without threatening soils, biodiversity, and food security. Currently, the biochar market is characterized by fluctuating prices (Haeldermans et al., 2020) and lack of commercialization (McGlashan et al., 2012). However, incorporating biochar in carbon pricing or carbon sequestration certification schemes can enhance its economic viability (Galgani et al., 2014; Wurzer et al., 2022).

Among different biochar applications, horticultural use of biochar has one of the highest GHG emission saving potentials (Azzi et al., 2022). This is because (a) substrates enriched with biochar can partly replace conventional carbon-intensive substrates (Azzi et al., 2022; Moelants et al., 2021), (b) biochar production can yield renewable energy when combusting the pyrolysis gas generated during the process, and (c) biochar sequesters carbon in the long-term when, for instance, applied to soils (Fryda et al., 2019). Biochar created from miscanthus also qualifies for permanent carbon sequestration when used as soil amendment (Rasse et al., 2017). Thus, as a low-input and high-yielding crop, miscanthus is a highly suitable biochar feedstock.

Despite the benefits of biochar and miscanthus, substrate alternatives have not yet gained widespread commercial adoption. One contributing factor is the continued abundance of inexpensive, high-quality conventional substrates, which makes replacing them challenging (Moelants et al., 2021). Additionally, other obstacles arise from the oversight of several crucial aspects necessary for successful implementation. Firstly, the relevant studies in the literature have focused mainly on the environmental aspects rather than crop performance and prices. Secondly, there is a variation in the evaluation procedures among substrates, which impedes comparability. Thirdly, the regulatory conditions and substrate availability were overlooked. Thus, high costs, uncertain performance, and regulatory barriers have diminished the commercial adoption of alternative substrates (Barrett et al., 2016; Hirschler et al., 2022).

Against this background, the objective of this paper is to study the value chains of horticultural substrates, biochar, and cascading applications from an interdisciplinary perspective. Moreover, the research aims at investigating the production and use of horticultural substrate as lever for climate change mitigation and a sustainable bioeconomy. Herein, the analysis aims at illustrating the trade-offs between economic profitability and climate change mitigation in relation to crop yield performance. This objective is reflected in the main research question; how do primary and cascading value chains of miscanthus and miscanthus biochar perform in terms of GWP and costs, compared to conventional substrates? The study targets decision makers as the presented assessments can help them in deriving strategies for promoting alternative substrates, such as initiating subsidies for farmers cultivating renewable resources and introducing carbon certification schemes. The research also addresses industry stakeholders, such as producers of growing media and horticultural practitioners (e.g., farmers).

Considering a full life cycle perspective for practitioners is crucial as decisions on adopting an alternative substrate are often based on secondary costs (Barrett et al., 2016). Also, considering the economic and environmental dimensions simultaneously should help the decision maker to select the optimum pathway (Dutta and Raghavan, 2014). Herein, tomato production in the German federal state of North Rhine-Westphalia has been selected as a representative case study, given its status as the state with the largest tomato cultivation area (yield in 2022 ≈ 15,500 tons) (LWK NRW, 2023b; Statistisches Bundesamt, 2023). Hence, this selection enables the extension of the results to other regions and horticultural crops. Tomato is also the leading vegetable crop in the

EU, yielding over 18 million tons annually and contributing one fifth to the total turnover of vegetable production (De Cicco, 2017; European Commission, 2022a).

2. Literature review

Many studies have used Life Cycle Costing (LCC) and carbon footprint (CF) to analyze the economic performances and GWP of horticulture substrates (Table 1). Most of the relevant environmental analyses assessed GWP using either mass or volume as the functional unit. These assessments indicated that the GWP was generally higher for conventional substrates like peat, stone wool, and coconut coir, compared to substrate alternatives. For example, the studies of (Eymann et al., 2015; Peano et al., 2012; Stucki et al., 2019) demonstrated that peat had a higher GWP than alternative substrates. Also, the analyses of (Peano et al., 2012) found that alternative substrates (perlite, bark, wood fibers, and rice hulls) generally result in lower GWP than peat and stone wool but display comparable emissions to coconut coir.

In (Eymann et al., 2015) and (Stucki et al., 2019), GWP from soilless substrates were the highest for peat, followed by green compost and coconut coir. Additionally, biochar GWP was either similar to coconut coir when made from marketable wood or much lower when pyrolyzed from waste wood. The lowest GWP was observed for wood fibers, miscanthus, reed, flax shives, peat moss cultivation, hemp fibers, and grain husks (Eymann et al., 2015; Stucki et al., 2019).

However, some studies showed different trends, which can be attributed to the system boundaries and methodological choices. The study of (Toboso-Chavero et al., 2021) displayed higher GWP for perlite than for peat, which was attributed to high transport emissions. Other studies (Peano et al., 2012; Vecchietti et al., 2013) concluded that green compost causes similar or slightly higher GWP than peat, mainly due to uncertainties and emission-intensive composting processes. The studies of (Paoli et al., 2022; Vinci and Rapa, 2019) also found that coconut coir has the highest GWP in their analyses. Herein, they considered coconut coir as a by-product rather than a waste, with the high emissions being linked to the intensive use of fertilizers in coconut cultivation (Paoli et al., 2022). Although these studies are insightful for some stakeholders along the value chain (e.g., substrate producers), they are not comprehensive enough as they relate results to substrate weight or volume. Relating results to yields, however, is indispensable for evaluating the entire value chain so that the service provided by the substrate is assessed.

On the other side, studies correlating the CF results to the yield as a functional unit, provided obscure results when conventional substrates were partially substituted with novel alternatives. In a study on lemon production (Hernández et al., 2022), the lowest GWP for one kilogram of lemons was observed when the substrate consisted of equal shares of port sediments and peat. Nonetheless, the impact of port sediments could not be clearly deduced, as both lower and higher shares of port sediment increased the GWP. In a relevant study on strawberry cultivation (Legua et al., 2021), GWP increased along with the amount of port sediments replacing peat, since the port substrate resulted in yield reductions. Thus, this ambiguity calls for a consistent approach and comprehensive assessment, relating life cycle analyses to yields so that also the substrates' productivity can be incorporated in the evaluation.

Additionally, there is an obvious shortage of studies that address economic performance, as only a few relevant ones have been identified. The comparative analysis of (Hernandez-Apaolaza et al., 2005) indicated that substrates containing waste and alternatives materials like pine bark are cheaper, compared to substrates containing conventional substrates like coconut coir. The paper of (Dorr et al., 2017) focused on rooftop farming in France. Their findings indicate that the substrates composed of compost and wood chips have superior economic performance and CF compared to conventional potting soil, which typically contain composted bark and peat moss. For the Italian market, sand was found a suitable substrate since costs and GWP are low, as presented in

Table 1
Overview of studies comparing carbon footprint and/or economic impacts of different soilless horticultural substrates. Substrates covered by this study are underlined. CF = Carbon Footprint, LCC = Life Cycle Costing, GWP = Global Warming Potential.

Study	Soilless substrates examined	CF	LCC	Functional unit based on	Main findings for comparative substrate assessments
Dorr et al. (2017)	compost and wood chip mix, conventional potting soil (composted bark and peat moss)	x	x	yield	GWP and costs: conventional potting soil > compost and wood chip mix
Eymann et al. (2015)	peat, green compost, wood fibers, bark compost, rice hulls, coconut coir, xylite, soil	x		mass/ volume	GWP: peat > green compost > coconut coir > other
Fryda et al. (2019)	peat, biochar	x		energy	GWP: peat > biochar
Hernández et al. (2022)	peat, port sediments and mixtures thereof	x		yield	GWP: port sediment/peat unequal mixtures > port sediment/peat 50:50 mixtures
Hernandez-Apaolaza et al. (2005)	pine bark, coconut coir, sewage sludge and mixtures thereof	x	x	mass/ volume	GWP and costs: conventional substrates (e.g., coconut coir) > alternative mixtures (e.g., including bark)
Legua et al. (2021)	peat, port sediments and mixtures thereof	x		yield	GWP: higher peat/lower port sediment shares > lower peat/ higher port sediment shares
Paoli et al. (2022)	peat, coconut coir, stone wool	x		mass/ volume	GWP: coconut coir > stone wool > peat
Peano et al. (2012)	bark, coconut coir, green compost, stone wool, black peat, white peat, perlite, rice hulls, wood fibers	x		mass/ volume	GWP: peat ≈ green compost > stone wool > coconut coir ≈ other
Stucki et al. (2019)	peat, biochar-compost, biochar from marketable and waste wood, hemp fibers, flax shives, miscanthus, grain husks, peat moss (cultivated)	x		mass/ volume	GWP: peat > green compost > coconut coir ≈ biochar (marketable wood) > biochar (waste wood) > other
Toboso-Chavero et al. (2021)	perlite, peat	x		mass/ volume	GWP: perlite > peat
Torrellas et al. (2012b)	stone wool, perlite	x	x	yield	Substrates not comparable, different agricultural systems analyzed
Torrellas et al. (2013)	stone wool, perlite	x		yield	Substrates not comparable, different

(continued on next page)

Table 1 (*continued*)

Study	Soilless substrates examined	CF	LCC	Functional unit based on	Main findings for comparative substrate assessments
					agricultural systems analyzed
Vecchietti et al. (2013)	peat, green compost, draining material and diff. mixes thereof	x		mass/ volume	GWP: green compost mixtures > peat mixtures
Vinci and Rapa (2019)	peat, stone wool, coconut coir, perlite, bark, sand, vermiculite	x	x	mass/ volume	GWP: coconut coir > bark > stone wool > vermiculite > peat > other Costs: peat > stone wool > bark > vermiculite > perlite > coconut coir > other

(Vinci and Rapa, 2019). Herein, the study highlighted the trade-offs associated with conventional substrates; peat exhibited high costs with relatively low GWP, coconut coir had low costs but high emissions, and stone wool entailed comparatively high costs and GWP.

