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Quantification of material flows: A first step towards integrating tomato greenhouse horticulture into a circular economy

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ABSTRACT

Reducing environmental impact is a necessary condition for sustainability, but it is not a sufficient one. The current 'linear' economy not only leads to environmental impact; it also depletes finite natural reserves. This is why moving towards a more 'circular' economy is desired. One of the obstacles in implementing a circular economy are knowledge gaps about the nature and quantity of input and output flows of production processes. The aim of this paper is not to quantify environmental impact, but rather to bridge these knowledge gaps for a particular type of vegetable production, by detailing the resource input and output of a typical high-tech glasshouse tomato crop in the Netherlands. In particular, this paper has focused on material flows potentially suitable for relatively short-term re-use and/or substitution in a circular economy. The paper describes how figures have been collected about the sub-processes involving each of the material flows, the accuracy and range of such numbers, and how their consistency can be finally verified.

After combining all numbers into three diagrams, this paper finally discusses the potential and obstacles for recycling of each of the material flows discussed. For instance, the results show that there is a good potential for recovering minerals from non-fruit biomass, where over half of Mg, Ca and S end up, at 58%, 70% and 70% respectively. However, its being virtually inextricably mixed with plastic is a huge barrier, requiring changes such as biodegradable plastics. Finally, by quantifying the flows per unit of produce (1 kg tomato), this paper provides numbers for dimensioning possible symbiotic production processes, such as aquaculture or animal husbandry.

1. Introduction

1.1. Background

The environmental impact of greenhouse horticulture has been studied many times, in particular its contribution to anthropogenic climate change (Anton et al., 2012; Gruda et al., 2019a; LLorach Massana, 2017; Montero et al., 2011; Torrellas et al., 2012; Torres Pineda et al., 2021; Weening and Vroege, 2014). Despite this, not all environmental impact is related to greenhouse gas emissions: Torrellas et al. (2012) executed a full life cycle analysis (LCA) including six impact categories and Zhou et al. (2021) focused on plastic pollution. Moreover, although reducing environmental impact, in particular from energy provision, is a necessary condition for sustainability, it is not a sufficient one.

Over the past few years, the worldwide need for a 'circular' economy, as opposed to the currently mostly 'linear' economy, has become widely recognised. The linear economy generates outputs that are harmful to the environment, whilst relying on non-renewable inputs (and their global supply chains) from finite natural reserves (Sariatli, 2017). The effects of climate change on the sector have been studied. One of these is water scarcity, which will require design changes to protected cultivation systems (Gruda et al., 2019a, b; Nikolaou et al., 2020). Similarly, the depletion of natural reserves poses a threat to greenhouse horticulture for other consumable inputs.

The risks to which linearity exposes greenhouse horticulture have become increasingly clear, with recent jumps in natural gas prices putting the sector under immense pressure (Schouten, 2021; Vakblad Onder Glas, 2022). Though fossil fuels are the most well-known example, these vulnerabilities apply to equally important inputs such

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as mineral fertilisers like phosphate, 85–90% of which is sourced in just five countries, all outside of Europe (Rosemarin et al., 2011). Fertiliser discharged and leaked into the environment also leads to environmental problems such as eutrophication (Torrellas et al., 2012). As a second example, the production of stone wool, a commonly-used growing medium, from virgin materials is energy-intensive and leads to CO_2 emissions (Hoes and de Lauwere, 2021; Nerlich et al., 2022), as well as being a non-biodegradable waste stream (Raviv, 2014; Savvas and Gruda, 2018).

Such risks – as well as their associated environmental impacts – could be reduced through more circular approaches. Economic activity can be decoupled from natural reserve depletion through (1) reducing material inputs by increasing efficiency; (2) recycling residual flows; and (3) extending usefulness through reuse, which includes exchanging material flows between different processes (Neves and Marques, 2022). Strategies such as these are often referred to as 'R-strategies' (Kirchherr et al., 2017). With respect to implementation of the R-strategies, one of the obstacles is the lack of quantitative knowledge concerning material flows within various sectors of the economy. By gaining insight into how much of each resource enters a process, and how much of it is transformed into which outputs, more informed efforts can be made to close loops.

This paper examines the example of Dutch high-tech greenhouse horticulture. Greenhouse horticulture is one of the Netherlands' 'top sectors' (knowledge-intensive and export-oriented industries). With its supply chains, it makes up 2.7% of GDP, 4.5% of R&D expenditure, and 4.7% of exports nationally (Centraal Bureau voor de Statistiek, 2020).

While increasingly efficient, Dutch greenhouse horticulture is still a mostly linear process, with the one partial exception of reuse of drain water, which is compulsory (van der Salm et al., 2020). Decades of research on this front has led to a much greater water- and nutrient use efficiency in Dutch greenhouses (DELTARES, 2021). The same applies to decreasing natural gas consumption (Smit and Velden, 2021). Whilst greater efficiency is helpful in reducing sensitivity to global supply chains and environmental impact, as well as slowing natural reserve depletion, it does not eliminate these problems altogether in the way circularity does.

In 2016, the Dutch government set the goal of total circularity for the Netherlands by 2050 (Rijksoverheid, 2021). The Ministry of Infrastructure and Water Management sees circularity as a means to reducing dependency on natural resources, reducing environmental impact, and ensuring the continuity of human activity generally. To achieve this, an intermediate target is to reduce the Netherlands' imports of fossil fuels, metals and other minerals by 50% by 2030 (Dijksma and Kamp, 2016; Rijksoverheid, 2021). The four strategies mentioned by the government (Hanemaaijer et al., 2021) are in line with the R-strategies like those mentioned above and in other publications (Kirchherr et al., 2017).

The government's vision on sustainable agriculture through circularity was published in 2018. For greenhouse horticulture, priorities include reducing emissions (greenhouse gases, fertilisers, and plant protection products), reducing dependence on fossil fuels, and becoming climate neutral by 2040. Developing renewable growing media and valorising organic by-products are also mentioned (Schouten, 2018). If greenhouse horticulture is to advance beyond good intentions, a quantitative understanding of the current situation of the sector is needed.

This paper will focus on tomatoes grown in high-tech greenhouses in the Netherlands, as it is one of the main crops in Dutch horticulture, making up over 30% of protected vegetable crops in terms of area (van der Meulen, 2021). Global tomato production in 2020 was estimated at 186 Mt (FAO, 2020), making it a major vegetable crop worldwide and resulting in a lot of research, innovation and new technology going into greenhouse-grown tomatoes (Heuvelink, 2018).

This paper quantifies six input/output material flows in Dutch high-tech tomato greenhouses. It does not aim to quantify environmental impact like an LCA. Instead, relevant material flows are quantified and their reproducibility verified across various references and calculation methods. In this way, the authors aim to help efforts to reduce environmental impact and natural reserve depletion, and to provide a means to quantify symbiotic circular production systems.

