



# Exploring the urban symbiosis potential of vertical farming systems: the case of Stockholm city

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## ABSTRACT

An increasing urban population is leading to a growing demand for food, putting pressure on already over-exploited resources. In regions with limited agricultural land and short growing seasons, such as Sweden, dependence on food imports makes the food systems particularly vulnerable to geopolitical instability and supply chain disruptions. Vertical farming systems (VFSs) have been proposed as a strategy to increase food self-sufficiency and resilience in urban areas. However, they are characterized by high energy consumption and greenhouse gas emissions. Urban symbiosis (UrS), the exchange of resource flows among organizations within the urban area, could improve VFSs' resource use efficiency and environmental performance. Yet, empirical evidence on UrS implementation in VFSs remains limited. This study investigates the resource flows of commercial VFSs in the City of Stockholm, assesses the current status of UrS, identifies potential synergies, and examines the key barriers and drivers influencing its implementation. Semi-structured interviews were conducted with representatives of five VFSs, complemented by on-site visits and secondary data analysis. The results show that all studied VFSs rely on similar key inputs, most of which are sourced from outside Sweden. Moreover, despite respondents' familiarity with potential symbiotic opportunities, UrS implementation remains limited. Four themes were identified as influencing adoption: resource compatibility and availability, business strategy, infrastructure, and economic feasibility. Output-based exchanges, such as waste heat recovery and reuse of organic waste, were found more feasible than input-based exchanges. The study suggests that facilitated UrS networks, supported by municipalities and academic partners, may represent the most suitable development model.

## 1. Introduction

By 2050, the global population is expected to reach nine billion, requiring a 70% increase in food production to meet the growing demand (FAO, 2009). The increase in population will primarily take place in urban areas (United NationsD. o. E. a. S. A.Population Division, 2019), where 80% of the food will be consumed (FAO, 2022). Sweden is facing a similar trend with almost 90% of its population living in urban areas (FAO, 2023a). The capital city of Stockholm is projected to reach 1.2 million people by 2050, with an increase of almost 25% (SCB, 2022). This urban population shift is causing food system stakeholders to reconsider production and distribution networks. Moreover, the current unstable geopolitical context, characterized by conflicts and

trade tariffs, further complicates the situation by disrupting food supply chains and causing volatility in energy markets (Sarwar and Rye, 2025).

Sweden uses about 6% of its total land area used for agriculture (FAO, 2023b) and has a relatively short growing season, thus it relies heavily on food imports. For example, imports account for over 70% of the fresh fruit and vegetable supply (FAO, 2009). This dependence makes Sweden vulnerable to global disruptions such as climate change, resource scarcity, and geopolitical instability. Additionally, the current food supply chain contributes significantly to greenhouse gas (GHG) emissions, land use change, freshwater use, and biodiversity loss (Crippa et al., 2021; Garnett, 2011; Poore and Nemecek, 2018; Willett et al., 2019).

In this context, urban farming (UF), the practice of growing food in

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cities, can become an important part of food provisioning in urban areas (Sanjuan-Delmás et al., 2018). UF can take place in many forms, including producing food in rooftop greenhouses, community gardens, or indoor farms (Eigenbrod and Gruda, 2014; Orsini et al., 2020). Vertical farming systems (VFSs), defined as the cultivation of crops in vertically stacked layers under artificial LED lighting (Kozai and Niu, 2020), are a type of indoor farm that have gained popularity in recent years in northern regions such as Sweden due to the relatively short growing season and benefits they can afford (Martin and Bustamante, 2021; Martin et al., 2024). VFSs have been proposed as a strategy to increase self-sufficiency and resilience in the food systems (Kalantari et al., 2017; Oh and Lu, 2023; Sowmya et al., 2024), increasing local production and reducing dependence on imports. However, for VFSs to contribute to resilient and sustainable food production in urban areas, their resource efficiency and link to urban systems will need to be developed. For example, VFSs are characterized by high energy consumption (Pennisi et al., 2025), especially due to artificial lighting (Kaiser et al., 2024; Weidner et al., 2019), and high GHG emissions (Piovano et al., 2026). Moreover, VFS entrepreneurs typically adopt a linear approach, sourcing many necessary consumables (e.g. growing media, fertilizers, and other supplies) through imports and disposing of their waste through conventional waste handling methods (Martin et al., 2022). Previous studies highlight how implementing circular production methods can improve environmental performance and reduce reliance on external resources (Martin et al., 2019, 2022; Sanyé-Mengual et al., 2019).

Moreover, VFSs within urban areas offer several potential advantages, such as shortening the supply chain and integrating with urban residual flows (Blom et al., 2023; Goldstein et al., 2016; Martin et al., 2019, 2022), a concept known as urban symbiosis (UrS) (Van Berkel et al., 2009). In such a system, one company's waste serves as an input for another company within the urban environment. Sweden has recognized the importance of industrial and urban symbiosis for accelerating the transition to a more circular economy (Regeringskansliet, 2023). As part of this, the government has supported the establishment of a national resource centre for industrial and urban symbiosis aimed at facilitating the development of symbiotic exchange (RISE, 2023).