While these studies provide valuable insights, potential combinations of substrates including miscanthus and biochar are often disregarded, and there is also a notable absence of analyses on substrate cascades. While there are studies centered on circular substrate applications in horticulture (Dunlop et al., 2015; Vandecasteele et al., 2023, 2020), they mainly focus on the plant performance, rather than including economic and environmental aspects. Even though a few studies explored and compared scenarios including post-use-phase valorization such as incineration and soil application (Fryda et al., 2019; Gievers et al., 2021), none of them regarded multi-use cycles within horticultural application. Cascading, however, offers the opportunity to more sustainable substrate value chains (Montero et al., 2009). Thus, there is a need for a combined CF and cost analysis specifically for promising substrate alternatives and different substrate cascades.

In tomato production, available CF and LCC studies do not primarily focus on the distinct CF of different substrates. The extensive review of (Torres Pineda et al., 2021) found that three quarters of studies disregarded substrates entirely (e.g., (Bosona and Gebresenbet, 2018; Maham et al., 2020)). Also, studies that considered substrates often did not vary (Antón et al., 2012; Torrellas et al., 2012a) or specify the substrate type (Sanyé-Mengual et al., 2015). If studies' scenarios covered various substrates, the horticultural production systems differed substantially, inhibiting meaningful substrate-based comparisons (Torrellas et al., 2013, 2012b). Therefore, there is a need for studies that explore different substrate scenarios while maintaining the same horticultural production system, in order to generate meaningful economic and CF analyses.

Hence, this study aims at filling these research gaps by addressing the CF and economic performance as well as considering miscanthus and miscanthus biochar-containing substrates and possible cascading. We also relate assessment results to crop yields as explained in the methodology in the following chapter.

3. Methodology

We conduct an integrated attributional life cycle-based approach for CF and LCC to assess the sustainability of miscanthus and biochar as substrate components. According to the guidelines provided by (Langhorst et al., 2022), this study considers both economic assessment and GWP analysis across all phases of life cycle assessment, i.e. goal and scope definition, life cycle inventory, impact assessment and interpretation. Herein, we assume stable conditions for the CF and LCC, opting for the reference year 2020 to avoid any negative effects stemming from the Ukraine war and the COVID-19 pandemic on costs, similar to (Schulte et al., 2021).

As shown in Fig. 1, our methodological framework comprises the following steps: Firstly, the required data is collected from experiments, ecoinvent 3.9 (Wernet et al., 2016), literature, governmental and industry institutions as well as from experts. Secondly, this data is then aggregated into emission, activity, and cost datasets. For the CF analysis, we combine emission and activity data. We use the impact category Global Warming Potential (GWP IPCC 2013 100a), following the ISO standards of life cycle assessment (ISO, 2006a, 2006b) and GWP calculations (ISO, 2018). We also consider specific guidelines developed for environmental substrate assessments (BSI, 2012; GME, 2021). The LCC is conducted according to (ISO, 2017; Swarr et al., 2011), using € 2020 present value. For CF and LCC, we use openLCA Version 2.0 (GreenDelta GmbH, 2023) and MS Excel (Microsoft Corporation, 2022) as software. Finally, scenario analyses are performed to enhance the evaluation of the findings.

3.1. Goal and scope

The study's objective is to compare conventional and alternative horticultural substrate value chains by integrating CF and LCC. Conventional substrates include peat, stone, wool, and coconut coir, while alternative substrates comprise novel options such as new and cascading miscanthus with or without biochar additions. Except for cascading miscanthus substrates, all substrates are single use. Herein, we evaluate GWP and costs while taking yield into account to identify potential trade-offs.

The functional unit (FU) is defined as 1 Mg tomatoes, with the corresponding reference flow being the mass/volume of substrate required to produce a yield of 1 Mg tomatoes. As the substrate's function and effectiveness can differ, it is crucial to regard the service of crop production as FU (Peano et al., 2012). For instance, FUs relating to the mass or volume of substrates can create skewed results due to different substrate amounts required per growing bag, different bulk densities, and different effects on crop productivity. Therefore, our yield-oriented FU incorporates the substrate's impact on the service it should provide (i.e. effective crop production). This facilitates the analysis of trade-offs between costs and GWP associated with crop yields. Additionally, this FU enables a consistent comparison across different substrates.

In terms of region of interest, the study is carried out for the German federal state of North-Rhine Westphalia. Similar to other studies (Fryda et al., 2019; Peano et al., 2012), single use substrates are replaced for each cultivation period, except for the cascading value chains. To ensure consistency in comparing single use and cascading value chains, we consistently examine two grow cycles. To consider the multiple stakeholders along the value chain (decision makers, farmers, growing media producers), we apply a comprehensive life cycle (cradle-to-grave) perspective within CF and LCC. Consequently, the system boundary is the same for both CF and LCC and includes the entire substrate life cycle; i.e. production, packaging and storage, tomato cultivation, end-of-life treatment, transportation and (potential) cascading use of substrates within horticultural application (Fig. 2).

For consistency, the study only regards activities directly linked to the substrate value chain. In tomato cultivation, agricultural inputs crucial to the cultivation process (fertilizers, herbicides, pesticides and irrigation water) are regarded, aligning with the studies of (Hernandez-Apaolaza et al., 2005; Legua et al., 2021). These inputs are assessed within the framework of the ecoinvent 3.9 tomato cultivation scheme optimized for stone wool but applicable across all substrate scenarios. Consequently, inputs may undergo modifications if cultivation schemes

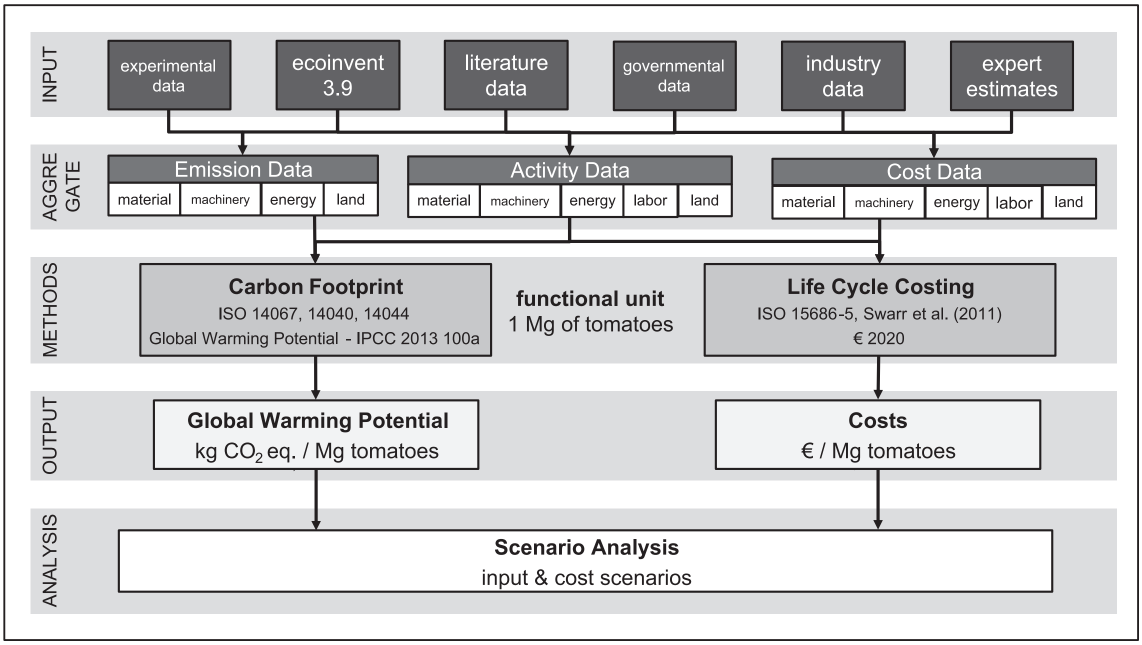

Fig. 1. Methodological framework, own visualization.