1.2. Scope & system boundaries

Six consumable resources were chosen: biomass, water, nutrients, carbon dioxide, plastics and substrate. Biomass is not a consumable input, but was included as a by-product of greenhouse horticulture. Natural gas is the most relevant consumable, both from an environmental (LCA) and financial perspective (Torrellas et al., 2012). This is probably the reason this one flow has been the most accurately quantified so far, and been subject of huge government programmes to reduce inputs (de Zwart et al., 2019). As this paper focuses on material flows that are potentially useful for recycling, natural gas is not considered here as an energy carrier, but as a resource indirectly relevant to carbon dioxide supplementation. In this case, rather than quantifying the natural gas input, only CO_2 enrichment is quantified, as supplemental CO_2 often comes from other sources (Mikunda et al., 2015).

Water, nutrients and carbon dioxide contribute directly to plant growth. Biomass includes non-sellable biomass such as stems and leaves, which may have potential applications in the circular economy (Manríquez-Altamirano et al., 2021). Substrate – most commonly stone wool in the Netherlands – is used instead of soil, which only around 3% of vegetable growers use (van der Meulen, 2018). The advantage of soilless systems is that water and fertiliser can be applied and controlled precisely. They also allow for easy collection and reuse of drain water, increasing water- and fertiliser use efficiency. The plastics in a greenhouse can have multiple functions, such as wrapping substrate, covering the floor, hanging tomato vines and supporting trusses.

The six aforementioned flows are the most important, common to most high-tech Dutch tomato greenhouses. Other important flows include plant protection products (PPPs), both organic and chemical; paper, as packaging material for resources coming in and products going out; temporary coatings such as chalk (used for sunlight regulation); and incoming plant material (i.e. seedlings). These were not included in this study for the following reasons. PPPs, despite their hazards, do not represent a large material flow, especially thanks to the widespread application of integrated pest control (Pilkington et al., 2010). They do not present a large environmental impact either (Torrellas et al., 2012), even if environmental impact is a separate issue to circularity, and a large driver for their reduction is food safety (European Commission, 2022). Moreover, the PPPs used in each tomato greenhouse differ considerably, with multiple chemical agents available for each possible pest (Van Iperen, 2022). This diversity, for the greenhouse horticulture sector as a whole, is reflected in surface water quality reports (Hoogheemraadschap van Delfland, 2021).

Most growers use stone wool, plastic twine, and other materials covered by the six flows above, whereas pest management strategies vary considerably and would therefore deserve a separate study to account for the complexity of the topic. Similarly, not all growers apply chalk to their greenhouses, even though it can be a sizeable material flow. The use of PPPs and chalk can also be eliminated (the latter through the application of movable shading screens), whereas for the six chosen consumables, elimination is either impossible or has not shown significant progress in becoming circular. Paper already has infrastructures set up for recycling (Holwerda et al., 2019). Virtually all

Dutch growers get seedlings from specialised young plant nurseries. However, this incoming flow was neglected since it is an integral part of the production process and seedlings are produced in a similar way to the tomatoes themselves, and make a negligible contribution to the overall biomass once the crop has matured.

The lifespan of the glass-metal structure of a high-tech glasshouse is at least 15 years (Torrellas et al., 2012). Although not all studies agree on its LCA impact (Torres Pineda et al., 2021), resources included in the greenhouse structure were disregarded, since glass and metals are often recycled after their useful life and are therefore already being handled in a circular manner (Montero et al., 2011). This study also focuses on consumables with a relatively short timeframe for potential integration within a circular economy.

The final numbers are expressed per kg of fresh yield. Arguably, giving the results per m^2 would make them more broadly applicable to other varieties, such as cherry tomatoes, where yield is much lower than for regular tomatoes but the system is otherwise comparable. However, numbers per kg directly relate the consumption of resources and a generation of by-products to the production of tomatoes, rather than the means used to do so. Although this study is not an LCA, quantifying per functional unit is also the convention for LCAs, and kg fresh yield represents the function of the system (Brentrup et al., 2004). Since many numbers in literature are often given per m^2, these and other original figures can be found in the Appendices.

1.3. Research questions

To investigate these six flows – biomass, water, nutrients, carbon dioxide, plastics and substrate – in Dutch high-tech tomato greenhouses, two research questions were formulated:

1. How does high-tech Dutch tomato greenhouse horticulture transform each of the six aforementioned material flows?
2. How much input enters the greenhouse, and how much of each output leaves the greenhouse, per kg of fresh yield?

2. Materials & methods

The research questions set out in Section 1.3 were mainly answered using figures from literature. The amounts per kg yield for each material flow were not always directly available. Because of this, they were often calculated from other data using the principle of mass balances. In this section, the approaches are explained for each flow. Different references gave differing numbers, a range of possible values within the same order of magnitude were obtained, rather than an exact result, to answer the second (quantitative) research question.

Several assumptions were made. The irrigation system was assumed to be typical of a high-tech greenhouse in the Netherlands, namely using stone wool as a substrate and employing a closed-loop irrigation system. Where applicable and no other yield figure was available, numbers were also normalised to an annual fresh yield of 73.4 kg m^{-2} (Raaphorst and Benninga, 2019). Similarly, when no other figure was available, a figure of 1.225 plants per m^2 was assumed with 2 stems per plant, based on the life cycle analysis done by Montero et al. (2011).

In the rest of this section, the calculation methodologies and sources for each material flow are presented. Since many flows depend on each other, this is given in a sequential order. For interpretability, some intermediate figures are also given. Complete figures can be found in the Appendices.

2.1. Biomass

This study looked at three types of biomass: fruits, plant material such as stems and leaves, and the roots. This step examined the total fresh weight produced. The water, carbon and mineral content of this biomass was calculated in later steps.

The amount of fruit biomass was simply the yield, assumed in this study to be 73.4 kg m^{-2} based on Raaphorst and Benninga (2019). This source also contained figures on stem and leaf production, 4.5 kg m^{-2}. This figure only relates to the mass of plant material collected by waste management companies. Before collection, 60% of the plant material's mass is lost through evaporation (Montero et al., 2011). Therefore, the true mass of plant material at the source is more: 11.3 kg m^{-2}. This figure was verified using figures from Torrellas et al. (2012), which were adjusted to the assumed yield. Figures from Weening and Vroege (2014) were also used but did not require scaling, since their yield was approximately 74 kg m^{-2}. Lastly, the stem and leaf production was calculated, using a harvest index of 72% (i.e. proportion of dry matter production going to fruits) and dry matter percentages found by De Koning (1994). This resulted in 10.5 kg m^{-2} for the assumed yield.

