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Exploring the Environmental Performance of Urban Symbiosis for Vertical Hydroponic Farming

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Abstract: Vertical farming has emerged in urban areas as an approach to provide more resilient food production. However, a substantial share of the material requirements come from outside their urban environments. With urban environments producing a large share of residual and waste streams, extensive potential exists to employ these material and energy streams as inputs in urban farming systems to promote more circular economy approaches. The aim of this article is to assess the environmental performance of employing residual material flows for vertical hydroponic farming in urban environments in order to support more circular, resilient, and sustainable urban food supply. Life cycle assessment (LCA) is used to assess replacing conventional growing media and fertilizers with urban residual streams. Paper, compost, and brewers' spent grains were assessed for replacements to conventional gardening soil employed in the studied system. Biogas digestate was also assessed as a replacement for conventional fertilizers used in the recirculating water bath. The results suggest that large environmental performance benefits are illustrated when conventional growing media is replaced. Although not as significant, employing fertilizers from residual urban streams also leads to large potential benefits, suggesting the two residual streams have the potential for more circular hydroponic systems.

Keywords: urban symbiosis; food; hydroponic; industrial symbiosis; urban farming; life cycle assessment (LCA); horticulture; circular economy

1. Introduction

Urban farming has been identified by a number of authors to provide promising solutions to secure food supplies, produce more sustainable food and reduce pressure on agricultural land by shifting food production to urban environments [1–5]. Urban farming encompasses a number of methods and approaches; although vertical and hydroponic farming have become popular options worldwide in recent years; see e.g., [1,6,7]. This is primarily promoted for its potential to extend the seasonal availability of regional foods, especially in Northern Europe [2,8,9]. The methods for vertical urban farming are typically defined by horticultural practices in controlled environments less affected by outside factors, typically employing LED lighting, controlled atmospheric conditions and hydroponic systems for nutrient and water management. These are commonly located within the urban environment, or in peri-urban settings. Furthermore, many urban environments have unutilized spaces which have led to the further promotion of such vertical farming methods [5,10–12].

Much of the literature available on urban vertical farming points to the expectations and technical solutions for these growing systems [3,6,13]. Much less literature is available outlining case studies, findings from development practices and business models required, in addition to the resource and sustainability of these systems, as vertical farming applications and research is still gathering momentum [4]. As such, advocates of vertical farming claim that these farming techniques can reduce environmental impacts from conventional production systems, increase productivity, significantly reduce transportation; offering many advantages to traditional greenhouses and agriculture [10,14]. However, studies reviewing the sustainability of these claims are limited [15–18].

Furthermore, few studies review the link these innovative urban farming techniques to their urban systems. Many of the previous studies review, with traditional linear approaches; employing conventional fertilizers, growing media and energy requirements. While these systems are being extensively expanded in urban environments, the potential for the use of urban residual material and energy is important to assess to promote a circular economy through industrial symbiosis [9,19]. Recently, several authors have explored approaches to integrate urban agricultural systems with urban systems to develop symbiotic networks; see e.g., [10,17,20–23]. Through symbiotic development, employing concepts from industrial symbiosis, the firms can collectively collaborate for shared management of resources; creating local circular economies, resilience and revenue [10,24,25]. Industrial symbiosis (IS), a research topic which applies concepts to promote collaboration between firms for exchanging energy, utilities, materials, or services. As such, it can create mutual benefits and valorized processes and has seen considerable interest and growth in recent years due to the popularity of the circular economy [24,26,27]. Despite the term implying that industrial production and practices are of primary importance, this limitation is not exclusive and exchanges may extend beyond the industrial setting with surrounding systems to include agriculture, horticulture, forestry, fisheries, and other municipal and urban systems [19,28]; extending the bounded geographical proximity generally associated with the concept. In previous assessments, significant resource and environmental impact reductions compared to linear approaches have been outlined by employing residual materials from urban sources and industrial firms through industrial and urban symbiosis [17,21,29,30].

The study is based on previous work by the authors [31], and expanding this to review the potential of more urban symbiosis to employ several urban residual streams. The aim of this study is to assess the environmental implications of employing residual material flows for vertical hydroponic farming in urban environments in order to support circular, resilient and sustainable urban food supply.

2. Materials and Methods

The following sections outline the case study system assessed, the methodology for reviewing the environmental performance and information about the theoretical scenarios for urban symbiosis.

2.1. The Case Study

The assessment is based on the annual production from a vertical hydroponic farming system, Grönska Stadsodling 365, in the south of Stockholm, producing 60,000 plants in pots annually. The system produces a variety of leafy greens and herbs (e.g., basil, cilantro, mint, and salad), sold to regional supermarkets and distributors. For this study, it is assumed that only basil is produced, as basil represents the majority of outputs from the system [11].

2.2. Life Cycle Assessment Method

The environmental performance assessment uses life cycle assessment methodology for symbiotic systems based on recommendations provided in [32] using physical allocation to partition impacts between products and by-products for firms involved in the symbiotic exchanges. The sensitivity to this choice is also tested in the analysis. While the studied scenarios review cases for urban symbiosis with several firms, in this study, only the impacts for the vertical farming firm are reviewed. This is motivated by the scope to explore the implications of employing urban residual streams for vertical hydroponic farming and not reviewing an industrial symbiosis network.

The functional unit employed for the environmental assessment is the annual production of basil available to consumers in a pot with growing medium and packaging (i.e., 60,000 plants), see depiction in the Supplementary material, Figure S1. The study is limited to the production and final availability of the plants to consumers. Thus, the study is conducted using a cradle-to-gate perspective, including all upstream processes in the cultivation, such as the production of the pot systems, seeds, soil and fertilizers, and packaging materials. No waste handling of the pots or waste was included in the assessment as the aim is to review the influence of using residual materials (see Figure 1).

The LCA for the different scenarios was conducted in the OpenLCA software. For this study, the CML 2014 [33] life cycle impact assessment (LCIA) method was employed. The impact categories included in this study include GWP (100)—global warming potential (measured in kg CO_2-eq), EP—eutrophication potential (measured in kg PO_4-eq), AP—acidification potential (measured in kg SO_2-eq), ABD—depletion of abiotic resources—fossil fuels (measured in MJ) and human toxicity (kg 1,4-dichlorobenzene eq.). These impact categories were chosen as they provide a review of the regional, global and resource implications of food systems. Life cycle inventory (LCI) data was obtained from LCI databases such as Ecoinvent [34] and relevant data and input from literature.