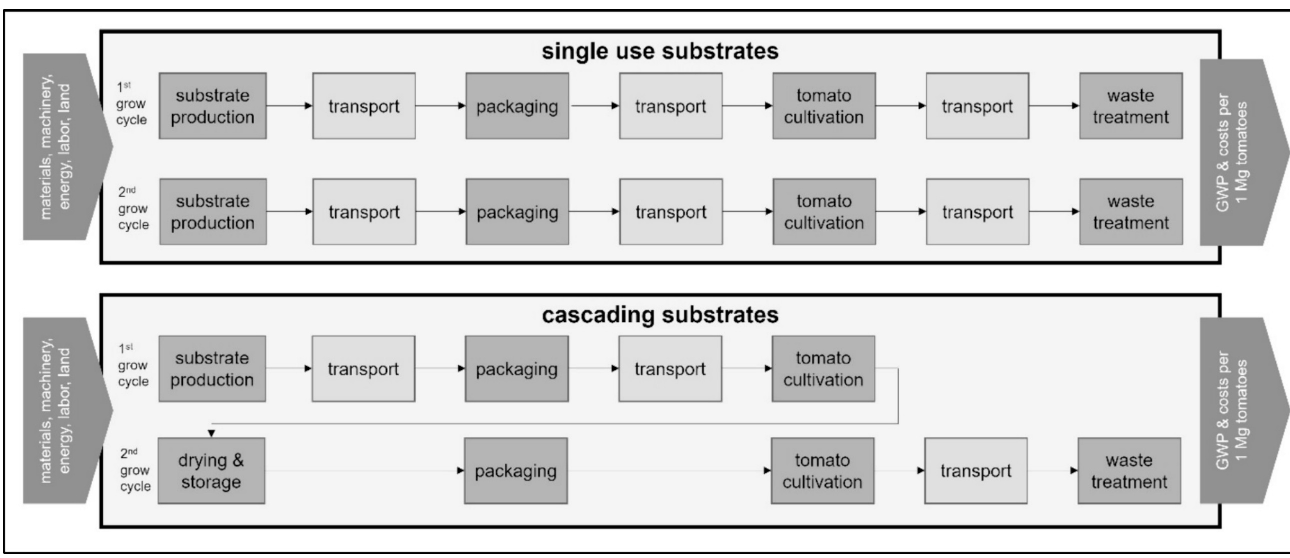

Fig. 2. System boundaries for single use (peat, stone wool, coconut coir, miscanthus with and without 1–2 % biochar) and cascading (miscanthus with and without 1–2 % biochar) substrates, GWP = Global Warming Potential, own visualization.

are optimized for the other scenarios in the future. For instance, miscanthus-based substrates may require more fertilizer as they exhibit higher nitrogen immobilization, whereas biochar can serve as a slow-release fertilizer, reducing fertilizer needs (Nguyen et al., 2022; Vaughn et al., 2021). Following (Peano et al., 2012), inputs can be disregarded when they remain unchanged upon adopting another cultivation scheme, such as greenhouse construction, equipment, working hours, planting activities, heating and removal of harvested tomato plant residues.

Hence, carbon stored or released by the tomato plant is excluded as it is considered equal for all scenarios and thus outside the system boundary. We include transport and packaging as it differs between substrates (BSI, 2012). GHG emissions that substrates emit or sequester after they were used in horticulture are attributed to the tomato cultivation (use phase), according to (BSI, 2012). The effect of such delayed GHG emission and sequestration is separately analyzed according to (European Commission, 2010a). This analysis enables a holistic comparison of the substrates' entire impacts beyond their immediate impacts. Peat predominantly releases GHG emissions post-cultivation, while biochar has the capacity for long-term carbon storage (Fryda et al., 2019). Particularly for value chains including biochar, these emissions are crucial for evaluating carbon sequestration potentials, as demonstrated in (Azzi et al., 2021).

Many studies, including those by (Fryda et al., 2019; Paoli et al., 2022; Roy et al., 2020), accounted for these delayed emissions by allocating them to the cultivation phase and/or reporting them separately. Similar to our study, they focus on analyzing the function provided by the substrates. Hence, our study includes the consideration of delayed GHG emissions and sequestration as well. In contrast, those studies that disregarded delayed GHG emissions solely focused on analyzing the substrate production phase and disregarded substrates' impact on yields (Toboso-Chavero et al., 2021; Vecchietti et al., 2013; Vinci and Rapa, 2019).

In alignment with the study of (Schulte et al., 2021), we maintain consistency by excluding biogenic CO_2 emissions, arising from combustion of organic matter and short-term biogenic CO_2 sequestration (e.g., soil organic carbon), for consistency. Regarding the end-of-life stage, we consider emissions from the waste treatment processes as they may vary depending on the substrates used (Fryda et al., 2019; Kraska et al., 2018; Paoli et al., 2022). Herein, we apply the cut-off directly afterwards due to high uncertainties. Therefore, the system boundaries exclude the services or benefits that the used substrates could provide post-tomato cultivation (e.g., increased yield following the application of biochar to soils (cf., Dees et al., 2023)). This assumption also applies for cascading substrates since the first grow cycle ends directly after the tomato cultivation (cut-off approach). Herein, the preparation of the used substrate is attributed to the second grow cycle (Fig. 2). We assume that new and reused substrate applications are applied in an alternating rotation. Herein, the new and reused substrates are used in the uneven and even grow cycles, respectively. We also employ an avoided burden/substitution approach when pyrolysis or waste incineration co-generates energy, following (Azzi et al., 2022). If allocation is necessary, we maintain consistency by applying mass-based allocation for both LCC and CF.

3.2. *Life cycle inventory and value chain specifications*

The substrate value chains examined cover conventional substrates such as peat, coconut coir, and stone wool, as well as alternative ones such as new and cascading miscanthus with or without biochar addition of 1 % and 2 % of the miscanthus mass (Table 2), corresponding to approximately 1.7 % *v*/v and 3.4 % v/v (Nagel et al., 2019; Nguyen et al., 2021). The greenhouse trials are conducted close to commercial scale. Herein, considering commercial scales is crucial to derive reliable outcomes and facilitate a possible subsequent market introduction (Barrett et al., 2016). The peat scenario is included as reference scenario to compare alternative substrates with a further conventional horticultural substrate applied in Germany and Europe (Schmilewski, 2017).

Table 2 provides an overview of the substrate value chains. The main differences arise in substrate production and end-of-life treatment. For end-of-life treatment, we adapted processes from previous studies, representing common waste management practices. Peat (PEAT) is produced by extraction from bogs and, for end-of-life treatment, tilled in an agricultural field as soil amendment (Boldrin et al., 2010). Coconut coir (COIR) is a waste product from coconut production in Sri Lanka and is composted after its use (Boulard et al., 2011; Paoli et al., 2022). Stone wool (WOOL) is produced in an industrial process, where we assume a mixed end-of-life treatment with one half eventually sent to landfill and the other half is prepared for recycling into bricks (Bussell and Mckennie, 2004; Cheng et al., 2011). Miscanthus is grown on an agricultural field and then stored. Biochar is produced from pelletized miscanthus by pyrolysis, similar to other studies producing biochar from lignocellulosic materials (Vaughn et al., 2013). For such materials, pelletizing is crucial to enable a constant biomass flow and a consistent pyrolysis process. At end-of-life-treatment, new miscanthus substrates (NEW) are (1) incinerated (Kraska et al., 2018) or, when biochar is added, (2) tilled into agricultural fields as soil amendment (Field et al., 2013; Fryda et al., 2019). Miscanthus substrate for cascading use (CAS) is dried after initial use and stored. We do not account for substrate sanitation after initial use due to insignificancy and lack of data (Vandecasteele et al., 2020). Finally, the substrate is (1) incinerated or, when biochar is added, (2) tilled into agricultural fields as soil amendment, corresponding to the substrate's single use counterparts. NEW+1/+2 and CAS+1/+2 denote the cases, in which biochar is added (1 or 2 % of the miscanthus mass). Further specifications and reasoning for value chain assumptions can be found in SI1. Also, the specifications of the pyrolysis process are provided in SI2, based on (Azzi et al., 2022).

The data of life cycle inventory are sourced according to the adjusted

Table 2
Substrate value chains and life cycle stage specifications. 1st = first grow cycle, 2nd = second grow cycle, PEAT = peat, WOOL = stone wool, COIR = coconut coir, NEW = single use miscanthus, NEW+1 = single use miscanthus with 1 % biochar added on a mass basis, NEW+2 = single use miscanthus with 2 % biochar added on a mass basis, CAS = cascading miscanthus, CAS+1 = cascading miscanthus with 1 % biochar added on a mass basis, CAS+2 = cascading miscanthus with 2 % biochar added on a mass basis, LDPE = low density polyethylene. Tillage refers to tillage in agricultural fields as a soil amendment. Agricultural inputs include fertilizer, herbicides, and water.