The amount of biomass in the substrate was taken from a study done by Nerlich et al. (2022), which showed that the dry mass of stone wool had increased by 8% by the end of the crop cycle. This figure was multiplied by the incoming mass of stone wool (Section 2.1.6), assuming a dry matter content of the roots similar to that of the stems at 13.9% (De Koning, 1994) since no figure could be found for the roots. A figure for fresh root biomass was also found in the recycling manual of a major stone wool substrate manufacturer, at 223 g m^{-2} greenhouse area (Grodan, 2018).

2.2. Water

Most water flows were calculated using the Waterstreams model, developed by Voogt et al. (2012). In this model, the default settings for a Dutch tomato greenhouse were used, with an 'average' (as described in the model settings) year in terms of temperature and precipitation (see Fig. 1).

Typically, there are four external sources of water available for Dutch greenhouses: rainwater, groundwater, tap water, and surface water, with rainwater being most preferable due to its low cost and low sodium content. The Waterstreams model calculates the total consumption from each of these sources on an annual basis. Because this depends on precipitation, radiation (which drives evapotranspiration) and also on water storage capacity, water consumption per source will differ per year, by geographical location and the specifications of the greenhouse. Typical weather and the default settings were used, to give a reasonable estimate of what can be expected in practice. The model's default settings also included 80% recovery of condensation water from the roof. This was seen as an internal flow, similar to the recirculation of irrigation water. In the model run used, the consumption of the four aforementioned water sources, in l m^{-2}, was 683, 128, 43 and 0 respectively, adding up to 854 l m^{-2} per calendar year. Total water consumption was verified using figures from other sources (Raaphorst and Benninga, 2019; van Woerden, 2005), which were between 750 and 950 l m^{-2} per calendar year.

A second method to determine the consumption of different water sources was to multiply the total consumption from the Waterstreams model with the proportions of water coming from each of the four aforementioned sources in a typical Dutch tomato greenhouse, according to figures from Schoenmakers and Scholten (2021). With these

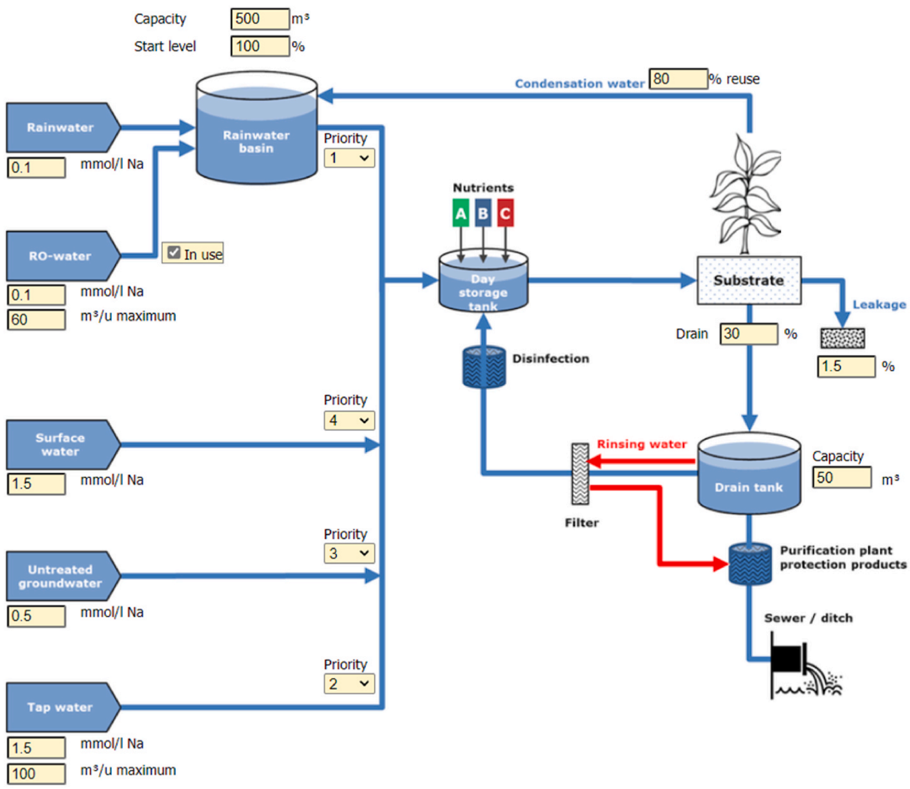

Fig. 1. A simplified diagram from the Waterstreams model's user interface, showing the flows between sources, the rainwater basin, and the various tanks in the greenhouse; with default parameter values for a 1-ha greenhouse. The size of the rainwater basin determines how much rainwater can be used throughout the entire year, with precipitation and demand fluctuating.

figures, the authors aimed to illustrate the range of possibilities that can be reasonably expected in practice.

On top of water consumption by source, the model also calculated discharge and leakage flows, which are different, despite sounding similar. Discharge is deliberately done when the concentration of sodium in a closed-loop system (calculated by the model) exceeds a crop-specific threshold, and was verified using figures from Beerling et al. (2014). Leakage can occur from the irrigation system (Van Ruijven et al., 2018), but also at the end of the crop cycle when cleaning and preparing the greenhouse for the next crop (Beerling et al., 2018). The model's discharge was 12 l m^{-2}, which lies within the broad range of 5.2–74.6 l m^{-2} found by Beerling et al. (2014). Discharge volume can differ greatly per grower, depending on factors such as water quality, rain water tank capacity and irrigation strategy (van Os et al., 2016). Leakage volume from the model was 18 l m^{-2}.

Water taken up by the crop goes to fruits and plant material, though most of it is transpired. Water in the fruits was determined by assuming a dry matter content of 5.5%, within ranges determined by Heuvelink (2018) and Pascual et al. (2013), for round tomatoes. The volume of water in residual plant material (stems and leaves) was calculated using dry matter content figures found by De Koning (1994) and Heuvelink (2018), using residual plant material found by Raaphorst and Benninga (2019). This was verified with figures from Torrellas et al. (2012) and Weening and Vroege (2014), assuming an average dry matter content in stems and leaves of 12.3% from De Koning (1994) and Heuvelink (2018). The amount of water in the substrate at the end of the crop cycle was determined using the recycling manual mentioned above, since it could not be found in academic sources. This was 0.855 l m^{-2}, but largely depends on actions taken at the end of the crop cycle (Blok et al., 2016). The contribution of water in the roots themselves was calculated by dividing root dry matter by its dry matter content, assumed to be equal to that of the stems (13.9%) from De Koning (1994).