Despite the growing attention to vertical farming as a sustainable UF approach, empirical evidence on the resource flows of commercial VFSs remains limited (Martin et al., 2023), with most existing studies exploring theoretical integrations of VFSs with urban resource flows (Blom et al., 2023; Martin et al., 2022). Overall, studies on UrS remain scarce, with few reviewing the barriers and drivers of its implementation (Fraccascia, 2018; Patricio et al., 2018), and none to our knowledge focusing on VFSs. Hence, this study aims to explore how commercial VFSs in the City of Stockholm could benefit from UrS, both by utilizing urban residual flows as inputs and by providing their residual flows for synergies within the urban environment. To achieve this, the study examines current VFSs operating in the city, analyzes their resource flows, outlines potential synergies, and investigates site-specific drivers and barriers influencing the implementation of UrS.

The paper continues with a background of the vertical farming and urban symbiosis literatures (Section 2), followed by the methodology (Section 3). Section 4 presents the results, which are discussed further in Section 5, including limitations and directions for future research. Section 6 summarizes the main conclusions from the study.

## 2. Background

### 2.1. Vertical farming systems

VFSs are a form of horticulture where plants are grown in indoor vertically stacked layers under artificial lighting and controlled environmental conditions (Kozai and Niu, 2020). These systems make use of closed-loop soilless techniques such as hydroponics, where water and

fertilizers are recirculated within the system (Son et al., 2020). VFSs can range from large warehouse-like facilities to smaller modular units such as container farms, in-store farms, and cabinet systems (Butturini and Marcellis, 2020; Martin and Bustamante, 2021; Martin et al., 2024; van Delden et al., 2021). Crops such as leafy greens, herbs, and micro-greens are mostly grown due to their high harvest index (the ratio of marketable or edible biomass to total plant biomass), small plant size, and short growth cycles (Pennisi et al., 2025; van Delden et al., 2021). VFSs require key material and energy inputs such as growing media, fertilizers, CO<sub>2</sub>, packaging materials, water, and electricity (Martin and Orsini, 2023).

Growing media is used as physical support for plants to enable root system development, ensure adequate aeration, water retention, and fertilizer uptake. Commonly used growing media include peat, perlite, coconut coir, and rockwool due to their optimal physical and chemical properties, including structural stability, air and water holding capacity, and sterility (Gruda et al., 2013). However, environmental concerns are associated with some of these materials. Peat is being gradually phased out in the horticultural sectors (Gonnella and Renna, 2021) as it is a non-renewable resource, and its extraction contributes to high GHG emissions (Savvas and Gruda, 2018). Coconut coir, although being a by-product of coconut production, is associated with long supply chains. Rockwool, instead, raises concerns due to energy-intensive production and potential health risk during handling, and its limited waste handling possibilities (Bussell and McKennie, 2004; Savvas and Gruda, 2018).

Fertilizers provide essential macro- and micronutrients to support plant growth and higher yields. Due to high nutrient solubility and precise composition, nutrient supply is typically provided through synthetic fertilizers in VFSs. However, nitrogen fertilizer production is associated with high GHG emissions (Menegat et al., 2022), while phosphorus and potassium rely on finite mineral resources (Cordell et al., 2009; Sardans and Peñuelas, 2015). Hence, alternative nutrient sources such as organic fertilizers and waste-based fertilizers (e.g. struvite) are being explored (Arcas-Pilz et al., 2022). Another key element in indoor cultivation systems is CO<sub>2</sub>, used to improve plant growth and yields (Chen et al., 2021; Mortensen, 1987). Typically, carbon dioxide is sourced from industrial gas suppliers in the form of pure liquefied CO<sub>2</sub> delivered in pressurized cylinders (Kaiser et al., 2024; Marchi et al., 2018).

Packaging material represents another key input for VFSs. Depending on how the final products are distributed, packaging may include plastic bags, or plastic and paper sleeves. Packaging is used to maintain product quality and extend shelf life; however, it contributes significantly to the overall environmental impacts of VFSs (Cavallo et al., 2025; Martin et al., 2023).

Today, most VFSs operate as stand-alone production units following a conventional 'linear' model, where materials and energy are sourced from virgin supplies, typically from abroad (Martin et al., 2023; Martin and Molin, 2019). However, studies have explored the opportunities to integrate VFSs with urban and industrial resource flows, such as the use of alternative growing media and fertilizers or the use of waste heat, demonstrating potential reductions in resource use and environmental impacts (Blom et al., 2023; Farkhondehmonfared, 2022; Martin et al., 2022).