Substrate value chain		Life cycle stage						
		Substrate production	Transport	Packaging	Transport	Tomato cultivation	Transport	End-of-life treatment
PEAT		peat extraction from bogs	0 km	LDPE	300 km	addition agri. inputs	20 km	tillage
COIR		coconut production	11,500 km	LDPE	300 km	addition agri. inputs	50 km	composting
WOOL		stone wool production	0 km	LDPE	300 km	addition agri. inputs	50 km	preparation for recycling, sanitary landfill (50:50)
NEW		miscanthus cultivation, harvest, storage	50 km	LDPE	50 km	addition agri. inputs	50 km	incineration
NEW+1	miscanthus	miscanthus cultivation, harvest, storage	50 km	LDPE	50 km	addition agri. inputs	20 km	tillage
	biochar	miscanthus cultivation, harvest, storage, pelletizing, pyrolysis						
NEW+2	miscanthus	miscanthus cultivation, harvest, pelleting, pyrolysis	50 km	LDPE	50 km	addition agri. inputs	20 km	tillage
	biochar	miscanthus cultivation, harvest, storage, pelletizing, pyrolysis						
CAS	1st	miscanthus cultivation, harvest, storage	50 km	LDPE	50 km	addition agri. inputs	/	/
	2nd	drying used substrate	0 km	LDPE	0 km	addition agri. inputs	20 km	incineration
CAS+1	1st	miscanthus cultivation, harvest, storage	50 km	LDPE	50 km	addition agri. inputs	/	/
	2nd miscanthus	drying used substrate	0 km	LDPE	0 km	addition agri. inputs	20 km	tillage
	biochar	miscanthus cultivation, harvest, storage, pelletizing, pyrolysis	50 km					
CAS+2	1st miscanthus	miscanthus cultivation, harvest, storage	50 km	LDPE	50 km	addition agri. inputs	/	/
	2nd miscanthus	drying used substrate	0 km	LDPE	0 km	addition agri. inputs	20 km	tillage
	biochar	miscanthus cultivation, harvest, storage, pelletizing, pyrolysis	50 km					

hierarchy of (SAIC, 2006). Herein, the activity data of tomato yields (Table 3) are taken from experimental data (NewBIAS, 2022). For the peat scenario, the average yield of both stone wool and coconut coir was used. This assumption is aligned with the study of (Xiong et al., 2017), which demonstrated that total tomato yield of peat-vermiculite substrate is the average yield of stone wool and coconut coir, combinedly. The peat needed per growbag was calculated from the bulk density supplied by the study of (Nguyen et al., 2022). For biochar-containing scenarios, we assume the same yields for substrates with and without biochar amendment, based on (Graber et al., 2010). The study of (Graber et al., 2010) demonstrated that no significant yield difference in soilless tomato cultivation exists when biochar is added in low percentages. Also, other studies such as (Moelants et al., 2021; Yan et al., 2020) have shown that partially replacing substrates with biochar has no negative impact on yields and plant growth. To still account for possible yield deviations for peat and the novel miscanthus-based substrates, we apply a 10 % sensitivity to the yields of peat and biochar-containing substrates.

Other emission and activity data was taken from ecoinvent 3.9 cut-off database (Wernet et al., 2016), unless indicated otherwise (SI1 provides further details). When possible, the ecoinvent processes were also adapted to the German or European markets. For all organic substrates, we assume that the substrates release 1.5 % of their nitrogen content as N_2O (Schmid et al., 2000). Biochar reduces N_2O emissions by 38 %, based on (Borchard et al., 2019; Stucki et al., 2019).

For life cycle costing, only direct costs that enter or exit life cycle stages within the system boundary are recorded, based on (Schulte et al., 2021). Since the temporal reference of the value chains in the study is steady-state, the associated costs are not discounted (Schulte et al., 2021; Swarr et al., 2011). For all scenarios, land costs were based on German agricultural lease (Statistisches Bundesamt, 2019) and average industrial land rent data of North Rhine-Westphalia (IHK NRW, 2021, 2020). We used the gross labor costs of (Landesdatenbank NRW, 2020), when working hours were available for a process. We applied a 20 % labor cost share on total costs (Statistisches Bundesamt, 2020), when estimates for working hours could not be identified. When possible, the UN COMTRADE data was also used for validation (UN COMTRADE, 2021). If multiple data sources were available, averages were used. The prices of peat, stone wool, coconut coir and miscanthus substrate were assumed as costs due to lack of data. The prices can still effectively represent the costs due to the low profit margins of these products. Other cost data is taken from ecoinvent 3.9, unless indicated otherwise. The data, information and assumptions are explained further in SI1.

3.3. Life cycle impact assessment

The study employs the GWP IPCC 2013 impact assessment method to evaluate the environmental impact category Global Warming Potential (GWP) for a reference period of 100 years. GHG sequestration was reported separately from GHG emissions, based on the guidelines of (European Commission, 2010a). Herein, the study focuses on GWP for various reasons: Firstly, this parameter serves as a suitable indicator when investigating the trade-offs between economic profitability and climate change mitigation (Hammond et al., 2011; Jukka et al., 2022). For example, carbon release is one of the major environmental impacts of peat, and carbon sequestration is one of the major traits of rather high-cost biochar. Secondly, GWP can serve as a proxy for other environmental categories, as highlighted by (European Commission, 2010b) and emphasized by (Dorr et al., 2017) in their comparison of compost-containing substrates with conventional peat-moss substrates. Their analysis revealed analogous trends across all impact categories, with conventional substrates displaying higher impacts in all categories (climate change, water depletion, human toxicity, fossil depletion, marine eutrophication). Thirdly, there are substantial data constraints inhibiting the evaluation of other impact categories than GWP.

Table 3
Cumulative fresh fruit yield of tomatoes grown on different substrates.

Substrate	Cumulative fresh fruit yield for one grow cycle (kg plant^{-1})	Source/calculation method
Peat	10.22	average of stone wool and coconut coir yields
Stone wool	9.85	NewBIAS (2022)
Coconut coir	10.59	NewBIAS (2022)
New miscanthus	9.37	NewBIAS (2022)
Cascading miscanthus	9.14	NewBIAS (2022)

In the LCC analyses, we use Euros (€, 2020 Present Value), aligning with the approaches of (Lu and El Hanandeh, 2019) and (Schulte et al., 2021). Herein, all costs were adjusted to € 2020 present value by using the producer price index (OECD, 2023). This adjustment is similar to studies that set prices to reference year levels such as (Lu and El Hanandeh, 2019; Sanyé-Mengual et al., 2015).

3.4. Scenario analysis

Besides the assessments outlined earlier, we conduct scenario analysis to investigate how modifying certain parameters can impact the outcomes. Herein, these analyses can be classified into two paths: Firstly, examining various input alternatives like increasing biochar content, using low-emission electricity, reusing growbags, and utilizing PLA-packaging. Secondly, exploring different cost scenarios, which involve including carbon sequestration certificates, implementing carbon pricing and reducing the costs of biochar. A brief explanation of the different scenarios is included in Table 4.

4. Results

From different scenarios of the integrated CF and LCC, we generated results to identify how primary and cascading value chains of miscanthus and miscanthus biochar perform regarding GWP and costs, compared to conventional substrates. Herein, we first descriptively illustrate the results on GWP and costs (4.1) and the scenario analysis (4.2). Thereafter, we analyze the results further and contextualize the quantitative assessment with current research and policies in the next chapter (5).

4.1. Global warming potential and costs

Regarding GWP, our research showcases three crucial findings (Fig. 3). Firstly, miscanthus-based substrates emit significantly less GWP compared to conventional substrates. The reductions range from 78.1 % to 82.2 % compared to PEAT and between 23.7 % and 38.1 % compared to WOOL. Secondly, cascading substrates have lower emissions compared to single use counterparts, with reductions of up to 10.1 %. Herein, CAS+2 displays the lowest emissions compared to all other alternatives. Thirdly, miscanthus substrates containing biochar exhibit lower emissions than those without.

In terms of total life cycle costs, we also identify three main outcomes (Fig. 3). Firstly, cascading substrates are cheaper than both conventional substrates and single use miscanthus substrates. The savings range from 0.5 % to 23.1 %, with CAS+1 being the most cost-effective. Secondly, single use miscanthus without biochar (NEW) is the most expensive substrate, followed closely by WOOL and PEAT. Thirdly, single use miscanthus substrates with biochar show lower costs than PEAT and WOOL, but higher costs than COIR. Reductions reach up to 7.0 % and 9.4 % compared to PEAT and WOOL, respectively, while increases are up to 2.6 % compared to COIR. Overall, the study displays that while the cost range (72 : 88 €) is relatively narrow, the range of GWP spans a much broader spectrum (52 : 292 kg CO_2 eq).

Table 4
Covered scenarios in the scenario analysis.