Evapotranspiration mass was assumed to be the difference between total consumption (from the Waterstreams model) and the flows going to all the aforementioned sinks, following the water balance of greenhouse irrigation systems (van der Salm et al., 2020). This was approximately 740 l m^{-2}, depending on figures used in the calculation.

2.3. *Nutrients*

Six macronutrients were examined: nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca) and sulfur (S), as single elements, rather than the chemical form in which they are supplied as fertilisers. Inputs of N, P, and K were taken from Anton et al. (2012). To obtain a second independent estimate for these three and to get values for Mg, Ca and S, inputs were assumed to equal the sum of nutrient sinks and outputs. Since these sinks and outputs have their own ranges, a maximum and a minimum total was calculated.

The mass of nutrients discharged was obtained by multiplying the discharge volume from the Waterstreams model with drain tank concentrations (Table 1). The total mass of emitted nutrients, from discharge and leakage, was verified using figures from a document made for the Dutch Directorate-General for Public Works and Water Management (Rijkswaterstaat) with the latest figures on nutrient emissions (DELTARES, 2021).

The amount of nutrients left behind in the substrate was determined by multiplying the volume of water left in the substrate with drain water

Table 1
Drain water concentrations used for discharge and leakage calculations, in mmol l^{-1}. Other ions are added, but these were beyond the scope of this study.

N	P	K	Mg	Ca	S	Source
16.1	1.0	8.0	4.5	10.0	6.8	Sonneveld and Voogt (2009); Kipp (1995)
12.0	0.5	5.5	5.1	8.6	7.2	Voogt (personal communication, 2022)

nutrient concentrations.

To determine the amount of nutrients in plant biomass, figures were taken from Voogt (1992), who used two approaches. The first approach was to directly measure the mineral content of dry matter. The second, called the 'depletion method', was based on mass balances, by analysing the recirculating nutrient solution weekly and thereby determining how much had been taken up by the crop. These total uptake figures were then multiplied by partitioning proportions found per nutrient in the same study. To verify these figures, similar figures from Davies et al. (1981) were used.

2.4. Carbon dioxide

Carbon dioxide enrichment of the air is a common practice in Dutch greenhouses. Supplemental CO_2 comes from the exhaust of the gas-burning heater or a combined heat and power (CHP) system, or is waste CO_2 from other industrial processes.

Incoming CO_2 either ends up in plant biomass, or is lost through ventilation. The input dosage came from various sources. De Gelder et al. (2012) gave figures for both optimised and non-optimised dosage, which were 23 and 46 kg m^{-2} per crop cycle respectively. Dosage numbers from practice were also used for verification (De Visser et al., 2019; Weening and Vroege, 2014) and lay within the range found by De Gelder et al. (2012).

The mass of carbon dioxide taken up by the crop was calculated by multiplying the amount of biomass produced, covered in Section 2.1, by the carbon content and correcting for the molar mass of CO_2 rather than just C. For fruits, the figure of 5.5% dry matter content was used, within the ranges found by Heuvelink (2018) and Pascual et al. (2013). 73.4 kg of tomatoes with a dry matter content of 5.5% is 4 kg dry matter. Subsequently, two approaches were used. The first was based on figures by Davies et al. (1981), which gave the proportion of different organic molecules in the dry mass. The percentage of carbon was calculated based on their molecular formulae. The second approach was to use the carbon content figure found by Carvajal (2010).

For stems and leaves, a similar approach was taken, but with a higher dry matter content: 12.3% from De Koning (1994) and Heuvelink (2018), and 12.7% from LLorach Massana (2017). Carbon content was found in multiple sources: LLorach Massana (2017), Ti-da et al. (2008) and Carvajal (2010).

Supplemented CO_2 is not the only CO_2 taken up by the crop: ambient CO_2 in the air is another important source of CO_2. Without supplemental CO_2, the crop would still grow, albeit at a lower rate. The crop treats ambient and supplemented CO_2 equally, but the contribution of each was important to know, to truly understand how much supplemental CO_2 would end up in the crop. This depends on the dynamics of how the greenhouse was run: for example, if windows were closed for a long time, the only CO_2 in the greenhouse (and therefore taken up by the crop) would be supplemented CO_2, and no supplemented CO_2 would leave the greenhouse. However, if the windows were always open, the role of ambient CO_2 would be much greater, and the uptake supplemented CO_2 much lower. In aggregate, CO_2 enrichment leads to yield increases of 20–30% in tomatoes (Nederhoff, 1994; Pan et al., 2019), with one study estimating 40% of carbon to come from supplementation (Enoch et al., 1984). Calculating backwards from the former range, between 17% (20 ÷ 120) and 23% (30 ÷ 130) of the organic dry biomass was assumed to come from supplemental CO_2, and the rest from ambient CO_2. Quantifying the amount of ambient CO_2 was seen as irrelevant to circularity goals, since ambient CO_2 is virtually limitless, like O_2, but was done to help understand how much supplemental CO_2 really ends up in the crop.

Emitted carbon dioxide was calculated as the difference between total dosage and supplemental CO_2 going into biomass, using the principle of mass balances. CO_2 is released by the crop throughout the crop cycle through respiration, but this is an internal flow that goes into the air and may be taken up by the crop again or emitted, leading to net figures given in this paper.

2.4.1. Oxygen release

The resulting figures were in kg CO_2, not kg C, since this study's calculations were to look at how much CO_2 is taken up to understand the efficiency with which CO_2 is used, ignoring the oxygen released during photosynthesis. 68% of the mass taken up and fixated as CO_2 remains in the plant as dry biomass, with the rest lost to O_2 release from photosynthesis (Stanghellini et al., 2019). To make sure the mass balances added up in the material flow diagrams in Section 3.2, this difference was assumed to be O_2 release and is displayed as such. Despite ignoring hydrogen and microelements, this approach was deemed sufficiently accurate for this paper's purposes.

2.5. Plastics

Four main sources of plastics in tomato greenhouse horticulture were examined: the bags in which substrate is wrapped (LDPE), foil laid out on the floor (LDPE), twine used to hang the vines (PP), clips to secure the vines to the twine, and truss arches (PP), which are sometimes used to brace the trusses during select phases of the crop cycle. Many other plastic products are used in tomato greenhouse horticulture, but these four are used by most growers.

The amount of plastic in substrate bags was estimated using the LCA done by Torrellas et al. (2012), and verified using the recycling manual mentioned above (Grodan, 2018). Figures for floor-covering foil and twine came from the study done by Weening and Vroege (2014). These amounts were all per m^2 of greenhouse area and would not be affected by yield, and so were not scaled for a yield of 73.4 kg m^{-2}. All figures were then divided by 73.4 kg m^{-2} to obtain the amount of plastic per kg of yield.