### 2.2. Urban symbiosis

Urban Symbiosis (UrS), a sister concept of Industrial Symbiosis (IS), refers to the exchange of resource flows (e.g., materials, infrastructure, utilities, services, and knowledge) among separate organizations within an urban area, with the aim of generating competitive advantage (Chertow and Ehrenfeld, 2012; Chertow, 2000; Mirata and Emtairah, 2005; Van Berkel et al., 2009). Through these exchanges, often referred to as synergies, waste or by-products produced by one actor can be used as inputs by another, potentially reducing the demand for virgin resources and improving environmental performance.

Industrial and urban symbiosis networks can emerge in different ways. Self-organized networks develop when existing companies engage in spontaneous collaboration based on mutual interest (Chertow and Park, 2016). Planned networks develop when external actors co-locate companies with matching input-output flows during the planning stage (Chertow and Ehrenfeld, 2012). Facilitated networks are established due to the involvement of facilitators (either organizations or individuals) which actively help to connect companies, identify potential synergies, and establish a symbiotic network (Domenech et al., 2019; Paquin and Howard-Grenville, 2012). Priority is often given to the so-called “low-hanging fruit”, which are synergies that require limited transformation or processing and therefore are easier to implement (Paquin and Howard-Grenville, 2012).

Previous studies have identified several drivers for engaging in symbiosis, including cost reductions, the creation of new revenue streams, and improvements in environmental performance (Chertow, 2008; Domenech et al., 2019). However, barriers such as long payback periods, financial risks, and lack of trust among partners have been highlighted in the literature (Aid et al., 2017; Domenech et al., 2019; Walls and Paquin, 2015). Trust is considered a key factor in network formation, as it influences the willingness to engage in resource exchanges and information sharing (Chertow and Lombardi, 2005; Hewes and Lyons, 2008; Walls and Paquin, 2015). It develops gradually through repeated interactions between actors, and once established, more complex exchanges become possible (Ashton, 2008; Hewes and Lyons, 2008).

VFSs may benefit from integration with urban residual flows and infrastructures. Potential exchanges include the use of waste heat from vertical farms in other processes, utilizing CO<sub>2</sub> from urban sources, utilizing wastewater, and providing organic residues from vertical farms for other purposes (e.g. composting and mushroom substrates) (Blom et al., 2023; Kozai and Niu, 2020; Martin et al., 2022). However, much of the existing research has focused on theoretical examples, and empirical studies investigating the integration of VFSs with urban residual flows remain limited.

### 3. Methodology

#### 3.1. Research design

Due to the relatively recent development of vertical farming and the limited body of research addressing its application within an urban symbiosis context, this study adopted an exploratory research approach to provide initial insights into the phenomenon (Stebbins, 2001). The study combines both quantitative and qualitative data. Quantitative data were collected to characterize the farms and quantify their resource flows. Qualitative data were collected to capture respondents' experiences and insights regarding current and potential UrS practices, as well as the drivers and barriers influencing their implementation. This combination was deemed necessary as it allowed for a more comprehensive understanding of both potential synergies that could be established and the reasons why they are or are not pursued.

#### 3.2. Case selection

The selection criteria for the farms included their location within the City of Stockholm and their operation as commercial vertical farms. The companies were identified both through the researchers' network and through the website allabolag.se (an online Swedish company information platform) under the categories “Grönsaker, Växthusodling” (Vegetables, Greenhouse cultivation) and “Frukt & Grönsaker, Butikshandel” (Fruit & Vegetables, Retail). A total of nine companies suitable for the study were identified. Upon further evaluation, companies without updated websites or sufficient information were removed. In the end, six companies were selected and contacted via email, with five agreeing to participate in the interviews (Table 1). The interviewees

**Table 1**

Characteristics of the commercial vertical farms included in the study.

|           | Farm 1       | Farm 2                | Farm 3                | Farm 4               | Farm 5                |
|-----------|--------------|-----------------------|-----------------------|----------------------|-----------------------|
| Founded   | 2020         | 2019                  | 2021                  | 2019                 | 2015                  |
| Sqm       | 200          | 10                    | 30                    | 300                  | 1                     |
| Employees | 5            | 10                    | 2                     | 6                    | 3                     |
| Product   | Leafy greens | Leafy greens<br>Herbs | Leafy greens<br>Herbs | Herbs<br>Microgreens | Leafy greens<br>Herbs |

were informed about the purpose of the study to ensure their informed consent, both via email and at the time of the interview. Furthermore, they were notified that the interview would be audio-recorded, that they were not required to answer all the questions, and that they could choose to remain anonymous.

#### 3.3. Data collection

Primary data were collected through semi-structured interviews with CEOs or relevant employees from each company. Semi-structured interviews were deemed appropriate given the limited number of interviewees selected and the goal to gather in-depth insights and experiences with UrS from individual farm perspectives, which can be difficult to capture in a standard survey or questionnaire format (Morris, 2015). Interviews were conducted face-to-face between November 2023 and April 2024 at the respective farms. Prior to each interview, a site visit was conducted to observe the production system and gain a better overview of the facility.