2.3. Scenarios

2.3.1. Baseline (Current Production System)

The baseline scenario is based on previous work [31] and modeled to represent the current production system at Grönska (in 2018). In this scenario, the plants are grown in pots made of primarily paper and peat; referred to hereafter as paper pots. This was modeled based as a mix of peat and paper fibers, assumed to be similar corrugated paper product production based on data from Ecoinvent [34]. Gardening soil is employed as the growing medium in the baseline case [31]. Data for the materials and environmental impacts of gardening soil from the Swedish market were obtained from [35]. The fertilizer used for the hydroponic system is blended into the water bath and recirculated. Data for the fertilizers were provided by producers. Only major nutrients were included and modeled, which included nitrogen (N), phosphorus (P), and potassium (K). All LCI data for fertilizers was obtained from Ecoinvent [34]; see Table 1 and Supplementary Material for further details. The final products are packaged in the paper pots with gardening soil and wrapped in a waxed covered paper with labels; see Figure S1 in the Supplementary materials.

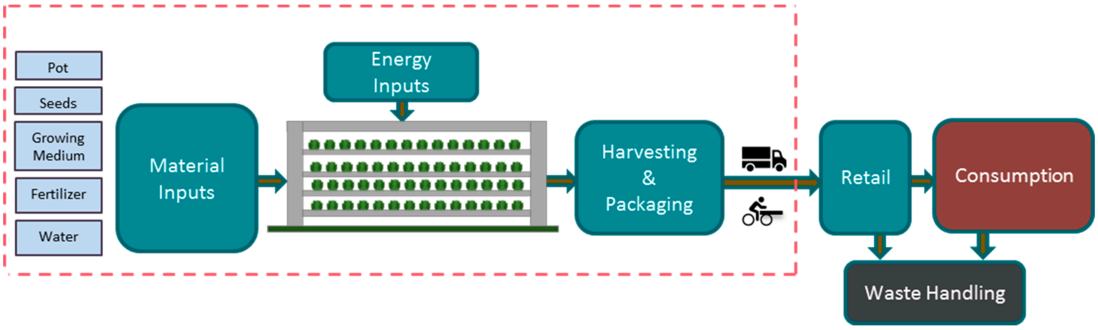

Figure 1. System boundaries of the study (Dashed line represents the system boundaries).

The transportation of the final products to retail, primarily to supermarkets in the Stockholm area is also included. In the case study, all transportation of plants was performed by cargo bike and electric vehicles; each encompassing 50% of the total deliveries, as the market is primarily local. The distance traveled annually for deliveries by the electric vehicle was assumed to be roughly 1390 km. Other transportation of the raw materials was assumed to be transported by truck, with distances outlined in Table 1. Data for transportation was provided by datasets in Ecoinvent [34].

The infrastructure employed in the vertical farming system, including LED fixtures, structures for the growing platforms, pumps, trays, tubing, heating, control units, and timers are also included in the assessment. See Table 1 and Supplementary Material for further information. All energy for the vertical farm, including electricity for lighting the LED fixtures, ventilation, pumps, and heating is included. For the operations, it is assumed that the ventilation systems is running 24 h per day and the LED fixtures roughly 12 h per day. The Swedish electricity mix and Nordic electricity mix were used for comparison and sensitivity to the choice; see analysis below. As outlined in [31] heating is regulated by an external heating unit during colder months and heat from the building (from district heating system) was not taken into account as the vertical farm is located in the basement, employing an unused space in an office building; while also producing residual heat from the LEDs that is sufficient for maintaining a constant temperature for production [11,22].

Table 1. Material and energy inputs for the annual production in the baseline scenario.

Main Category	Process/Flow	Amount	Unit	Transport (km)	Lifetime (Years)
Infrastructure	Steel Structure	242	kg	100	30
	LEDs	8640	units	100	15
	Trays (PET)	36	kg	100	15
	Tubing/Other Plastics	10	kg	100	5
	Pumps	2	units	100	10
	Heater and Other Electronics	3	units	100	10
Raw materials	Paper Pot	223	kg	100	-
	Seeds	6	kg	100	-
	Growing Medium (Soil)	12,350	kg	50	-
	Nitrogen (N)	10	kg	100	-
	Phosphate (P)	12	kg	100	-
	Potassium (K)	14	kg	100	-
	Paper	449	kg	100	-
	Wrapping Paper	38	kg	50	-
	Label	480	m^2	50	-
	Water	144,890	liters	-	-
Energy Inputs	Lighting	26,490	kWh	-	-
	Ventilation	490	kWh	-	-
	Heating and Electronics	3290	kWh	-	-
	Pumps	2190	kWh	-	-
Outputs	Plants	60,000	plants	1390	-

2.3.2. Symbiotic Scenarios

Vertical farming systems can benefit from the use of many urban residual materials. This includes wastewater, carbon dioxide, heating and cooling, and packaging. In the scenarios which review the use of urban residual streams, only the growing media and fertilizers are reviewed; see Figure 2. This was done considering they were found more feasible with the existing production methods and require less add-on technologies and infrastructure, see a review of potential options for urban symbiosis for the case study vertical farm in [36], previous literature [22], and based on communication with the case study firm [2]. Furthermore, these flows were shown to have a large impact on the overall environmental impacts in a previous study of the baseline scenario [31] and therefore, were explored further.