No reference could be found for the amount of plastic used in the clips, so this was calculated manually using an estimate of the number of clips per stem, obtained from a grower. The assumed stem density was obtained from Montero et al. (2011), at 2.45 stems per m^2. This density was multiplied by the total area, the estimated number of clips per stem, and the mass of each clip, which was obtained from a manufacturer (Paskal Group, 2022) and a retailer (All4Plants).

Lastly, for the truss arches, the number of arches per stem and the mass of each one was obtained from a manufacturer (Paskal Group, 2018). This was also adjusted for the assumed yield.

2.6. Substrate

Figures for the amount of stone wool substrate used were obtained from Montero et al. (2011) and the recycling manual (Grodan, 2018). Since the amount of substrate per m^2 remains the same regardless of the crop's productivity, no adjustment for yield was applied. They were also verified experimentally, by measuring the dimensions of the substrate slabs at Wageningen Research's greenhouse facilities in Bleiswijk (15 cm wide × 10 cm tall, or 15 l m^{-2}) and multiplying it by the area and spatial density of the rows (0.625 rows per m^2), to obtain the total mass of substrate per hectare. To convert the volume into mass, the densities of various stone wool substrates from the two major producers in the Dutch market were used (Cultilene, 2021; Grodan, 2020).

3. Results

This section starts with a detailed description of each of the flows, with relevant figures. The final subsection contains diagrams to summarise these results, with all flows put together for context.

3.1. Detailed description per material flow

Each summary table in this section shows the figures with their sources. This shows the variability of many metrics, though these are

Table 2
The quantities of biomass produced, in g kg^{-1} fresh yield. Figures included in the diagrams are indicated with an asterisk (*). Root biomass is (1) a smaller flow and (2) mixed with substrate, so its figure is not included directly in the diagrams. Instead, only its water content (Table 4) is included, using total mass (**) from this table.

Output	Amount (g kg^{-1})	Source
Fruits	1000*	–
Plant material (fresh)	170	Montero et al. (2011)
	170*	Raaphorst and Benninga (2019)
	160	Weening and Vroege (2014)
	140	Calculation based on De Koning (1994)
Roots in substrate	3.0	Grodan (2018)
	5.9	Calculation based on Nerlich et al. (2022), dry matter content from De Koning (1994) and average of figures from Raaphorst and Benninga (2019) and authors' own stone wool measurements
	3.3**	Calculation based on Nerlich et al. (2022), dry matter content from De Koning (1994) and Grodan (2018)

mostly within the same order of magnitude. Where relevant, qualitative descriptions are given of how each flow is transformed during the crop cycle.

3.1.1. Biomass

The majority of the biomass produced, by fresh weight, is fruit biomass; other sources of biomass are relatively small (Table 2). The amount of plant material produced per kg of fresh yield is consistent across various references. Despite the differing order of magnitude for root biomass, anyhow a negligible amount of dry matter is produced per kg fresh yield. Nevertheless, its presence hinders the recycling of stone wool, as it must be separated as much as possible first (Grodan, 2018).

3.1.2. Water

Table 3 gives an overview of the amount of water input for each of the four water sources and in total, for the assumed fresh yield. Most figures come from the Waterstreams model (Voogt et al., 2012) and calculations based on source distribution figures from Schoenmakers and Scholten (2021), as explained in Section 2.1.2.

As discussed in the Materials and Methods section, the quantities used from each of the four water sources depend on many factors. Therefore, these numbers give an order-of-magnitude estimate, but the total amount of water per kg of yield from the Waterstreams model seems to match figures from other references. Table 4 shows similar information for the water outputs.

Most water leaves the greenhouse through evapotranspiration. Because it is one order of magnitude larger, evapotranspiration is negligibly affected by the values of other quantities when calculated. The second largest sink are the fruits. The amount of water ending up in the fruits will greatly depend on the variety chosen, as different varieties have different sizes and dry matter percentages. Similarly, there is an even larger range of possibilities for discharge according to Beerling et al. (2014), as discharge will depend on factors such as the grower's irrigation strategy and input water quality.

Table 3
Water input quantities, in g kg^{-1} of fresh yield. Figures included in the diagrams are denoted with an asterisk (*).

Input	Amount (g kg^{-1})	Source	Calculation method
Rainwater	9300*	Waterstreams model (Voogt et al., 2012)	80% of total input (Schoenmakers and Scholten, 2021)
	11 500		Waterstreams model default
Groundwater (reverse osmosis)	1700*		15% of total input (Schoenmakers and Scholten, 2021)
	0		Waterstreams model default
Tap water	600*		5% of total input (Schoenmakers and Scholten, 2021)
	100		Waterstreams model default
Surface water	0		Both model and Schoenmakers and Scholten (2021) agree, at 0
Total	11 600	Waterstreams model (Voogt et al., 2012)	Total sum from model
	12 000	van Woerden (2005)	Figure taken directly from source
	10 200–12 900	Raaphorst and Benninga (2019)	
	9500–11 600	Torrellas et al. (2012)	
	14 100	Torrellas et al. (2012)	

Table 4
An overview of the water outputs and sinks, in kg kg^{-1} fresh yield. Figures included in the diagrams are denoted with an asterisk (*). Discharge and leakage figures (**) were added together for a total of 0.40, displayed in the diagrams.

Output	Amount (g kg^{-1})	Source
Evapotranspiration	10100*	Calculation as described in Section 2.1.2
Fruits	910–960 (950*)	Heuvelink (2018), Pascual et al. (2013)
Plant material	150*	De Koning (1994), Heuvelink (2018)
Leakage	240**	Waterstreams model (Voogt et al., 2012)
Discharge	160**	
	70–1020	Beerling et al. (2014)
Substrate	10*	Sum of Grodan (2018) and root water from Table 2 using dry matter content from De Koning (1994)

3.1.3. Nutrients

There is considerable variation in the amount of each nutrient per kg of yield (Table 5). Although the numbers are all within a similar order of magnitude, the relative difference between the highest and lowest figures is not always negligible.

Table 6 shows where these nutrients end up, and in which quantities.

A slim majority of the macronutrients N, P and K end up in fruit biomass, typically about 60%. 25–40% of these three macronutrients go to residual plant material, despite residual biomass making up a relatively small proportion of the total fresh biomass produced (as seen in Section 2.1.1), showing how nutrient-dense this residual biomass is compared to the fruits. Mg, Ca and S seem to mostly go to residual plant material, at 58% for Mg and even well over 70% for Ca and S.

Table 5
An overview of the amount of nutrients entering the greenhouse, in g kg^{-1} fresh yield. All weights are the total for each individual element. Figures included in the diagrams are denoted with an asterisk (*).