An interview guide, provided in the Supplementary Material, was used during data collection and consisted of two parts. The first part focused on the farms' characteristics and resource flows, while the second part addressed respondents' knowledge of symbiosis, current and potential exchanges, and the barriers and drivers influencing implementation. The type of questions and data collected was inspired by previous studies on similar topics (see, e.g., Patricio et al., 2018; Martin and Bustamante, 2021). To triangulate data, secondary data sources such as company websites, technical reports, academic theses, and publicly available information were analyzed (Yin, 2014) (Table 2). In particular, the quantitative data for F2 were drawn from an academic thesis based on a modeled system rather than on operational measurements.

**Table 2**

Overview of the data collection.

| Respondent | Position     | Date       | Duration | Additional Data                                                                              | Source                                                   |
|------------|--------------|------------|----------|----------------------------------------------------------------------------------------------|----------------------------------------------------------|
| Farm 1     | Farm Manager | 2023-10-18 | 58:20    | VFS visit<br>Email<br>communication<br>VFS website<br>Social media posts                     | Internal<br>Internal<br>External<br>External             |
| Farm 2     | Co-founder   | 2023-11-21 | 44:28    | VFS visit<br>VFS website<br>Academic thesis                                                  | Internal<br>Internal<br>External                         |
| Farm 3     | CEO          | 2023-11-22 | 54:41    | VFS visit<br>VFS website<br>Social media posts                                               | Internal<br>Internal<br>External                         |
| Farm 4     | CEO          | 2023-11-29 | 42:14    | VFS visit<br>Email<br>communication                                                          | Internal<br>Internal                                     |
| Farm 5     | Co-founder   | 2024-04-22 | 50:26    | VFS visit<br>Email<br>communication<br>VFS website<br>Social media posts<br>Technical report | Internal<br>Internal<br>External<br>External<br>External |

### 3.4. Data analysis

The interviews were audio-recorded and later transcribed for quantitative and qualitative analysis. The quantitative analysis focused on the characteristics of the companies, including company size, number of employees, and quantification of input and output resource flows, as well as their source of origin and associated costs. During data collection, input and output resource flows were reported using different units and time periods. For this reason, these were first harmonized to a common annual basis to account for the differing reporting periods provided by respondents (Table 3). To enable cross-case comparison across farms of different sizes, resource flows were then normalized per kg of produce (Table S1). The only exception concerns the amount of fertilizers for F2, which is reported using a different unit as it was the only company using fertilizer in the form of salts at the time of the study. As noted above, the quantitative data reported for F2 were provided by the company and derive from a modeled system.

Subsequently, a qualitative analysis was done to identify patterns, themes, and insights regarding current or potential UrS practices at the company level. During the analysis, the five stages described by Morris (2015) were followed: (1) reading through the transcripts and taking notes, (2) highlighting notable quotes, (3) coding and finding themes, (4) selecting the themes, and (5) interpreting them. Given the number of interviewees, coding was done manually. The selection of the themes was partly inspired by the literature and partly inductively derived from the interviews. Four overarching themes related to barriers and drivers were identified: Resource Compatibility and Availability, Business Strategy, Infrastructure, and Economic Feasibility. Each theme was then examined to identify barriers and drivers influencing the implementation of UrS across cases and identify respondents' convergent and divergent views.

## 4. Results

This section presents the findings from the interviews with the vertical farm representatives, complemented by secondary data. The results are structured in three parts. The first part outlines the main resource flows of the vertical farms, including both inputs and outputs. The second part presents the current status of UrS and identifies potential resource exchanges between vertical farms and other urban actors. The third part reports the results of the thematic analysis, investigating the main drivers and barriers influencing the implementation of UrS across the themes.

### 4.1. Resource flows of vertical farms

#### 4.1.1. Input flows

The vertical farms varied in size, with production output ranging from 240 kg to 30,000 kg per year. However, all farms rely on similar key inputs, including water, growing media, fertilizers, packaging, and CO<sub>2</sub> (Table 3).

Water use varied across farms, with an average consumption of 1.5–14.2 L per kg of produce. All the farms rely on municipal tap water; however, F3 gets water delivered every 4 weeks due to the lack of a water connection.