The scenarios, labeled Circular A-D represent different theoretical configurations of these urban resource circularity pathways for vertical hydroponic farming; assuming they produce similar outputs as the baseline scenario with the altered material configurations. This includes single or combined approaches for using urban resources. See further details in the proceeding text, Table 2, and Figure 2 for a depiction of these scenarios. In the scenarios Circular A–Circular D, equivalent volumes (m^3) of growing media derived from residual urban materials were used to replace conventional gardening soil. These include a combination of compost, shredded recycled paper (in Circular A and C), and combined with dried brewers' spent grains (BSG) (in Circular B and Circular D) from local breweries. The growing media mixtures, containing both nutrients and fiber were assumed to produce similar growing results in the hydroponic system employed. The mixtures were identified for their potential to provide nutrients and a fibrous base in the hydroponic systems. Allocation of impacts to the brewers' spent grains was based on economic allocation in the LCI dataset for dried grains from ethanol production [34], resulting in only 2.3% of the impacts being allocated to brewers' spent grains. Drying of the grains was also included in the assessment. For the recycled paper, no impact resulting from the paper was allocated to the product, only the collection and treatment (shredding) of the paper. Composting emissions were based on LCI data from [34] for compost. It was assumed that the transportation of BSG to the vertical farm required a distance of no more than 20 km due to geographical proximity. For the compost and paper, this was increased to 40 km to account for increased transportation of collecting the materials in the urban setting.

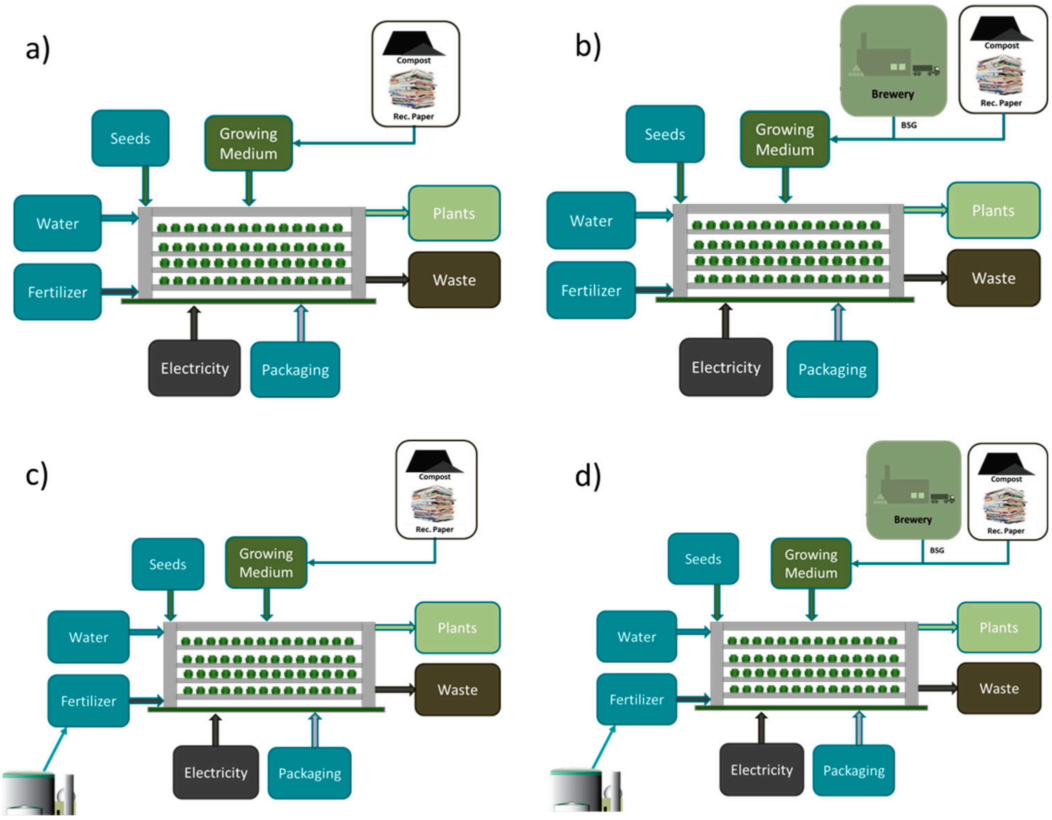

Figure 2. Depiction of circular scenarios A–D (shown in **a**–**d**) for vertical hydroponic systems using resources from urban environments; (**a**) depicting Circular A, (**b**) Circular B, (**c**) Circular C and (**d**) Circular D

In the scenarios Circular A-Circular D, equivalent volumes (m^3) of growing media derived from residual urban materials were used to replace conventional gardening soil. These include a combination of compost, shredded recycled paper (in Circular A and C), and combined with dried brewers' spent grains (BSG) (in Circular B and Circular D) from local breweries. The growing media mixtures, containing both nutrients and fiber were assumed to produce similar growing results in the hydroponic system employed. The mixtures were identified for their potential to provide nutrients and a fibrous base in the hydroponic systems. Allocation of impacts to the brewers' spent grains was based on economic allocation in the LCI dataset for dried grains from ethanol production [34], resulting in only 2.3% of the impacts being allocated to brewers' spent grains. Drying of the grains was also included in the assessment. For the recycled paper, no impact resulting from the paper was allocated to the product, only the collection and treatment (shredding) of the paper. Composting emissions were based on LCI data from [34] for compost. It was assumed that the transportation of BSG to the vertical farm required a distance of no more than 20 km due to geographical proximity. For the compost and paper, this was increased to 40 km to account for increased transportation of collecting the materials in the urban setting.

Conventional fertilizer was also substituted for a concentrated biofertilizer. The biofertilizer is produced from biogas digestate and concentrated through water removal. The biofertilizer is sourced from a regional biogas producer (and tested in Circular C and D) and mixed into the water bath. Figures from the nutrient blend are obtained from [37,38] for digestate from co-digestion plants employing large shares of food waste and other biological urban residual streams. The application of the biofertilizer was assumed to require a similar nutrient content as the conventional fertilizer. However, as outlined in [39], the availability of certain nutrients in biofertilizers from digestate may be a limiting factor for their employment and may not fully substitute conventional fertilizers. As such, additional phosphorous and potassium from conventional fertilizers were added to nutrient blend as the biofertilizer employed required additional input of these nutrients, while ammonium was assumed to meet requirements. Allocation of impacts to the biofertilizer were based on economic allocation, which resulted in no impact being allocated to the biofertilizer, as it does not typically result in a profit for co-digestion plants in Sweden [40,41]. The transportation distance for the biofertilizer was assumed to be 30 km from the nearest co-digestion plant. Further details on the nutrient amounts can be found in the Supplementary Material.