Input amount (g kg^{-1})						Source
N	P	K	Mg	Ca	S	
2.99	0.31	2.73	–	–	–	Anton et al. (2012)
2.60	0.39	3.95	0.29	1.43	0.54	Sum of largest values in Table 6
1.57	0.35	2.84	0.23	1.00	0.46	Sum of smallest values in Table 6
2.39*	0.35*	3.17*	0.26*	1.21*	0.50*	Average of other values in this table

Table 6
Figures for where nutrients end up, in g kg^{-1} fresh yield. All masses are of the individual element, e.g. N is just nitrogen, not a compound form such as nitrate. Figures included in the diagrams are not denoted here, since they were obtained by scaling the average of the output figures to add up to the input amounts (Table 5).

Output/sink	Amount (g kg^{-1})						Source
	N	P	K	Mg	Ca	S	
Fruits	1.76	0.21	2.90	0.11	0.13	0.11	Davies et al. (1981) assuming 16% N in protein
	1.10	0.21	1.91	0.06	0.07	0.08	Voogt (1992), depletion
	0.92	0.22	1.84	0.06	0.05	0.07	Voogt (1992), dry matter
	–	0.23	2.33	0.08	0.09	–	Balemans et al. (2014)
Plant material	0.70	0.14	1.00	0.15	1.24	0.39	Voogt (1992), depletion
	0.58	0.14	0.97	0.15	0.90	0.35	Voogt (1992), dry matter
Discharge	0.09	0.01	–	–	–	–	DELTARES (2021)
	0.04	0.00	0.02	0.01	0.02	0.02	Kipp (1995), Waterstreams model (Voogt et al., 2012)
	0.03	0.00	0.01	0.01	0.02	0.02	Wim Voogt (2022), Waterstreams model (Voogt et al., 2012)
Leakage	0.05	0.00	0.03	0.02	0.03	0.02	Kipp (1995), Waterstreams model (Voogt et al., 2012)
	0.04	0.00	0.02	0.02	0.03	0.02	Wim Voogt (2022), Waterstreams model (Voogt et al., 2012)
Substrate	0.003	0.000	0.001	0.001	0.002	0.001	Kipp (1995), Grodan (2018)
	0.002	0.000	0.001	0.001	0.001	0.001	Wim Voogt (2022), Grodan (2018)
Total not taken up (discharge, leakage, substrate)	0.14	0.01	0.05	0.03	0.05	0.04	Sum of maximum values
	0.07	0.00	0.03	0.03	0.05	0.04	Sum of minimum values

Table 7
Different amounts of CO_2 supplementation, in g kg^{-1} fresh yield, adjusted for the assumed yield of 73.4 kg m^{-2}. The figure included in the diagrams is denoted with an asterisk (*).

CO_2 supplementation (g kg^{-1})	Source
545	Weening and Vroege (2014)
316–629	De Gelder et al. (2012)
613*	De Visser et al. (2019)
477	Raaphorst and Benninga (2019)

3.1.4. *Carbon dioxide*

The range of possible CO_2 dosages is large (Table 7). This is to be expected, since it depends on the grower's decisions, based on personal attitudes but also a cost-benefit analysis heavily dependent on the price of CO_2. This affects how efficiently the CO_2 is used within the greenhouse, in particular whether or not supply compensates for ventilation requirements.

Table 8 gives an overview of where this supplemented CO_2 ends up.

Most supplemented CO_2 is not taken up by the crop, but is lost through ventilation. Even with a more advanced supply strategy, emission remains a large flow.

Within crop biomass, most CO_2 goes to the fruits. This is to be expected: even though the fruits have a lower dry matter content, the harvest index of tomatoes is 72% (Heuvelink, 2018), meaning 72% of the total dry matter produced is in the fruits. In this study's figures, 75.5% of the CO_2 taken up goes to the fruits.

Table 9
The different sources of plastic, their amounts per kg fresh yield, and where they end up at the end of the crop cycle (the sink). Figures included in the diagrams are denoted with an asterisk (*).

Plastic type	Sink	Amount (g kg^{-1})	Literature
Substrate bags (LDPE)	Substrate	0.4	Montero et al. (2011)
		0.3*	Grodan (2018)
Foil (LDPE)	Disposal	0.7*	Weening and Vroege (2014)
Twine (PP)	Plant material	0.6*	
Truss arches (PP)		0.3*	Estimate based on Paskal Group (2018)
Clips (PP)		0.9*	Estimate based on Montero et al. (2011) and retailer (All4Plants)
		0.6	Estimate based on Paskal Group (2022)
Total		*2.5–2.9*	–

Table 10
A collection of figures for stone wool substrate used in tomato production, in g per kg fresh yield. The figure included in the material flow diagram is denoted with an asterisk (*).

Amount (g kg^{-1})	
5.7	Grodan (2018)
6.1*	Montero et al. (2011)
9.4–11.0	Raaphorst and Benninga (2019) and authors' own measurements

Table 8
An overview of the different CO_2 sinks depending on the % yield increase from CO_2 enrichment, in g kg^{-1} fresh yield, adjusted for the assumed yield. Figures included in the diagrams is denoted with an asterisk (*).

Sink	Amount (g kg^{-1})		Enrichment yield increase (%)	Source
	Total	Of which supplemental		
Emission	585*	(585)	30 (Nederhoff, 1994)	Calculation as described in Section 2.1.4, using De Visser et al. (2019)'s supplementation, a strategy based on a low CO_2 price
	593	(593)	20 (Pan et al., 2019)	
	288	(288)	30	Calculation as described in Section 2.1.4, using De Gelder et al. (2012)'s supplementation, a strategy focused on savings
	296	(296)	20	
Fruits	93*	21*	30	Carvajal (2010)
		15	20	
Plant material	31*	7*	30	Heuvelink (2018), Carvajal (2010), Section 2.1.2
		5	20	

3.1.5. Plastics

Table 9 gives an overview of the figures found for each source of plastic, per kg of fresh yield, and where they end up at the end of the crop cycle.

Unlike many other flows, plastic flows are not transformed during the crop cycle beyond minimal ageing, but they can be mixed with other flows. The twine and clips, about 40% of the plastic consumables included in this study, are mixed with plant material, leading to challenges for reuse or recycling. Similarly, substrate bags must be separated from the substrate itself, either before or after shredding. Shredding facilitates the decomposition of biomass and drying of the substrate.

3.1.6. Substrate

Dutch tomato crops virtually all use one form of substrate: stone wool (with others being a small minority using coconut coir or soil). The amount of stone wool used can still differ (Table 10).