Growing media use ranged from 0.01 to 0.70 kg per kg of produce, with the difference due to the composition and hydration level of the selected media. F1 uses a coconut fiber plug, which is already moistened with water when received from the supplier. F2 uses rockwool, an inorganic and lightweight growing media (Savvas and Gruda, 2018), while F3 uses a combination of coconut fiber and peat. F4 mainly uses cellulose pads for microgreens and a mixture of coconut powder and wood chips for leafy greens and herbs. F5 uses wood pulp and peat pots filled with coconut coir. All the farms import growing media from resellers located in the Netherlands and Germany. F2 and F5 also

**Table 3**  
Annual input and output resource flows for each vertical farming system.

|                                  | Farm 1                     | Farm 2                                 | Farm 3                     | Farm 4                      | Farm 5                                     |
|----------------------------------|----------------------------|----------------------------------------|----------------------------|-----------------------------|--------------------------------------------|
| <b>INPUT</b>                     |                            |                                        |                            |                             |                                            |
| <b>Electricity (kWh/year)</b>    | <b>570,000</b>             | <b>30,246</b>                          | <b>43,800</b>              | <b>37,960</b>               | <b>2810</b>                                |
| Photoperiod (day/night, h)       | 18/6                       | 18/6                                   | 14/10                      | 14/10                       | 14/10                                      |
| <b>Water (L/year)</b>            | <b>424,800</b>             | <b>13,170</b>                          | <b>4800</b>                | <b>43,200</b>               | <b>2433</b>                                |
| <b>Growing Media (kg/year)</b>   | <b>21,360</b>              | <b>132</b>                             | <b>48</b>                  | <b>5923</b>                 | <b>124</b>                                 |
| Type                             | Coconut coir               | Rockwool                               | Coconut coir<br>Peat       | Coconut Coir<br>Cellulose   | Coconut Coir<br>Peat<br>Wood Pulp          |
| Source                           | The Netherlands (reseller) | Poland (producer)                      | The Netherlands (reseller) | The Netherlands (reseller)  | Germany (reseller)<br>Sri Lanka (producer) |
| <b>Fertilizers (L/year)</b>      | <b>2160</b>                | <b>29 (kg)</b>                         | <b>120</b>                 | <b>180</b>                  | <b>NA</b>                                  |
| Type                             | Liquid                     | Powder                                 | Liquid                     | Liquid                      | Powder                                     |
| Source                           | France (reseller)          | Israel (producer)<br>Norway (producer) | Sweden (reseller)          | Germany (reseller)          | NA                                         |
| <b>Packaging (kg/year)</b>       | <b>3231</b>                | <b>130</b>                             | <b>32</b>                  | <b>227</b>                  | <b>18</b>                                  |
| Material                         | Plastic bag                | Plastic sleeve                         | Plastic bag                | Plastic pot<br>Paper sleeve | Paper sleeve                               |
| Source                           | Germany                    | The Netherlands                        | NA                         | The Netherlands             | China                                      |
| <b>CO<sub>2</sub> (kg/year)</b>  | <b>5400</b>                | <b>NA</b>                              | <b>90</b>                  | <b>NA</b>                   | <b>NA</b>                                  |
| Type                             | Tank                       | NA                                     | Tank                       | Propane burner              | NA                                         |
| <b>OUTPUT</b>                    |                            |                                        |                            |                             |                                            |
| <b>Crop Production (kg/year)</b> | <b>30,000</b>              | <b>9026</b>                            | <b>2500</b>                | <b>15,972</b>               | <b>243</b>                                 |
| Unsold crops (%)                 | 7                          | NA                                     | 1                          | NA                          | NA                                         |
| <b>Organic Waste (kg/year)</b>   | <b>66,000</b>              | <b>983</b>                             | <b>730</b>                 | <b>8606</b>                 | <b>NA</b>                                  |
| Disposal Costs (SEK/year)        | 43,200                     | NA                                     | 6800                       | 18,000                      | NA                                         |
| <b>Plastic Waste (kg/year)</b>   | <b>3600</b>                | <b>120</b>                             | <b>NA</b>                  | <b>NA</b>                   | <b>NA</b>                                  |
| Disposal Costs (SEK/year)        | 9000                       | NA                                     | Shared with organic waste  | NA                          | NA                                         |
| <b>Wastewater (L/year)</b>       | <b>12,000</b>              | <b>3951</b>                            | <b>NA</b>                  | <b>31,200</b>               | <b>NA</b>                                  |

mention the origin of the raw material beyond the reseller, with rock-wool sourced from Poland and coconut coir from Sri Lanka.

Fertilizer use differed across farms due to the use of fertilizer in either liquid or powder form. Four of five farms used liquid fertilizer, with usage ranging from 0.01 to 0.07 L per kg of produce. The low amount used in F4 is due to the growth of microgreens, which require lower nutrient requirements according to the respondent. Instead, F2 uses 0.003 kg of fertilizer powder blends per kg of produce. Fertilizers are sourced from resellers in Sweden, France, and the Netherlands, as well as from producers in Israel (e.g. Haifa) and Norway (e.g. Yara).