Table 2. Comparison of the different material flows for the baseline vs. circular scenarios.

	Baseline	Circular A	Circular B	Circular C	Circular D
Growing Medium	Conv. Soil	Paper and Compost	BSG, Paper, Compost	Paper and Compost	BSG, Paper, Compost
Fertilizer	Conv. Fertilizers	Conv. Fertilizers	Conv. Fertilizers	Biofertilizer + Conv. Fertilizer	Biofertilizer + Conv. Fertilizer

3. Results and Analysis

The results indicate potential environmental benefits for circular employment of residual materials for vertical hydroponic farming. As illustrated in and Table 3 and Figure 3, large reductions in greenhouse gas (GHG) emissions are possible. However, no significant change in the other reviewed environmental impact categories is illustrated. As further exemplified in Figure 4, the results point to the growing media as the primary beneficial material for reducing GHG emissions. All scenarios with growing media from residual sources have largely reduced GHG emissions; with the scenarios utilizing a blend compost and paper showing the largest reductions (e.g., scenarios Circular A and C); with GHG emissions by over 60% and 62% compared to the baseline scenario respectively. Circular C scenario, which illustrated the largest emissions reductions, is primarily due to the reduction of impacts from the growing medium. The impacts from the growing media employed in Circular B and D are only slightly higher (50 kg CO_2-eq annually) compared to Circular A and C; see also Table 3. Replacing conventional fertilizers with biofertilizer also illustrated GHG emission reductions compared to conventional fertilizer (reducing the impact of the fertilizers by roughly 90 kg CO_2-eq annually) for the Circular C and D scenarios, although the reductions were not as substantial compared to other inputs. See also Supplemenatry Material, Table S6 for further details.

Table 3. Comparison of the environmental impacts of the Baseline and Circular scenarios. GHG—Greenhouse gas emissions, Acid.—Acidification, Eutrop.—Eutrophication, Human Tox—Human Toxicity, Abiotic Res. Dep.—Abiotic Resource Depletion.

	GHG	Acid.	Eutrop.	Human Tox.	Abiotic Res. Dep.
	(kg CO_2-eq)	(kg SO_2-eq)	(kg PO_4-eq)	(kg 1,4 DCB-eq)	(MJ eq.)
Baseline	5241	15.16	204.8	6458	32,261
Circular A	2089	13.77	204.4	6338	29,100
Circular B	2179	14.38	204.7	6373	29,945
Circular C	2000	13.30	204.2	6291	28,655
Circular D	2090	13.91	204.6	6326	29,501

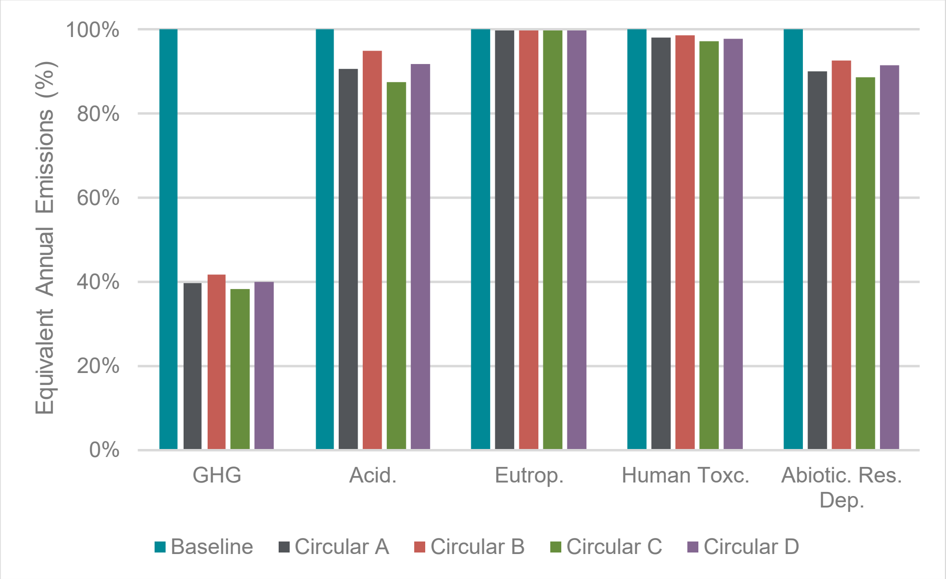

Figure 3. Comparison of the environmental impact categories for the Baseline and Circular scenarios reviewed, normalized to Baseline Scenario.

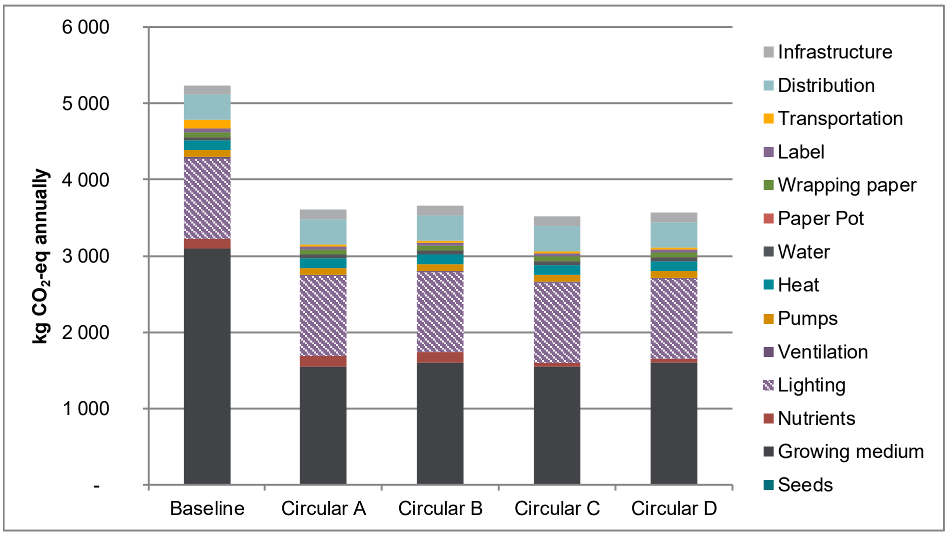

Figure 4. Review of the annual GHG emissions for the hydroponic system separated into different categories of material and energy inputs (measured in kg CO_2-eq annually).