The differences in the figures in Table 10 can be explained by the differences between varieties of stone wool substrates on the market, which have different dimensions and densities. Despite this, the same volume was assumed per m^2 of growing area: 0.011 m^3 m^{-2} (Raaphorst and Benninga, 2019). This was verified with the authors' own measurements and calculations, which gave 0.0094 m^3 m^{-2}. Both figures resulted in the range seen in Table 10. Like plastics, stone wool is chemically untransformed by the crop cycle. However, it is physically deformed and mixed with other flows mentioned in previous sections: water, nutrients, root biomass, and often plastics.

3.2. All flows together

Fig. 2 shows how water is by far the largest input by mass. This is followed by CO_2 enrichment, which is in a different order of magnitude. Nutrients, stone wool, and plastics, in descending order, are in an even smaller order of magnitude.

Fig. 3 shows the sinks and outputs of tomato greenhouse horticulture. Oxygen released during photosynthesis is not included. Because of this, and the fact that ambient CO_2 was not included in Fig. 2, the total area of both treemaps is not identical (though on this scale, the difference is imperceptibly small), but they are on the same scale.

Evapotranspiration is by far the biggest output, but has no environmental impact as it is safely returned to the natural water cycle. The second largest output are the fruits. The remaining outputs add up to a mass slightly larger than that of the fruits. Without recovery, they involve either environmental impact or natural reserve depletion, as do the fruits after consumption.

Fig. 4 shows (1) the efficiency for each flow separately and (2) the composition of the various outputs.

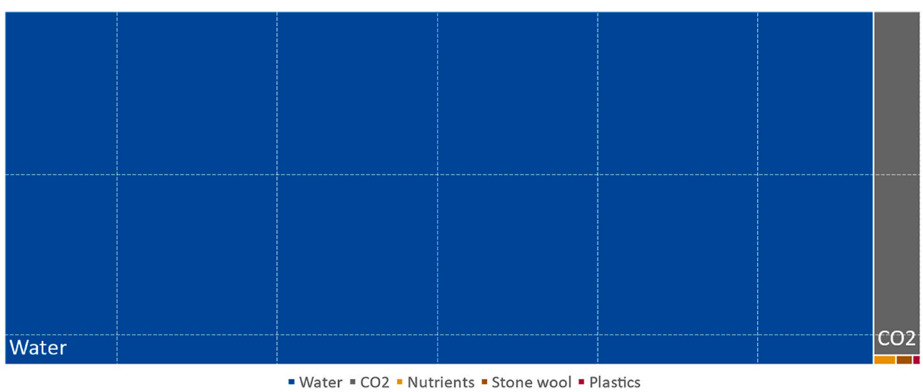

Fig. 2. A treemap of the five inputs for tomato greenhouse horticulture, where area is proportional to mass. Ambient CO_2 has not been included. The scale is identical to that of Fig. 3. One square on the dotted-line grid represents 1 kg kg^{-1} fresh yield.

Fig. 3. A treemap of the seven sinks/outputs of tomato greenhouse horticulture, where area is proportional to mass. The scale is identical to that of Fig. 2. On this scale, plastics disposal is not visible (lower right corner). Released O_2 is not included. One square on the dotted line grid represents 1 kg kg^{-1} fresh yield.

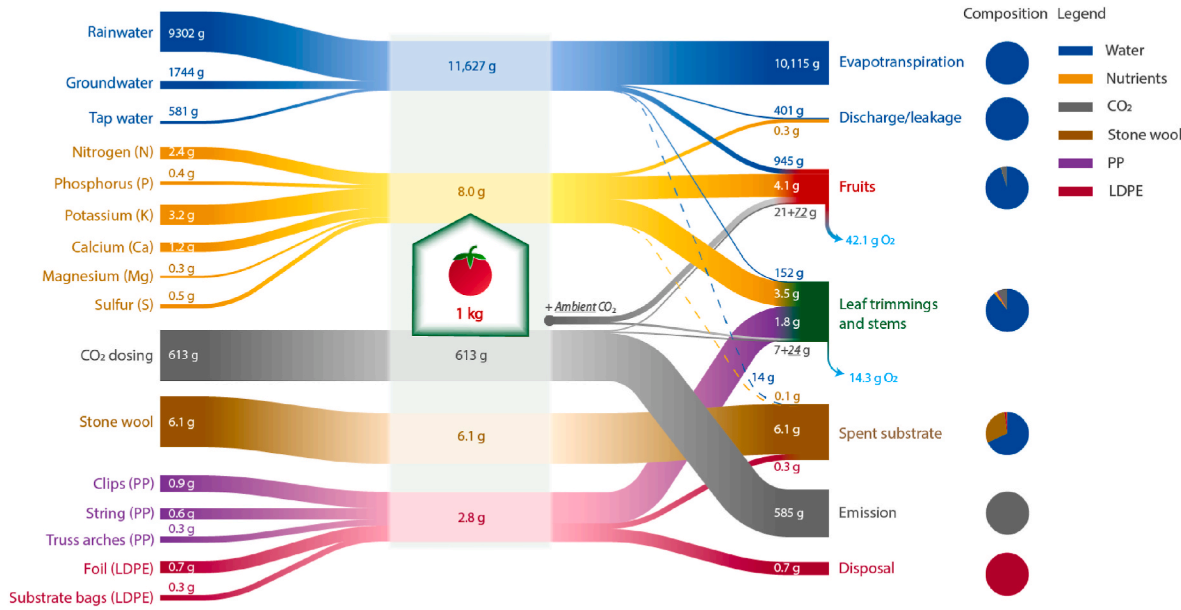

Fig. 4. A material flow diagram of six flows in Dutch tomato greenhouse horticulture, in g kg^{-1} fresh produce. The flows are not in proportion to each other, which may initially seem counter-intuitive (e.g. tomatoes are over 90% water, but the water flow is the smallest of the three going to the fruits). For each sink/output, pie charts help visualise their composition in terms of the five inputs. Excessive significant figures are sometimes given (e.g. for water) to ensure flows add up and match input/output masses, since flows are often in a different order of magnitude to each other.

4. Discussion

4.1. Results' implications

This study's results show that even a high-tech food production system such as a greenhouse is far from 100% resource efficient and produces emissions as well as residual material flows. For each of the three inputs that directly become constituents of the fruits – water, carbon, and nutrients – a large proportion does not end up in the tomato itself at 92%, 85%, and 49% respectively.

Since over 85% of water is lost through evapotranspiration, the biggest efficiency gains can be made by recapturing this water. Rather than only capturing water condensed from the roof, a closed or semi-closed greenhouse, which are actively cooled, would allow for far more water to be recovered. Recollection and re-use of water collected at the cooling element has reduced the external input to about 4 kg water kg^{-1} yield (Tsafaras et al., 2022), compared to the 11.6 found in this study.