Packaging use ranged from 0.01 to 0.10 kg per kg of produce, varying mainly due to the diverse materials and ways of packaging products. F1 sells cut leafy greens without the growing media, packaged in zipped plastic bags. F2 and F3 sell their products together with the growing media inside a plastic sleeve and a plastic bag, respectively. F4 uses black plastic pots for microgreens and waxed paper sleeves for herbs, which are sold together with the growing media. Similarly, paper sleeves are used to package leafy greens from F5. The companies source packaging material from Germany, the Netherlands, and China.

Data on CO<sub>2</sub> supply was only available from F1 and F3, which used 5400 kg and 90 kg per year, respectively. CO<sub>2</sub> is delivered in pressurized cylinders that are returned to the provider for refilling once emptied. The amount of CO<sub>2</sub> used also depends on the concentration (part per million, ppm), which varies among farms. In F3, there is no separation between the growing area and processing area, so the CO<sub>2</sub> supply is interrupted when employees are present. F2 can make use of the CO<sub>2</sub> released by customers in the stores; however, no data was provided. F4 uses a propane burner as a CO<sub>2</sub> source. The associated combustion by-products, such as heat and moisture, were not addressed by the respondent.

#### 4.1.2. Output flows

The main output flow is crop production, which ranges from 243 to 30,000 kg per year. Of the total production, only a small portion remains unsold due to overproduction, plant defects, or unmet customer requirements. To minimize waste, the farms adopt different strategies: F1 donates the portion that is still edible, F2 redirects unsold crops to the deli section inside grocery stores, and F3 recollects unsold bags from grocery stores, mixes their contents, and sells them at a reduced price.

Organic waste production ranges from 700 to 66,000 kg per year, where the variance is due to production rates and how the final product is sold. F1 sells fresh-cut lettuce, so the plugs, roots, and stems are discarded, including the moisture-saturated spent growing media. This results in a far larger organic waste stream. The other farms sell their produce together with the growing media, thus reducing waste output at the farm level. The cost of organic waste disposal among the companies varies between 6800 and 43,200 SEK per year.

Plastic waste is mainly generated from the disposal of gloves, faulty bags, and growing media trays. Cost information was provided only by F1, which spends around 9000 SEK each year for plastic waste disposal.

Another output flow is wastewater, which ranges from 3900 to 31,200 L per year and is generated from cleaning water tanks and the facility. F1 empties and cleans their water tanks twice per year, with the wastewater received by a wastewater treatment plant without special treatment.

#### 4.2. Current state of UrS and potential exchanges

All the respondents were familiar with the concept of symbiosis and are actively looking for potential partners. At the time of the interviews, three farms were already involved in symbiotic exchanges. F1 installed a heat exchanger during the establishment of the company, which would allow for the excess heat generated by LED lighting to be provided to the hosting parking lot. F2 reported utilizing the CO<sub>2</sub> released by customers in the grocery stores where their farms are located; however, no quantitative data was available. F4 shares the waste collection service with

other companies co-located within the same industrial district. Additionally, F1 and F3 make use of underutilized urban spaces through partnerships with property owners, benefiting from reduced rental costs.

Although no other symbioses were implemented, all the respondents were able to identify potential opportunities involving both input and output flows. F1 is aware of being a potential donor of organic waste due to the large and stable volume generated. F2 highlights how co-location with wastewater treatment plants could enable the use of reclaimed water and recovered nutrients. F3 is actively looking for symbiotic partnerships with residential and office buildings as potential sources of CO<sub>2</sub>. F5 is actively looking for alternatives to conventional growing media by sourcing forestry by-products from Swedish industries.

Additional potential partners mentioned by respondents included bakeries, breweries, and mushroom farms. Mushroom farms were considered promising symbiotic partners as organic waste from vertical farms could be used as a substrate in the mushroom farms, while the CO<sub>2</sub> produced by mushrooms could be used for plant growth in VFSSs. Despite the identification of different potential symbiotic partners, respondents reported several barriers and drivers influencing the feasibility of implementing such synergies, which are presented in the following section.

#### 4.3. Barriers and drivers for UrS implementation

The thematic analysis identified four main overarching themes: 1) Resource Compatibility and Availability, 2) Business Strategy, 3) Infrastructure, and 4) Economic Feasibility. A summary of the key drivers and barriers identified in the study is presented in Table 4.

##### 4.3.1. Resource compatibility and availability

A main driver for establishing synergies with nearby companies was the potential establishment of a local supply chain that would reduce reliance on resources coming from distant countries. Yet, all the interviewees highlighted issues in finding alternative resources within an UrS network that could match the qualities of the conventional ones. For example, the most frequently used growing media in the industry are chosen due to their optimal chemical and physical properties, such as porosity and water retention (Savvas and Gruda, 2018).