Scenario	Explanation	Method
MORE BIOCHAR	• accounts for the possibility that conventional substrate can be replaced by up to 15 % *v*/v biochar (Vaughn et al., 2013).	calculate single use miscanthus and cascading miscanthus value chains with a 15 % biochar share.
REUSING GROWBAGS	• accounts for a multi-cascade option. Not only substrate, but also low density polyethylene packaging could be used for two grow cycles.	calculate cascading value chains with reused growbag packaging. We do not regard reusing growbags for conventional substrates since this is currently not done in practice.
POLYLACTIC ACID GROWBAGS	• covers using bioplastic-based growbags from polylactic acid instead of conventional, low density polyethylene growbags.	calculate all value chains with Global Warming Potential (Rosenboom et al., 2022) and price of polylactic acid (Business Analytiq, 2023) instead of low density polyethylene.
LOW EMISSION ELECTRICITY	• covers possibly decreased GHG emissions of electricity in the value chain. • Such a decrease is anticipated due to ambitious greenhouse gas reduction plans, e.g., in the German climate protection plan 2050 (BMUB, 2016).	calculate the carbon footprint with a 50 % reduction of emissions from electricity in foreground processes.
LOWER BIOCHAR COSTS	• covers the opportunity for lower biochar costs. • Biochar costs may be lower than in our study when, e.g., using a waste organic material for biochar production instead of primary material. • Biochar price is essential for biochar production's profitability (Haeldermans et al., 2020).	conduct the Life Cycle Costing for the average (450 €) of the price range identified by (BZL, 2023). Includes *HIGH BIOCHAR* scenarios to assess effects of higher biochar content.
CARBON REMOVAL CERTIFICATES	• accounts for a possible carbon sequestration certificate issued for the carbon stored by biochar. • addresses the recent proposal of the European Commission to develop a carbon removal certification scheme (European Commission, 2022b). • covers internalized costs, as recommended by (Swarr et al., 2011).	conduct the Life Cycle Costing for all value chains with carbon certificates from 50 € to 600 € issued for stable carbon stored in biochar. Includes *HIGH BIOCHAR* scenarios to assess effects of higher biochar content.
CARBON EMISSION PRICING	• accounts for carbon price on substrate production and substrates' fossil emissions during and after cultivation. • Carbon pricing in the agriculture sector, particularly targeting peat, can be a suitable measure for reducing greenhouse gas emissions (Isermeyer et al., 2019; Stepanyan et al., 2023). • covers internalized costs, as recommended by (Swarr et al., 2011).	conduct the Life Cycle Costing for all value chains for carbon emission prices between 50 € and 500 €. We base the range on the 100 € price which Stepanyan et al. (2023) identified and extend it to higher prices due to projected carbon price increase.

In the following, we analyze the contribution of life cycle stages to GWP and costs (Fig. 4 & SI3). In terms of GWP (Fig. 4a), tomato cultivation has a significant contribution, especially if miscanthus-based substrates are applied. However, for substrates like PEAT and WOOL, production processes contribute more to GWP. Waste treatment and packaging also make significant contributions to emissions. Transport, albeit playing a minor role overall, demonstrates greater importance in the case of COIR. Moreover, the adoption of biochar and district heat offsets presents promising potential for reducing GWP by up to one tenth.

In terms of costs (Fig. 4b), tomato cultivation incurs the highest expenses, particularly noticeable if miscanthus-based substrate is used. Substrate production follows, with costs varying depending on the substrate type and whether biochar is included. Packaging costs remain relatively consistent across all types of substrates. Although transport costs are typically modest, they show exceptions for PEAT and COIR, where they tend to be elevated. The costs associated with waste treatment fluctuate across substrates, with COIR, NEW, and CAS bearing higher shares. Also, district heat offsets derived from pyrolysis offer cost reductions, albeit to a modest extent. In the sensitivity analysis, GWP and costs increase in the same magnitude as the yield changes. In case of a 10 % yield increase (decrease), GWP and costs for PEAT and single use miscanthus substrates with biochar decrease (increase) by 9.1 % (11.1 %), while it is only half as high for cascading substrates. Please refer to SI4 and SI5 for detailed information on the CF and cost results.

4.2. Scenario analysis

Cost scenarios display effects only on costs, whereas input scenarios affect both GWP and costs, as explained in the following. Detailed results for scenarios can be found in the supplementary information (SI3, Tables 4–10). As shown in Fig. 5, increasing biochar in miscanthus substrates (*MORE BIOCHAR*) reduces GWP but increases costs. For every percent increase in biochar added, GWP decreases by 7.6 % for single use and 4.1 % for cascading miscanthus. However, costs increase by 0.8 % for single use and by 0.5 % for cascading miscanthus per percent of biochar added. The scenario of *REUSING GROWBAGS* reduces both GWP and costs. Herein, GWP decreases by 7 kg CO_2 eq. for all cascading substrates. Also, costs decrease by up to 0.18 €, representing 0.2 % of the overall costs. Utilizing *POLYLACTIC ACID GROWBAGS* instead of low density polyethylene growbags reduces GWP by 9.1 to 11.0 kg CO_2 eq., saving up to one fifth of total GWP. However, substrate costs increase by up to 5.3 %. *LOW EMISSION ELECTRICITY* (here: halving electricity GHG emissions) has minimal impact on conventional substrates but decreases GWP by 0.2 % to 1.3 % for miscanthus-based substrates.

In the base case, the costs of biochar stand at 1390 €/Mg biochar. If biochar costs fall below 770 € (745 €) for single use (cascading) substrates, total life cycle costs start decreasing, the more biochar is added. For *LOWER BIOCHAR COSTS* of 450 €, incorporating more biochar leads to cost savings for both cascading and single use substrates. For example, substrate costs are 1.3 %, 2.5 % and 17.1 % lower for NEW+1, NEW+2 and NEW+15, respectively, compared to the base costs. When *CARBON EMISSION PRICING* is applied to tomato cultivation and substrate production, conventional substrates face significant cost increases compared to miscanthus-based substrates (Fig. 6a).

Comparing the 0 € to the 600 € carbon emission price case, we find that PEAT costs increase by 164.5 %, WOOL costs by 25.8 %, and COIR costs by 15.3 %. In contrast, miscanthus-based substrates display lesser cost increases of up to 8.8 %. PEAT costs exceed NEW costs at a carbon emission price of 18.41 €/Mg CO_2 eq., while for WOOL to exceed NEW, a price of 28.35 € is required. The cost order of all other substrates remains unchanged.

Applying *CARBON REMOVAL CERTIFICATES* to the carbon

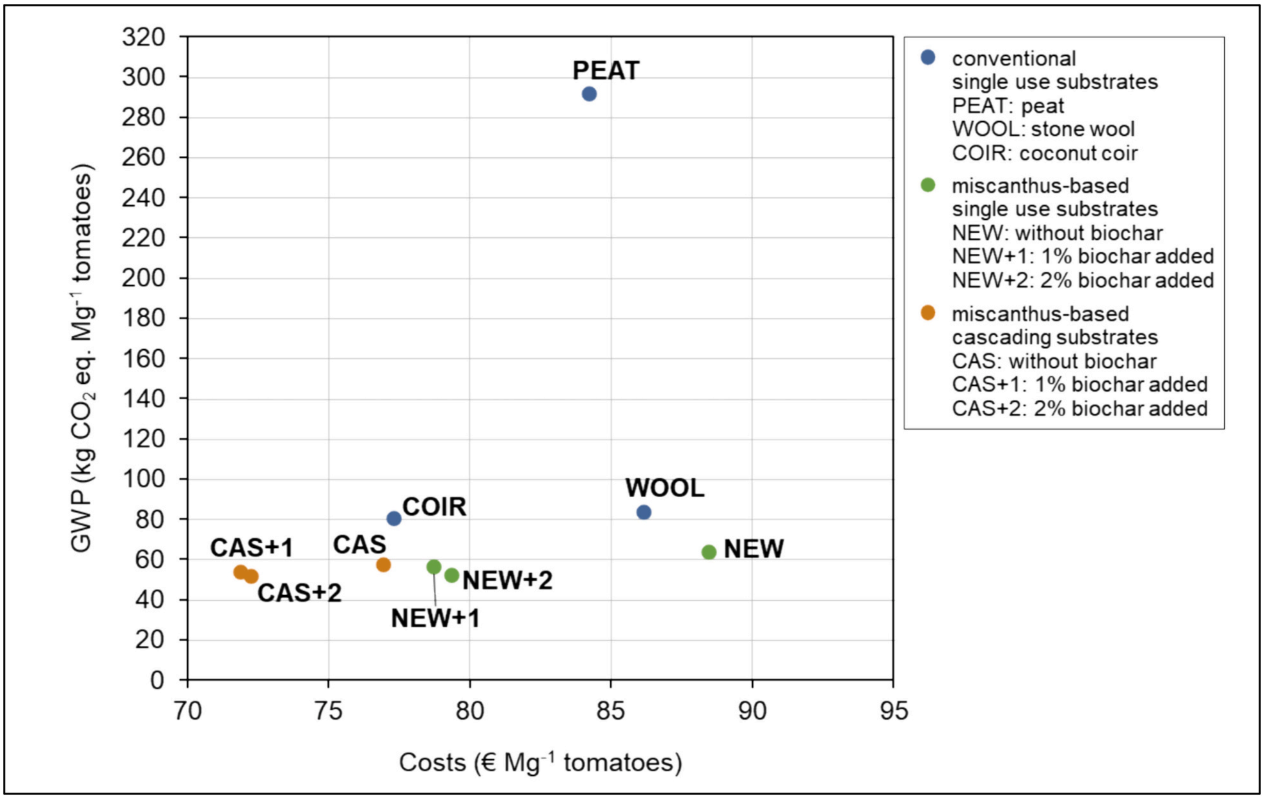

Fig. 3. Global Warming Potential (kg CO_2 eq. Mg^{-1} tomatoes) and costs (€ Mg^{-1} tomatoes) for conventional and miscanthus-based substrate value chains with or without biochar addition on a mass basis. For detailed figures, see SI3, Table 1.

sequestered by biochar decreases costs, with lower costs as more biochar is included, especially at higher certificate prices (Fig. 6b). For example, at carbon certificate prices of 15 € (95.32 €), the costs of NEW+15 are lower than the ones of WOOL (PEAT). When the carbon certificate price is higher than 250 € (200 €)/kg CO_2 eq., the prices of single use (cascading) substrates decrease the more biochar is included.