While the GHG emissions reductions are dominated by the growing media, the acidification impacts are due primarily to the electricity use in lighting and the wrapping paper used in the final product. The overall acidification impacts are only slightly reduced by substituting the gardening soil with residual materials. It is further reduced, only slightly, by the use of biofertilizers, see Figure 5.

Eutrophication impacts are also dominated by the paper pots used in the final product and the distribution of the final plants. Therefore, as illustrated, the use of residual products had little effect on reducing the emissions from fertilizers and growing media employed, see Figure 6.

Human toxicity impacts are also dominated by the processes related to the paper pot, the infrastructure employed and the lighting. Once again, no pronounced reductions in human toxicity impacts can be illustrated from the residual use of materials to replace conventional fertilizers and growing media, see Figure 7.

The abiotic resource depletion shows a marked reduction from the baseline scenario from the reduced transportation involved in using available urban residual materials; the only impact category to show such a significant reduction. Thereafter, the use of abiotic resources is also reduced considerably by the replacement of conventional gardening soils with urban residual materials, see Figure 8.

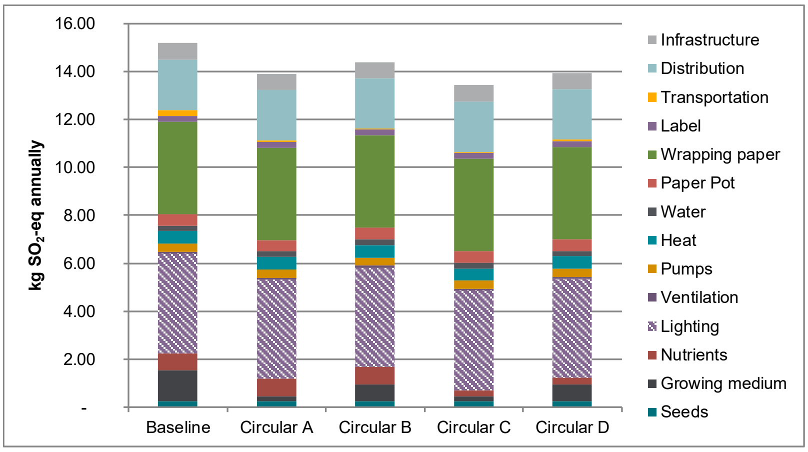

Figure 5. Review of the annual acidification impacts for the hydroponic system separated into different categories of material and energy inputs (measured in kg SO_2-eq annually).

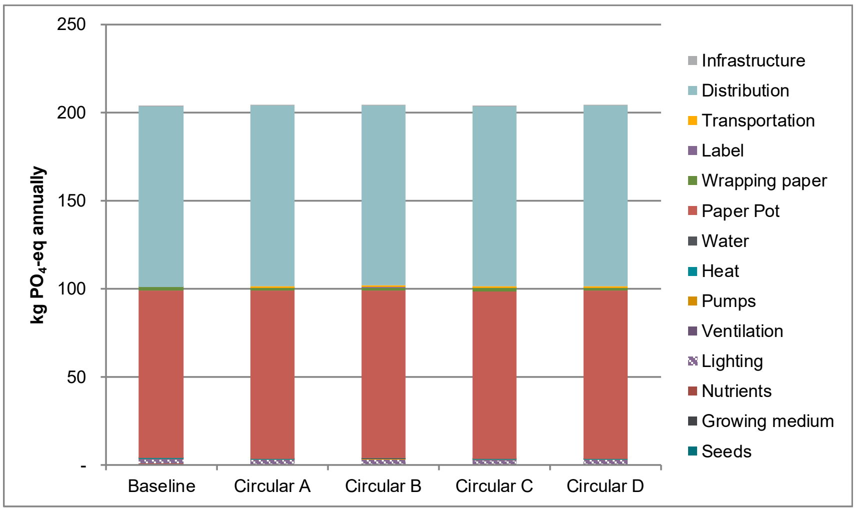

Figure 6. Review of the annual eutrophication impacts for the hydroponic system separated into different categories of material and energy inputs (measured in kg PO_4-eq annually).

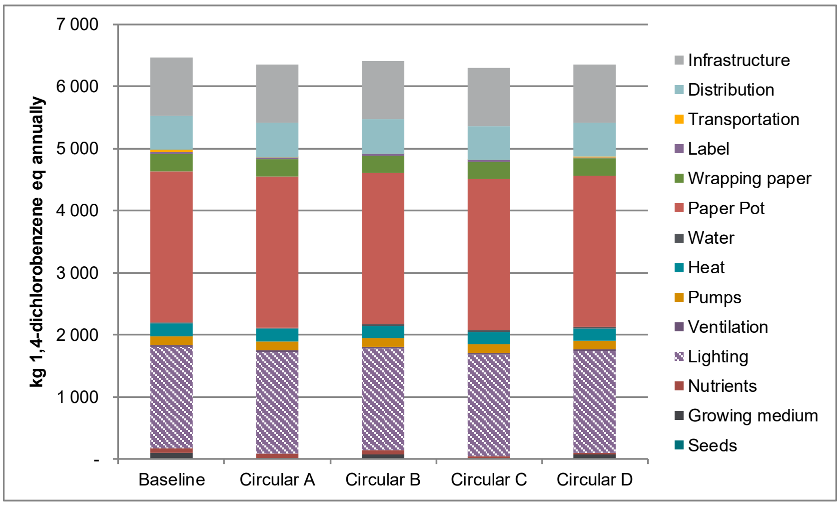

Figure 7. Review of the annual human toxicity impacts for the hydroponic system separated into different categories of material and energy inputs (measured in kg 1,4 dcb-eq annually).