Similar challenges were found in the use of organic fertilizers, which have low nutrient content and need to be supplemented with additional fertilizers. Moreover, organic fertilizers were considered more difficult to handle, as they offered less control and predictability over nutrient composition and cannot guarantee the same level of cleanliness as synthetic fertilizers. As F2 put it:

**Table 4**  
Summary of key drivers and barriers identified in the study.

| Theme                                   | Barriers                                                                                                                                                                                                                   | Drivers                                                                                                                    |
|-----------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------|
| Resource Compatibility and Availability | <ul style="list-style-type: none"> <li>• Lack of suitable substitutes for conventional inputs</li> <li>• Reduced handling efficiency</li> <li>• Extra processing required</li> <li>• Lack of suitable receivers</li> </ul> | <ul style="list-style-type: none"> <li>• Stable output flows volumes</li> <li>• Establishing local supply chain</li> </ul> |
| Business strategy                       | <ul style="list-style-type: none"> <li>• Need to establish core business</li> <li>• Limited resources to explore collaborations</li> </ul>                                                                                 | <ul style="list-style-type: none"> <li>• Increase circularity and integration with other businesses</li> </ul>             |
| Infrastructure                          | <ul style="list-style-type: none"> <li>• Complexity of retrofitting existing facilities</li> <li>• Trade-off between customer and symbiotic partner proximity</li> </ul>                                                   | <ul style="list-style-type: none"> <li>• Feasibility when planned at design stage</li> </ul>                               |
| Economic Feasibility                    | <ul style="list-style-type: none"> <li>• High upfront investment costs</li> <li>• Long payback time</li> <li>• Lack of subsidies and financial incentives</li> </ul>                                                       | <ul style="list-style-type: none"> <li>• Reduction of operational costs</li> </ul>                                         |

*"The organic nutrient is not the same every time. If you just need to add a little bit of magnesium, then what do you do? Then you need to empty the entire system and put fresh, virgin organic nutrients in; so, you can't reuse organic nutrients".*

In addition, the companies aim to have standardized production to meet the requirements set by customers (e.g. supermarkets); hence, the use of organic fertilizer, with its variable nutrient composition, could hinder homogeneous growth of crops.

Different packaging alternatives have been tested by the farms, such as starch bags and paper bags. However, the shelf-life of the produce was affected. Bags that can be easily recycled by the end consumers were mentioned as another important selection criterion. For example, F2 did not choose polylactic acid bags (PLA) as they cannot be recycled in household plastic bins, requiring industrial composting instead.

Regarding output flows, the stable production of organic waste could be a driver for establishing synergies and diverting it from municipal waste collection. F1 and F4 sought to establish synergies with nearby farms where organic waste was used as animal feed. However, these exchanges could not be established due to the extra processing required to separate the growing media from the edible portion of the waste (e.g. leaf trimmings and stems). The animals can consume only the green fraction, and since the spent growing media was mixed in, one of the actors in the exchange would need to take on the additional burden of separation, which neither was willing to do. In the case of F1, an additional issue was the mismatch between the high volume of organic waste produced and the limited capacity of the receiving farms.

#### 4.3.2. Business strategy

The interviewees emphasized that their companies were recently established, with some undergoing significant changes in rebranding and business models. Consequently, their primary focus has been on stabilizing core operations and increasing sales rather than establishing UrS collaborations and experimenting with alternative resources. As F1 put it:

*"The main focus is on production. It would be great to have someone who could focus on this kind of things [urban symbiosis]: to set it up, to contact people, to test and try things".*

F3 and F5 expressed similar views on prioritizing core business consolidation, though under different circumstances: F3 as a recently established company, and F5 following a downsizing of the company.

Moreover, several respondents emphasized being local food producers as a key element in their business strategy, which influenced site selection and took precedence over potential UrS partnerships. F3 expressed this through the concept of the "15-min city", aiming to serve customers placed within a short radius from the farm. Similarly, F1 is located less than 3 km from their main customer, while systems from F2 and F5 are found inside supermarkets and restaurants.

Despite these constraints, all respondents expressed interest in pursuing circularity and integration with other businesses. F1 previously operated a mushroom farm to explore symbiotic opportunities. However, after a company restructuring there was no dedicated R&D team lead. This, coupled with limited time, led the company to shut down circular activities in favor of consolidating core production. F5 conducted experiments with fertilizers derived from a biogas plant, which required compensation with salts and more frequent replenishment due to the low nutrient concentration of the fertilizer. The project was discontinued once project-based funding supporting the initiative ended, with the company downsizing as well.

#### 4.3.3. Infrastructure

The respondents highlighted that additional infrastructure is required to implement synergies such as heat recovery, CO<sub>2</sub> utilization, and the use of recovered nutrients, which can be seen as challenging. F2 noted that building infrastructure for water reuse or heat recovery

within their existing systems is not viable due to the limited volumes exchanged and the complexity of retrofitting small-scale systems. Moreover, F2 stated that such integration would be feasible in newly planned projects where symbiotic exchanges are considered at the design stage. Indeed, F1 installed a heat exchanger during the initial establishment of its farm.