5. Discussion

In this chapter, we analyze our results in the context of current research and policies. We firstly discuss the implications of our results regarding global warming impact (5.1) and costs (5.2) before we evaluate the trade-offs between the CF and economic dimension in the scenario analysis (5.3) and place our findings in the broader context of sustainable horticultural substrates (5.4).

5.1. Global warming potential

We find that miscanthus-based substrates are climate-friendly alternatives to conventional substrates, which is aligned with the outcomes of other studies. For instance, the studies of (Eymann et al., 2015; Stucki et al., 2019) demonstrated that miscanthus is associated with lower emissions compared to peat and coconut coir. Similarly, lower GWP was observed in biomass-based mixes compared to conventional substrate mixes (Dorr et al., 2017; Hernandez-Apaolaza et al., 2005). However, some studies display different trends, explained by their methodological choices. For example, the analyses of (Peano et al., 2012) compared coconut coir and alternative substrates and concluded that they have similar CF, which can be attributed to the functional unit they have used. Also, two other studies found higher emissions for coconut coir than for peat and stone wool (Paoli et al., 2022; Vinci and Rapa, 2019), a difference that can be linked to the variation in their system boundaries. For example, the study of (Paoli et al., 2022) disregarded land use change and use phase emissions.

In our study, the lower GWP of miscanthus-based substrates primarily stems from lower production emissions as miscanthus cultivation requires minimal inputs and generates high yields (Clifton-Brown et al., 2004; Lewandowski et al., 2000). In contrast, conventional substrates like peat, coconut coir and stone wool entail high emissions from extraction, cultivation, and processing (Grunert et al., 2016; Leifeld et al., 2019; Paoli et al., 2022). Additionally, we illustrate that tomato cultivation emissions are significantly lower with miscanthus-based substrates compared to peat. This difference is primarily attributed to the fossil carbon oxidation associated with peat. Moreover, lower transportation emissions contribute to lower GWP of miscanthus-based substrates. Herein, waste treatment emissions are similar for all substrates. Extending system boundaries to waste product utilization could alter results, for instance when considering offset credits from miscanthus combustion.

The contribution of life cycle stages to GWP varies from that observed in other studies. This is because many studies evaluated only cradle-to-gate emissions of substrate production (e.g., (Eymann et al., 2015; Peano et al., 2012)) or restricted system boundaries to specific stages of tomato cultivation, hindering a comprehensive assessment (e.g., (Bosona and Gebresenbet, 2018; Dorr et al., 2017)). Hence, our study represents a novel contribution by evaluating the complete value chains of the relevant substrates.

For miscanthus-based substrates, cascading use and adding biochar has been found to achieve the lowest GWP, indicating the potential of biochar to further reduce emissions in substrate value chains. This is also in line with the previous studies that identified low GWP for biochar-containing substrate value chains such as (Fryda et al., 2019; Stucki et al., 2019). Our results indicate that miscanthus and miscanthus biochar are promising low-emission substrate components. Since substrate costs can present implementation barriers (Moelants et al., 2021), we integrated the substrates' life cycle costs into the analyses.

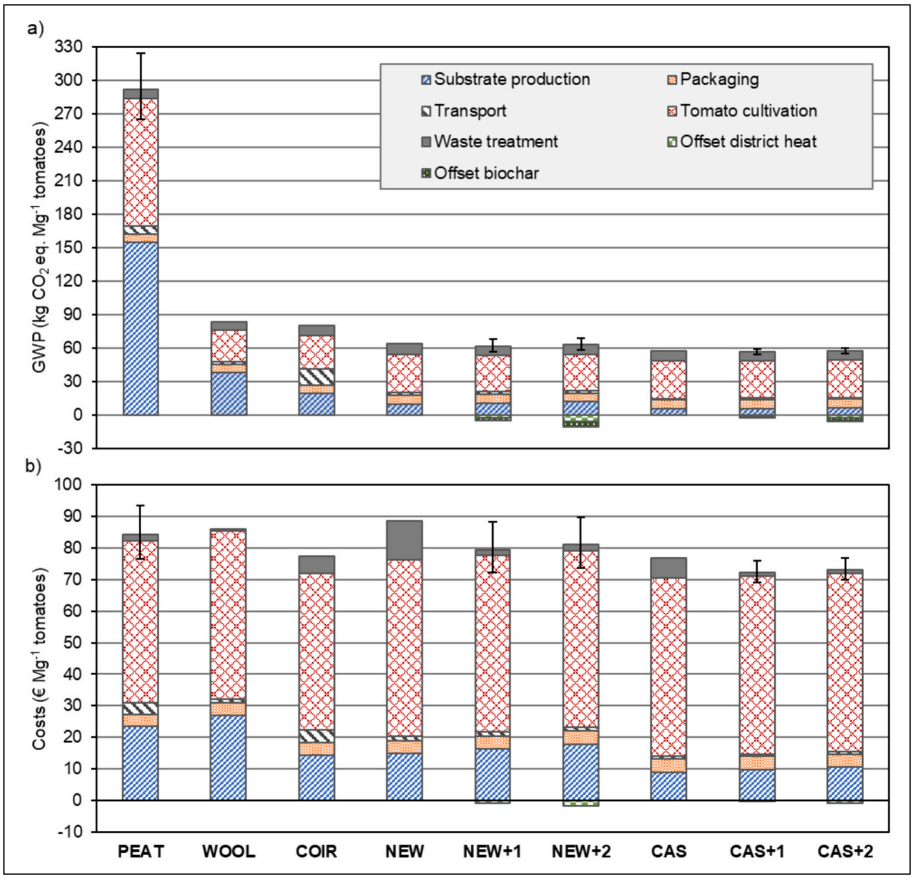

Fig. 4. Life cycle stage contribution to a) Global Warming Potential (kg CO_2 eq. Mg^{-1} tomatoes) and b) costs (€ Mg^{-1} tomatoes) for conventional and miscanthus-based substrate value chains with or without biochar addition. Whiskers display sensitivity analysis for ±10 % yield. PEAT = peat, WOOL = stone wool, COIR = coconut coir, NEW = single use miscanthus, NEW+1 = single use miscanthus with 1 % biochar added on a mass basis, NEW+2 = single use miscanthus with 2 % biochar added on a mass basis, CAS = cascading miscanthus, CAS+1 = cascading miscanthus with 1 % biochar added on a mass basis, CAS+2 = cascading miscanthus with 2 % biochar added on a mass basis. For detailed figures, see SI3, Tables 2 and 3.

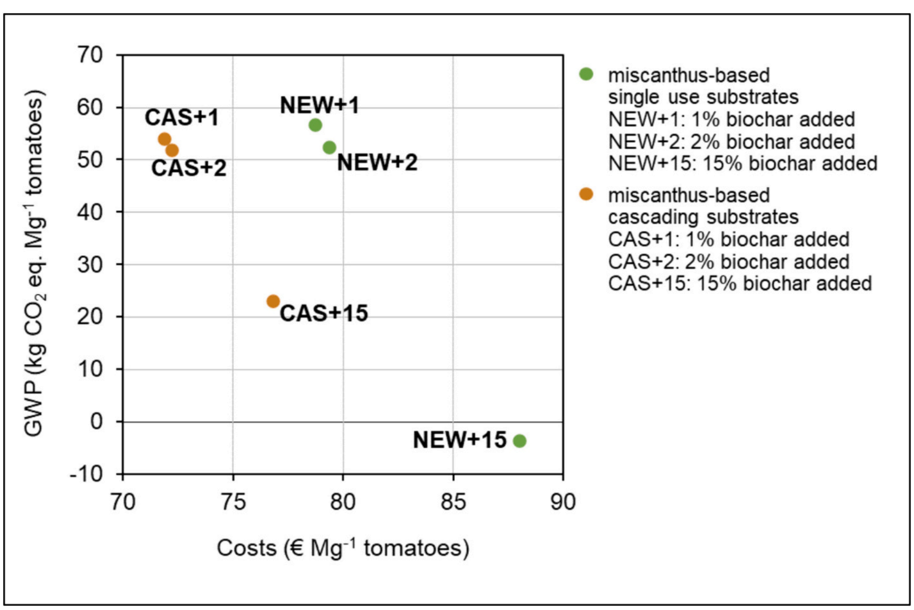

Fig. 5. Global Warming Potential (kg CO_2 eq. Mg^{-1} tomatoes) and costs (€ Mg^{-1} tomatoes) for single use and cascading miscanthus-based substrate value chains with 1, 2 and 15 % biochar addition on a mass basis.