The largest non-yield sink for nutrients is residual biomass. It contains nearly half of the nutrients that went in, with the majority of Mg, Ca and S ending up in leaf trimmings and stems. This makes it an interesting option for nutrient recovery, or a source of nutrients elsewhere in the circular economy. Still, the nutrients in all flows leave in a diffuse manner, and residual biomass is no exception, being only 2% nutrients by mass. Getting these nutrients back to the same concentration in which they were supplied will therefore be a challenge.

Like for water, supplemented CO_2 shows an extremely low efficiency, with over 95% leaving the greenhouse through ventilation. To reduce environmental impact and dependency on natural reserves, a helpful step would be to optimise dosage. As mentioned in Section 2.1.4, optimal dosage could reduce CO_2 requirements by 50% (De Gelder et al., 2012). This would at least reduce the absolute amount emitted. As very little CO_2 goes to residual biomass, recovery efforts from leaf trimmings and stems are insignificant compared to direct emissions.

Stone wool leaves the greenhouse as a relatively concentrated flow, making up nearly 95% of spent substrate by dry mass. However, the remaining nutrients and plastics pose a challenge for end-of-life resource recovery: not only for stone wool, but also for these other flows, of which so little ends up in the substrate. Shredding is a helpful first step, but flawless separation still remains a challenge. Drum filters are used, but a considerable proportion remains in the reusable substrate granulate, which increases costs and may even lead to rejection by recyclers (Grodan, 2018).

Plastics that do not end up in the substrate flow are mixed with residual biomass. This makes it challenging to use this biomass elsewhere in the circular economy, which is why this flow is currently either thrown away or incinerated. The plastics themselves are also diluted by this biomass, making them hard to recover. Biodegradable plastics are currently more expensive than their conventional counterparts, and are prone to degradation during the crop cycle, leading to vines falling down.

4.2. Applications

Even 100% resource use efficiency would not make for a circular or sustainable production system if the materials were not recovered. If the CO_2 dosed in greenhouses comes from fossil sources, it will still contribute to resource depletion and climate change. Similarly, 100% phosphate efficiency without post-consumption recovery would still lead to natural reserve depletion. Instead, the entire supply- and (re)use chain has to be considered for material flows. An alternative for fossil CO_2 could be to shift towards renewable sources such as biomass or direct air capture technology. The same applies to nutrients: Greenhouse technology allows for very efficient use of water and fertiliser (Beerling et al., 2014), but minerals will still have to be recovered from residual- and waste streams to avoid the depletion of natural reserves such as phosphate and potassium mines. No matter the efficiency, circular approaches to greenhouse horticulture will be needed, on top of efforts to reduce natural gas energy consumption.

Residual flows from greenhouse horticulture should be recycled or otherwise reused in other processes, and greenhouse horticulture should do the same with residual flows from other sectors. One approach to doing this are 'cross-overs', combinations where greenhouse horticulture exchanges material flows with another process in a symbiotic fashion. A well-known example of this is aquaponics, where nutrient-rich water from aquaculture is given to crops. There, depending on what is being grown, rules of thumb are common for the proportioning of vegetable crops to aquaculture, to keep nutrients in balance: for example, 2 m^3 of hydroponic grow beds for every 1 m^3 of aquaculture tanks has been suggested (Lennard and Goddek, 2019). Hopefully, figures from this paper will inform similar rules of thumb, calculations and design decisions for new cross-overs that involve any of these six flows. For example, questions such as how many m^2 of greenhouse can be supplied with CO_2 from the fungiculture industry or biodigestion, or the number of pigs required to give 1 ha of tomato greenhouse all its nutrients, can be more easily answered.

4.3. *Calculation methodology*

The extent to which this study's numbers depend on the assumed yield should also be discussed. The assumed figure is an average: The exact number can change depending on the grower or variety of tomato grown. Because of this, the unadjusted numbers are given in the Appendices. This section briefly outlines how this study's figures could be adjusted. In short, it depends on the biology of the crop and specifications of the system.

The proportion of water, nutrients and carbon in the fruits depends on the variety of tomato being grown. In varieties where the dry matter content is higher, the yield is usually lower, as is the case with cherry tomatoes (Reina-Sánchez et al., 2005). Uptake of CO_2 and nutrients in fruits will be the same per m^2, but higher per kg yield. Water going to fruit biomass will be lower both per m^2 and per kg yield. Generally it is only the water relationships (fresh weight) that change and dry matter allocation is hardly affected (Ho, 1996). Hence some quantities will not differ much per m^2 between varieties: non-yield biomass is approximately the same, as is substrate and plastics such as floor coverings and substrate casing. Therefore, a lower yield will lead to higher figures per kg yield. There is one exception, where consumption per m^2 goes down: a lower stem density means less plastic twine. The amount of plastic used in truss arches depends on the number of trusses formed, so in a cherry tomato where there are just as many trusses but with a lower yield per truss, this figure per kg yield would increase.

Lastly, the way the amount of nutrients in the slab was calculated does not reflect reality: for instance, many growers will decrease fertiliser dosage at the end of the crop cycle, meaning less nutrients would stay behind. However, nutrients are also deposited on the slab in solid form throughout the crop cycle, compensating for this. Within the order of magnitude this number was likely to be, the authors' simplified approach was deemed satisfactory.

5. Conclusion

As quantification is a crucial step in closing loops, this paper aims to contribute to improving the circularity of greenhouse horticulture, and facilitate efforts to include it in the circular economy. By knowing (1) how much of each material is used and (2) where the majority of a certain flow ends up, better-informed decisions can be made to increase efficiency or increase the rates of recycling and reuse. For example, if the goal is to increase water use efficiency of greenhouses, recovering water from the evapotransporation flow would by far have the most potential; and for nutrient recovery, it is useful to know that most Ca, Mg and S ends up in non-yield biomass and how much. Figures from this paper can also be used to dimension symbiotic 'cross-overs', for example using biogenic CO_2 or organic nutrients from other processes in the economy, such as biodigesters. This paper has quantified six main material flows within greenhouse horticulture consistently to aid efforts in reducing environmental impact and resource depletion, rather than only investigating its environmental impact, which has been done before. Energy use from natural gas, not examined in this paper, still has the largest environmental impact and should be replaced with cleaner sources, but the problems posed by linear supply chains will still have to be solved for other flows for greenhouse horticulture to remain viable.

CRediT authorship contribution statement

Alexander van Tuyll: Writing – original draft, Writing – review & editing, Methodology, Investigation, Conceptualization. **Alexander Boedijn:** Conceptualization, Methodology, Investigation, Supervision, Writing – review & editing. **Martine Brunsting:** Methodology, Investigation. **Tommaso Barbagli:** Writing – review & editing. **Chris Blok:** Writing – review & editing. **Cecilia Stanghellini:** Supervision, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.134665.

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