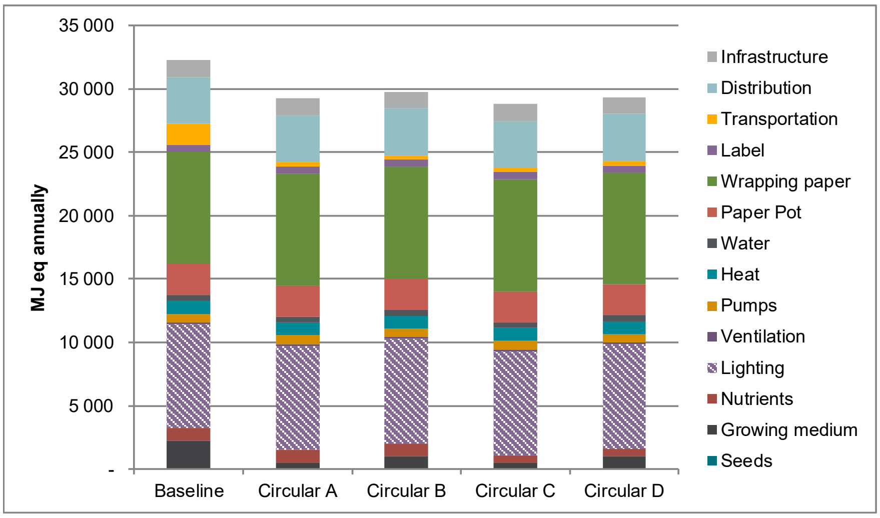

Figure 8. Review of the annual abiotic resource depletion for the hydroponic system separated into different categories of material and energy inputs (measured in MJ-eq annually).

3.1. Growing Media

While no significant change in the overall environmental impacts in other environmental impact categories other than GHG emissions were highlighted, Table 4 illustrates the implications for the environmental impacts for the use of residual materials as growing media. Again, large reductions are illustrated for GHG emissions, with all circular scenarios reducing the GHG emissions by over 3 tonnes CO_2-eq annually. Furthermore, reductions of over 70% are illustrated for acidification, human toxicity, and abiotic resource depletion. The scenarios, Circular A and Circular C show the largest potential environmental impact reductions; see Table 4.

In order to identify the sensitivity to this choice, comparisons were made for the baseline scenario and one of the circular scenarios employing different growing medium blends. A growing medium containing an increased amount of peat was employed to compare with the blend currently used (labeled Baseline (Incr. Peat). This was done as conventional gardening soils contain larger shares of peat than what is used in the case studied [35]. Furthermore, as Circular B and D had a large share of BSG (i.e., 80%), the sensitivity to the share of BSG was also reviewed by assuming it could be increased to 100%.

Table 4. Environmental impacts from growing media reviewed in the different scenarios.

	GHG	Acid.	Eutrop.	Human Tox.	Abiotic. Res. Dep.
	(kg CO_2-eq)	(kg SO_2-eq)	(kg PO_4-eq)	(kg 1,4 DCB-eq)	(MJ eq.)
Baseline	3087	1.30	0.44	101	2173
Circular A	21.7	0.11	0.03	9	322
Circular B	63.9	0.39	0.20	25	683
Circular C	21.7	0.11	0.03	9	322
Circular D	63.9	0.39	0.20	25	683

As illustrated in Figure 9, the GHG emissions may be sensitive to the choices made in the modeling. Increasing the amount of peat could increase the emissions by roughly 30%, with an increase in growing medium emissions of over 1000 kg CO_2-eq annually, with a notable effect when comparing with the circular scenarios. If BSG was assumed to make up 100% of the share of the growing medium in the Circular B scenario, the impacts would increase by 20%, or roughly 20 kg CO_2-eq annually. For the overall system´, this has little effect and only a slight increase in emissions for the BSG due to an increase in drying required for the added amount of BSG.

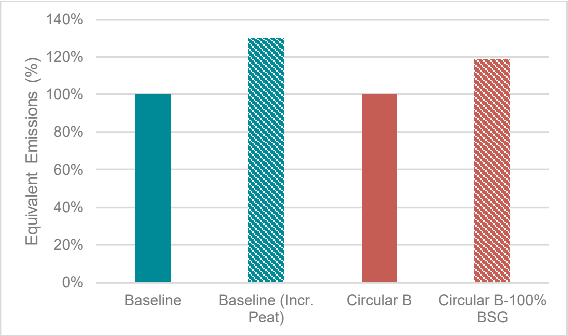

Figure 9. Sensitivity to choices made in modeling the growing medium (measured in %).

3.2. Fertilizers

Despite being less significant for the overall emissions of the vertical farming system, the use of biofertilizer from regional residual materials also led to reductions in nearly all impact categories for the Scenarios Circular C and D employing biofertilizer. As illustrated in Figure 10, over 60% reductions in emissions of greenhouse gases, acidification and human toxicity impacts resulted from employing biofertilizer. Eutrophication impacts were reduced by over 50%, while the abiotic resource depletion was reduced by over 40%, see further details in Tables S6–S10 in the Supplementary material for further details. As illustrated, this provides a discernible reduction in impacts compared to those from conventional fertilizer use in the baseline scenario; see Figure 10.

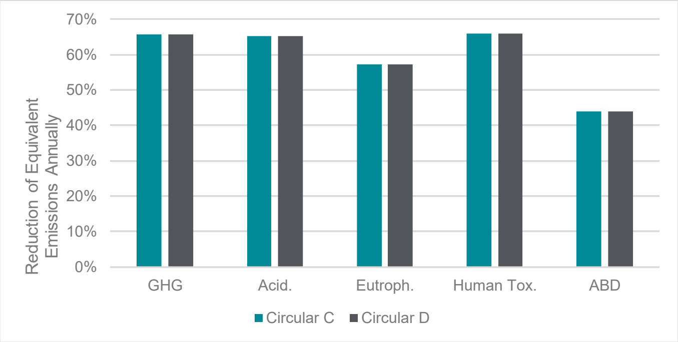

Figure 10. Reduction of emissions for different impact categories (illustrated in % reduction) for the use of biofertilizer in the Circular C and Circular D scenarios compared to the impacts from conventional fertilizers in the baseline scenario.

3.3. Influence of Methodology

As the life cycle assessment followed the approach for employing LCA to review the environmental performance of IS networks, employing the physical allocation method as outlined in [32], the results could be sensitive to this choice. For example, many previous studies have employed the system expansion approach as outlined in [32]; see e.g., [19,35,42]. However, this study, due to the magnitude of the materials being employed, employs only the physical allocation method. This choice of methodology could have an affect on theo overall impacts allocated to the final product, due to the physical allocation of impacts to the residual materials used in the vertical hydroponic farm. The sensitivity to this methods is illustrated in Figure 11.