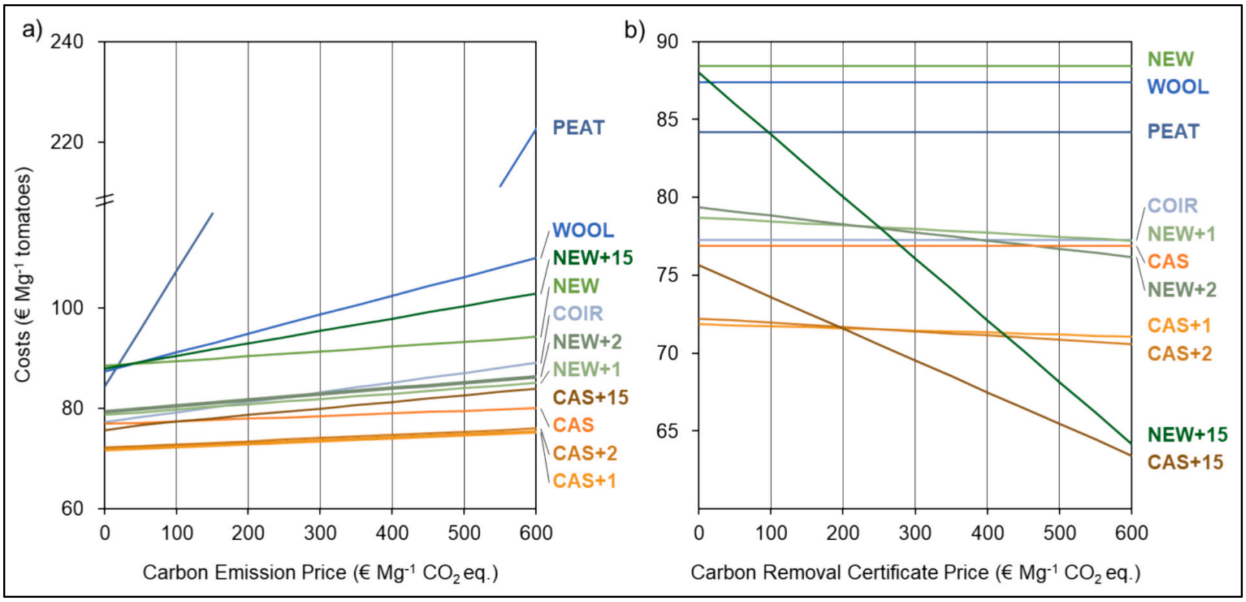

Fig. 6. Costs (€ Mg^{-1} tomatoes) for conventional and miscanthus-based substrate value chains with or without biochar addition at a a) carbon emission price for substrate production and substrate-related use phase emissions and b) carbon removal certificate price for carbon removed by biochar. PEAT = peat, WOOL = stone wool, COIR = coconut coir, NEW = single use miscanthus, NEW+1 = single use miscanthus with 1 % biochar added on a mass basis, NEW+2 = single use miscanthus with 2 % biochar added on a mass basis, NEW+15 = single use miscanthus with 15 % biochar added on a mass basis, CAS = cascading miscanthus, CAS+1 = cascading miscanthus with 1 % biochar added on a mass basis, CAS+2 = cascading miscanthus with 2 % biochar added on a mass basis, CAS+15 = cascading miscanthus with 15 % biochar added on a mass basis.

5.2. Costs

Cascading miscanthus are identified as the lowest cost substrates, mainly due to lower production and transportation costs, compared to single use substrates. Single use miscanthus, stone wool, and peat incur the highest costs. Previous studies, comparing conventional substrates (Vinci and Rapa, 2019) and conventional substrate mixes with alternatives like pine bark and wood chips (Dorr et al., 2017; Hernandez-Apaolaza et al., 2005), also support these findings.

Tomato cultivation contributes significantly to the overall costs. We observe similar absolute contributions across substrates as a result of using the same fertigation regimes. Substrate production and waste treatment are identified as key drivers for cost difference, with miscanthus and coconut coir production costs being similar and higher for peat and stone wool. The pyrolysis process also increases costs of biochar-containing substrates. However, cascading decreases the production costs, since only drying and storage are required in the second grow cycle.

Generally, costs of waste treatment are dependent on the intensity of material and energy inputs. Therefore, the costs are higher for coconut coir and miscanthus without biochar, surpassing the costs associated with other substrates, since the processes require more expensive inputs. For miscanthus without biochar, waste treatment costs are higher since its incineration-based waste management requires more energy, material, and labor, compared to low-input treatments like tillage and landfilling. Herein, the inclusion of revenues from cascading, such as miscanthus combustion, can be a suitable approach to decrease the costs of waste treatment (Kraska et al., 2018). Also, industrial composting, applied to coconut coir, requires more inputs than landfilling and preparation for recycling, used for stone wool as waste treatment. Therefore, waste treatment of stone wool is comparatively cheaper. Despite the higher production costs, incorporating biochar can lower the total costs due to the low-input tillage waste treatment. Transportation and packaging costs make up relatively small portions of the total costs, with transport costs fluctuating depending on transport distance. Offsetting district heat reduces costs only marginally, with potential for increased reduction when syngas is used to offset electricity (Schmidt et al., 2015) or when energy prices rise.

5.3. Scenario analysis

The scenario analysis has illustrated the impact of certain parameters on the outcomes. The analysis emphasizes that switching to sustainable substrates is the most effective way to reduce emissions in substrate value chains. For instance, shifting from coconut coir to single use miscanthus without biochar saves 16.6 kg CO_2 eq. Other measures, alone or combined, cannot surpass this emission reduction. Thus, applying packaging-related measures directly to miscanthus-based substrates would be even more beneficial for emission reduction. Cost increases induced by polylactic acid packaging apply to all substrates similarly. However, even if polylactic acid is only used for miscanthus-based substrates, total costs are still lower compared to peat and stone wool with conventional packaging. Reusing growbags may be fostered by future bioeconomy policies, but such measures require careful planning due to the logistical challenges. However, these measures could reduce packaging costs, especially as fossil-based material prices rise.

While reducing GHG emissions in electricity is crucial for reaching climate goals (BMUB, 2016), the impact on substrate emissions is minimal. Switching to low-emission substrates like miscanthus, adding biochar, reusing growbags, or using polylactic acid packaging are more effective measures. When adding biochar, however, careful examination of feasible biochar amounts is needed as yield results can be ambiguous (Dunlop et al., 2015; Massa et al., 2019; Simiele et al., 2022) and costs can increase.

Even low carbon prices can already have the potential to greatly enhance the commercial viability of miscanthus-based substrates. A carbon price of 18.41 and 28.35 €/Mg CO_2 eq already leads to lower miscanthus-substrate prices, compared to peat and stone wool. These prices are much lower than prices suggested in literature (Isermeyer et al., 2019; Stepanyan et al., 2023) and the current EU ETS carbon price (75 €/Mg CO_2 eq) (Börse Frankfurt, 2023). Although a stringent carbon price in the agricultural sector would slightly increase the costs of miscanthus-based substrates, policies could exempt renewable biomass production, like miscanthus cultivation, from carbon pricing to promote it further.

Upon the introduction of carbon certificates at similar expenses as free market prices (e.g. 130 €/Mg CO_2 eq. (puro.earth, 2023)), the 15 % biochar-containing substrates would be more competitive than conventional ones. For lower biochar shares, certificate prices would need to be four to five times higher than current prices. Both carbon certificates and low biochar production costs could be lucrative for biochar producers. This is particularly the case when profits from district heat offsets or carbon credits are higher than biochar production costs. Herein, rising the prices of carbon removal certificates is more plausible once the market has been established. Lower biochar costs could also be achieved through using organic waste products, reducing feedstock costs, and optimizing the pyrolysis process. To summarize, we find that introducing carbon pricing, carbon removal certificates and/or lower biochar prices can reduce the costs of miscanthus-based substrates considerably. The measures thus highly impact the potentials of substrates' commercial adoption.

5.4. Sustainable horticultural substrates

Miscanthus-based substrates represent better alternatives in terms of CF and economic performance. If we assume that the entire European tomato cultivation used cascading miscanthus substrate with 2 % biochar instead of the standard substrate stone wool, 267,568,000 € and 513,840 Mg CO_2 eq. would be saved. Hence, a sector-wide adoption of cascading miscanthus substrates with biochar could lead to substantial emission savings and cost reductions compared to conventional substrates. In North Rhine-Westphalia, as a heavily industrialized area, such changes could contribute to urgently required cross-sectoral decarbonization.