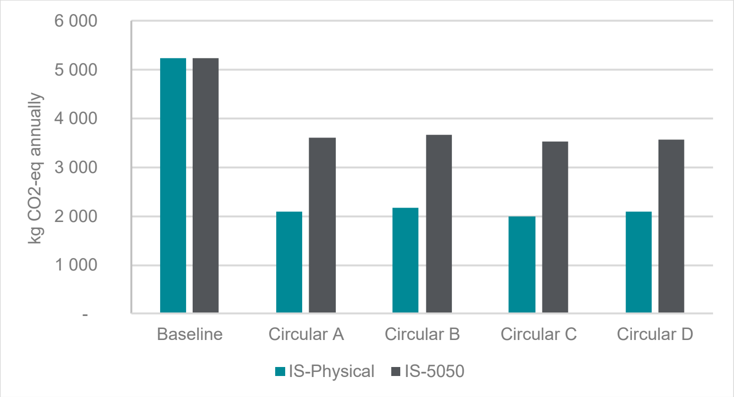

Figure 11. Sensitivity to chosen method for allocation (or avoidance) for exchanges of materials. IS-Physical refers to physical allocation and IS-5050 refers to the system expansion method outlined in [32].

As illustrated, the overall GHG emissions can be influenced by the choice of method to allocate or avoid allocation employing different methods. The 50/50 method outlined in [32] illustrates higher impacts. For example, in each scenario the 50/50 methodology increases the annual GHG emissions by over 1400 kg CO_2-eq. This is due to the fact that the hydroponic farm is on the receiving end of the synergies. It is therefore burdened with half the impact of the conventional raw materials for these exchanges and any upgrading impacts for their processing before use. In the employed method, i.e., applying physical allocation, impacts are allocated to the by-products used in the hydroponic farm based on their economic value, see more in [32]. Due to the fact that the by-products employed have little economic value, their impacts are reduced, illustrated in Figure 11 above.

3.4. Energy

Also, of importance is the processes employing energy, where a considerable share of the impacts can be attributed to the electricity used for different processes; primarily due to lighting, see also [31]. A sensitivity analysis for the electricity mix is reviewed subsequently. The sensitivity to the electricity mix employed for energy employed in the different processes was also reviewed; see Table 5. In this study, the Swedish electricity mix was employed. However, if the Nordic electricity mix was used, the overall impacts would be considerably increased. By using the Swedish mix, compared to the Nordic mix, in the circular scenarios (i.e., A–D) the emissions are nearly halved. The same is true for the GHG emissions per edible kg of plants produced; exemplifying the importance of this choice. See Supplementary material for a listing of the LCI data used in all scenarios, including datasets for Nordic and Swedish electricity mixes.

Table 5. Review of the sensitivity of the GHG emissions to the choice of electricity mix (Comparing the Nordic mix to the Swedish mix). Shown in annual GHG emissions.

F.U.	Electricity Mix	Baseline	Circular A	Circular B	Circular C	Circular D
Annual Impact (kg CO_2-eq/year))	Nordic Mix	7219	3985	4005	3850	3870
	Swedish Mix	5241	2089	2179	2000	2090

4. Discussion

As the results from this study show, urban environments have the potential to provide resilient, sustainable and competitive food systems through symbiotic networks. This can be done by exploring the potential to employ residual streams to directly reduce the environmental impacts associated with traditional material and energy flows for vertical hydroponic farming systems. The following sections provide a discussion of the results in relation to other studies and potential improvements to improve more symbiotic development.

4.1. Urban Symbiosis

The results indicate that environmental performance benefits, primarily GHG emission reductions, are possible through synergies with urban firms. Similar findings have been suggested in previous research through integration with utilities and waste heat [17,20,22] and claims in further studies (see e.g., [3,4,10]). For example, Chance et al. [10] review the material flows and social implications of an urban symbiotic network for hydroponic systems and stipulate on the sustainability of the system, although no quantitative were developed. Marchi et al. [23] also explore the possibility of employing symbiotic networks to improve horticulture, focusing primarily on the potential economic benefits. Few assessments of the environmental performance of such potential urban symbiosis networks are available in the literature, pointing to the novel results provided in this study. However, the benefits of such systems are not limited to environmental performance improvements. The urban symbiosis, and due to the relative geographical proximity, can provide many opportunities for shared learning; leading to human and social capital development [10,43]

4.1.1. Residual Products for Growing Media

The results suggest that the growing media has a substantial contribution to the environmental performance of the system. Replacing conventional soil containing a large shares of peat, with other media was shown to reduce the environmental impacts greatly. Similar results were also found in [44], also suggesting that using industrial by-products can improve the sustainability of their systems. Several previous reviews have studied the potential of residual products as growing medium, showing extensive viability for a number of different horticultural applications, also suggesting minimal effect on the plant production see, e.g., [44–47]. As [48] suggests, materials with high cellulosic content are a good source of organic matter, including e.g., municipal compost, paper waste, brewer's spent grain and paper mill waste. For traditional potted plants, these materials have been utilized up to 100 percent of the substrate used in the growing media, although blends of these have also proven important to take into account the different characteristics (e.g., salts, pH and moisture retention (ibid). However, employing residual products, may require added infrastructure for handling in automated processes for e.g., filling the pots; and also require further assessment to meet standards and requirements in the industry [49]. While this study did not assess these parameters more in detail, further research may be needed and testing in the case study systems will be required to maintain economic viability. Sparked by the potential impact of growing media on horticulture sustainability, recently, there has also been a push to harmonize assessments of growing media sustainability, despite the lack of studies available in the area [50].

While this study reviews the use of brewing industry residues, residual products from the brewing industry are not currently explored to their fullest potential [51,52]. This is especially true for small-scale breweries, which may not have handling processes to deliver by-products and wastes in an efficient manner. While there are a few large-scale breweries in Sweden with well-developed markets for by-products, small-scale breweries have been increasing in number, from roughly 10 in 2008 to over 340 in 2018 [1], and lack efficient handling methods for their by-products, increasing the need to manage resources more sustainably. Additionally, the use of by-products and waste handling is also quite divergent amongst producers. While many large-scale producers may currently use their by-products for low-value applications, i.e., to produce animal feed or even fuel for boilers [9,10], it is unclear how much of the small-scale producers handle their by-products, providing a potential revenue stream for this residual stream, although this may entail added infrastructure and processes to upgrade these to a marketable product.