In addition to emission and cost savings, utilizing miscanthus-based substrates circumvents the disposal challenges and high costs associated with stone wool waste streams (Cheng et al., 2011; Göhler and Molitor, 2002). Also, miscanthus cultivation on a regional scale leads to lower transportation emissions, serves to inhibit carbon leakage (i.e., importing emission-intensive substrates from abroad), and supports resource self-sufficiency (Hirschler et al., 2022). Hence, miscanthus cultivation contributes to climate change mitigation (Schneckenberger and Kuzyakov, 2007) and enhancing biodiversity (Emmerling and Pude, 2017). Besides carbon sequestration, biochar can also increase soil organic carbon, improve yields (Xu et al., 2021), and avoid nitrogen leaching (Yang et al., 2017).

Nonetheless, there are implementation barriers for miscanthus and biochar as alternative substrate components and cascading as novel management practice. Firstly, the availability of miscanthus and biochar is limited. The current annual miscanthus production in Germany can cover only 5.3 % of the annual German substrate production (BMEL, 2020). Also, although biochar production has been increasing (EBI, 2023), capacities could not provide supply for substrate production at large scales. Secondly, the price of miscanthus exceeds that of comparable lignocellulosic products (e.g. straw) by one third (Greifenberg, 2023) inter alia leading to biochar costs three times higher than the average market price in our case. Thirdly, transport costs could increase when further raw material reserves are explored, e.g., if the processing facilities are not located near new biomass resources (Hirschler et al., 2022). Fourthly, economic and technical considerations can pose a challenge for farmers and substrate producers to switch to or reuse the new substrates (Barrett et al., 2016). For instance, biochar application can result in lower fertilizer usage, while miscanthus substrates may require more nitrogen fertilizer, leading to uncertainty regarding costs and environmental impacts (Barrett et al., 2016; Nguyen et al., 2022; Vaughn et al., 2021).

Fifthly, although miscanthus has performed well in the trials of tomato and cucumber (Kraska et al., 2018), its suitability for replacing a substrate and maintaining profitable yields must be carefully evaluated for each growing system. For instance, GWP and costs increase (decrease) for single use miscanthus in similar magnitudes like the yields decrease (increase), as our sensitivity analysis displays. Changes in yields also affect cascading miscanthus, but in lower magnitudes. Herein, the first grow cycle with single use miscanthus buffers the effect. Sixthly, the availability of substrates is limited since there may arise competition with other biomass cultivation and other uses, particularly energy generation (Gievers et al., 2021; Hirschler et al., 2022). Miscanthus has also been increasingly used as component in construction materials and offers applications in the paper industry (Danielewicz and Surma-Ślusarska, 2019; Moll et al., 2020). Additionally, biochar is also used as soil amendment (Gievers et al., 2021), and filler material (Tadele et al., 2019). Seventhly, from a farm management perspective, cascading substrate use can spread pathogens and reduce the quality of the substrate's physical and chemical properties (Gruda, 2019). Eighthly, supply chain management consideration can also present challenges in more circular supply chains (Bressanelli et al., 2019). For example, cascading requires drying and storing, implying additional operations and involving more stakeholders.

Despite these challenges, miscanthus and biochar are promising substrate alternatives, considering their CF benefits, low costs, as well as potential for carbon sequestration and cascading use. Taking the limitations above into account, miscanthus and biochar currently cannot replace conventional substrates entirely, but can be one option for substrate diversification. Herein, adoption of miscanthus-based substrates and novel substrate management (e.g. cascading) could be facilitated by (1) introducing financial incentives targeted at farmers and biochar producers, and (2) initiating carbon pricing and carbon removal certification mechanisms. For example, the European Council and the European Parliament have decided to introduce a carbon removal certification scheme (European Council, 2024) and standards for biochar certification have already been developed (Bier et al., 2020). Such mechanisms will undoubtedly support the value chains of miscanthus and biochar further in the coming years. In an established carbon removal market, biochar production can become more beneficial for pyrolysis producers, compared to energy production (Kung et al., 2015). Also, when carbon removal certification is coupled with carbon emission pricing, alternative substrates' prices are anticipated to be substantially lower than those of conventional options. However, combining two different schemes has to be considered cautiously as they may have different regulatory and financial conditions (Bier et al., 2020; Wurzer et al., 2022). Promoting local substrate production (Kraska et al., 2018) and exploring alternative biomass sources (Hirschler et al., 2022) could introduce further pillars to promote sustainable horticultural substrates. In this regard, the recent amendment of EU regulation 2019/1009 has already widened the spectrum of allowed fertilizing products.

Based on the explanation above, miscanthus and biochar can emerge as viable substrate alternatives, contributing to sustainable horticulture practices and climate change mitigation efforts.

6. Conclusions

The study aimed at investigating the value chains of horticultural substrates and cascading applications from an interdisciplinary perspective. The analyses illustrate the trade-offs between economic profitability, climate change mitigation, and crop yield performance, thus providing the first economic and CF assessment of miscanthus and biochar substrate value chains compared to conventional substrates. Accordingly, we evaluate how to establish biochar as a Biomass Carbon Removal and Storage (BiCRS) option in substrate value chains. We demonstrate that miscanthus-based and biochar-containing substrates are climate-friendly and low-cost alternatives for conventional substrates. Thus, miscanthus and biochar application in horticulture can be levers for implementing a sustainable bioeconomy. Moreover, the analyses evaluate possible cascading pathways for both substrates and packaging, advancing the transition towards a circular bioeconomy. The study is also the first to systematically analyze the impacts of carbon pricing and carbon removal certification on substrate costs.

Miscanthus-based and biochar-containing substrates exhibit lower emissions than conventional substrates. Switching to miscanthus-based substrates saves more emissions than any other emission-reduction strategy investigated (e.g., bioplastic packaging, reusing packaging and lower electricity emissions). Adding more biochar and implementing cascading practices in miscanthus-based substrates reduce emissions, with higher biochar amounts resulting in more emission reductions. The costs associated with cascading use of miscanthus-based substrates are lower compared to conventional substrates, although the overall difference between the two types of substrates is not significant. However, with the future adoption of carbon emission pricing and carbon removal certificates, miscanthus-based and biochar-containing substrates are poised to become the more economical alternatives.

Thus, miscanthus-based substrates can play a substantial role in reducing emissions in the agricultural sector. As North Rhine-Westphalia is a heavily industrialized area, this could be a contribution to urgently required cross-sector decarbonization. Moreover, the study's outcomes could be transferred to other regions and horticultural crops in the future. Herein, it should be highlighted that successfully establishing sustainable substrate value chains requires (1) advancing instruments to increase the prices of emission-intensive substrates and decrease the costs of low-emission ones, (2) creating incentives to sustainably grow biomasses such as miscanthus and, potentially, use organic waste streams, (3) facilitating the commercial adoption of alternative substrates, and (4) promoting cascading uses both within and beyond horticultural applications.

Looking forward, there are some limitations that could be addressed in future research. As the region of interest influences the analysis' outcomes, the transfer of results to other regions needs to be considered cautiously. Despite the meticulousness in collecting the data and ensuring its correctness, particularly the cost, agricultural input, yield, and biochar decay rate data can be improved further by retrieving data from practice. Future studies could also expand the system boundaries and regard the services that used substrates may provide beyond horticultural application (e.g. soil improvement) (Vollmer et al., 2022). Also, different waste treatment scenarios for substrates and cascading applications can be explored. Additionally, studies could further investigate opportunities and risks of adopting novel substrates on farm, supply chain and policy scales. Future investigations could consider higher biochar shares and cultivation schemes optimized for miscanthus and biochar, which could lead to different environmental impacts (Barrett et al., 2016).

If future research provides more detailed information, the results will undoubtedly be more robust. While the economic analysis provides several insights into life cycle costs, conducting a cost-benefit analysis for stakeholders along the value chain can enhance the decision-making process further. The potentials and availabilities of biomass as well as optimized substrate production and application need to be investigated. Herein, as demonstrated, switching to sustainable substrates such as miscanthus-based and biochar-containing substrates is a cost-effective approach to reduce GHG emissions and, at high biochar levels, to sequester carbon dioxide.

CRediT authorship contribution statement

Johanna Ruett: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ali Abdelshafy:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Grit Walther:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT by OpenAI in order to enhance readability of complex sentence structures. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: This research was financially supported by the Bioeconomy Science Center's NewBIAS project. The scientific activities of the Bioeconomy Science Center were financially supported by the Ministry of Culture and Science within the framework of the NRW Strategieprojekt BioSC (No. 313/323-400-00213).

Acknowledgements

This research was financially supported by the Bioeconomy Science Center's NewBIAS project. The scientific activities of the Bioeconomy Science Center were financially supported by the Ministry of Culture and Science within the framework of the NRW Strategieprojekt BioSC (No. 313/323-400-00213).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2024.06.016.

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