4.1.2. Fertilizer

The results suggest that biofertilizers from biogas plants could offer a sustainable alternative to conventional fertilizers. Few studies have reviewed the use of biogas residues for hydroponic farming [39], although the material is widely employed in traditional agriculture [53–57]. Furthermore, hydroponic farming could provide a new market for biogas plants, where the market for this residual product has been identified as a bottleneck in their production system [40,58]. While this study assumes that the product is available, upgrading and further infrastructure may be needed to extract and include nitrification of the digestate for use in hydroponic farms [39].The results of this study illustrate that identifying and influencing the use of fertilizers can also improve hydroponic systems. Recent research suggests that the impacts associated with applications of conventional fertilizers for urban farming (e.g., in hydroponic systems) is important to take into account, influencing the overall life cycle impacts of the system [18].

4.1.3. Energy

As illustrated, electricity for the different processes was found to be a major influencing input, primarily a result of LED lighting systems employed, which accounted for the largest share (over 80%) of GHG emissions from the energy use. These results concur with previous studies, which illustrate that the control of the systems, e.g., through energy consumption for artificially maintained climatic and light regimes, constitute a significant contribution to the environmental impacts of such systems; see e.g., [9,10,15].

Furthermore, as reviewed in this study, the choice of LCI data used for the electricity in the assessment has a substantial influence on the overall impacts. Similar results were tested in a study by Romeo, Vea, and Thomsen [15]. The assessments in this study reviewed only the use of Swedish electricity mix, compared to the Nordic electricity mix. However, by purchasing more sustainable electricity from the market, e.g., from only renewable sources, the impacts may be significantly lower.

4.2. Extending the Synergies

While this study reviews the pilot case for a limited production of 60,000 plants per year, the case study firm has expanded production. With the new setup and increased number of LEDs, the hydroponic farm may have issues with excess heat [11,22]. As such, the residual heat could be utilized in the district heating system, and improve the efficiency of the LEDs and district heating network; see e.g., further elaboration in [22] with specific application in a Swedish context. Improving energy efficiency may also take place through synergies with other urban systems and buildings, e.g., by powering the LEDs with solar energy. These can be placed on the roofs of the occupied buildings for operations or on other buildings in proximity to the production site, which has also been stipulated in several previous assessments to reduce impacts and demand for grid electricity [59–61].

As outlined previously, many urban residual streams can be used for growing media; although many of these require drying and further processing before they can be used in current processes and machines for automated filling of the pots. Synergies with small-scale breweries be explored further to dry BSG. Small-scale breweries are also large consumers of energy and have an abundance of residual heat which is not used further; which can also be explored to dry the product [62,63]. The excess heat from the breweries may also be used in place of the electric heaters used in the case study [22], in case of expansion. However, the amount of heat required was not found to be important in the scale of production explored in this study, as it is primarily used during colder months (as the LEDs provide enough heat), it was out of scope in this study. However, previous studies have shown this to greatly benefit larger systems, see e.g., [22]. In addition to previously described material and energy synergies with the brewing industry, the carbon dioxide produced during fermentation may be used to expedite plant production. Similar studies have shown this to be possible [30], although again, these utility synergies were not explored in this study due to the scope and size of the production system. However, in the current system, which has expanded considerably, the use of carbon dioxide may be interesting to expedite growing and revenue.

While this study builds on theoretical potential for synergies between different firms in an urban context, it should be noted that the identification and reviews of viable options for further synergies is often not enough to lead to successful symbiotic development [64–66]. The vertical farming representatives alone will require support which can help with the success of synergy options. This can come from more hands-on facilitation to develop dialogues between the firms involved in these residual synergies. Many researchers have suggested that facilitation is key for successful industrial and urban symbiosis networks [19,28,67–69]; where trust, above all, has been identified as a critical resource to allow for industrial symbiosis to be feasible [70–73].

4.3. Limitations

This study includes a number of limitations which may influence the results. As illustrated in the analysis, the results may be sensitive to data choices; this is shown for the electricity LCI data employed. Several datasets were not available, e.g., forming of the paper pots and drying of the brewers' spent grains and assumptions on comparable processes were made. With hydroponic systems, it is also important to include water consumption, as a hallmark of the system is the limited use of water. However, few datasets and LCIA methods allow for such assessments; thus it was not included.

The chosen environmental impacts were also included as they are representative for studies of conventional agriculture. However, few studies have been made which review impacts other than GHG emissions and thus the results for these additional indicators cannot be compared with more than a few previous studies [15,31]. We recognize also that the vertical hydroponic system can offer many other benefits regionally [10], although this assessment was only confined to environmental impacts. Finally, while this study was made on a theoretical potential of these substrates and their output, it is important to note that a number of studies have been conducted for using residual materials with good results for the production of different types of plants and leafy greens [21,44,45] and the synergies could also be extended to review the impact of utility synergies (e.g., heat, carbon dioxide and water) [22,23,74].

5. Conclusions

Vertical hydroponic farming methods have emerged in urban areas worldwide to viably produce and sustain urban populations with sustainable food supplies. This study has reviewed the potential of employing urban residual streams to create a more circular vertical hydroponic system in Stockholm. Through symbiotic development, the results point to the potential to improve the environmental performance of these systems. This is achieved by employing residual streams for growing media, bio-based fertilizers and reducing transportation of raw materials. Overall, the largest environmental performance improvements come from the replacement of conventional gardening soil with residual materials for the growing media, i.e., recycled paper, compost and brewers' spent grains, reducing the GHG emissions from the entire system annually by over 60%. The impacts from fertilizers can also be reduced by employing biofertilizers, reducing fertilizer GHG emissions by over 66%. Furthermore, as similar to previous studies, the results also address a number of processes to improve the sustainability of these systems and many further synergies to improve the performance of vertical hydroponic farming through urban symbiosis.

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