Moreover, for synergies that require geographical proximity, relocating to potential symbiotic partners was also identified as a barrier. A common concern was that relocating closer to symbiotic partners would place the vertical farms farther from customers. Maintaining proximity to customers was considered a priority as it is perceived as being more sustainable and is a core part of the business strategy for many farms, as outlined in the previous section. As F3 put it:

*"If we would guide where we land the farm based upon where we can get CO<sub>2</sub> [...] we would be further away from the customer".*

However, if the proximity is already fulfilled, there is openness among the respondents to engage in UrS exchange.

#### 4.3.4. Economic feasibility

Economic aspects emerged as both barriers and drivers for UrS implementation. Among barriers, the higher upfront costs needed for enabling resource exchanges were frequently mentioned. F2 decided not to invest in heat recovery infrastructure with the hosting supermarket due to the long payback time.

High operational costs and lack of dedicated personnel and time for testing alternative resources were also reported as barriers. As a strategy to overcome these barriers, all respondents are involved in research collaborations with academic partners, which provide access to grants and allow experimentation with alternative resources and processes.

The lack of financial incentives for setting up exchanges was also highlighted, as it does not make companies prioritize this kind of collaboration. Moreover, respondents noted the absence of subsidies for vertical farming compared to conventional farming (e.g. through the Common Agricultural Policy (CAP)), further limiting their capacity to invest in UrS initiatives.

However, economic factors were also identified as drivers for engaging in UrS, due to opportunities to reduce operational costs. As rent is one of the main costs for VFSS, some firms established partnerships with landlords or real estate companies to make use of underutilized space to reduce costs. As F3 puts it:

*"We partner with real estate companies in a really early stage to also find out who are motivated to offer land that is not utilized for any other purpose. [...] we are paying (rent), but it is more a symbolic sum. It is not a significant cost [...]; so, for a real estate company to have the benefit of providing space for something like this, it makes them look good."*

Similarly, F1 pays reduced rent thanks to previously established contacts with the parking garage owner. In another case, F4 pays reduced waste management fees thanks to shared waste management services with neighboring companies.

## 5. Discussion

The study aimed to explore how VFSSs in the City of Stockholm could benefit from integration into UrS networks. Findings reveal that all the VFSSs rely on similar key inputs such as growing media, fertilizers, and packaging, which are mainly sourced from outside Sweden. This highlights a tension between the view of VFSSs as a strategy to increase food self-sufficiency in urban areas (Kalantari et al., 2017; Oh and Lu, 2023; Sowmya et al., 2024) and to reduce fresh produce imports, with their dependence on imported consumables for their production. Even if VFSSs are promoted as strategies to strengthen urban food resilience, the lack of supply chain transparency, highlighted by the inability of respondents to identify the source of key inputs, can further compound the vulnerability of these systems, especially in the current context of geopolitical

instability and trade tariffs (Sarwar and Rye, 2025). Hence, UrS integration can play an important role by strengthening urban food resilience through shortening supply chains and increasing reliance on domestically available resources (Haller et al., 2022; Mohareb et al., 2017; Parker and Svantemark, 2019). Yet, to do so, key tensions will need to be addressed, which are discussed in the following sub-sections.

### 5.1. VFSs as UrS anchor tenants: from theoretical potential to practical challenges

The study found that VFSs possess characteristics that make them theoretically suitable as anchor tenants in UrS networks. By operating all year-round under controlled environmental conditions, VFSs generate stable and predictable input and output flows, which are essential for UrS establishment (Fraccascia, 2018). Moreover, VFSs can be integrated with several resource flows produced in urban areas (Kozai and Niu, 2020). Previous studies have highlighted the potential for VFSs to source inputs from surrounding businesses such as breweries, pulp and paper mills, and biogas plants (Martin et al., 2019, 2022), while also providing outputs such as waste heat to host buildings (Blom et al., 2023; Martin et al., 2022). Despite this theoretical potential, the findings of this study reveal that symbiotic exchanges involving VFSs remain limited in practice. Exchanges involving the replacement of key input flows are absent, while output exchanges (e.g., waste heat and shared waste management) remain limited. This highlights a clear gap between theoretical potential and practical implementation.

The limited compatibility of by-product inputs compared to commercial ones was identified as a key barrier. This was especially true for inputs that directly influenced crop performance, such as growing media and fertilizers. Although respondents mentioned potential alternatives, including brewers' spent grains, spent mushroom substrate, compost, and recovered nutrients from wastewater treatment plants, their adoption is still hindered by handling constraints and a low degree of control. As commercial and high-productive systems, VFSs prioritize process stability and yield consistency (Bergstrand et al., 2020; Seufert et al., 2012), which would be compromised by the use of by-products. Previous studies have highlighted the risks associated with such inputs, including phytotoxicity, spoilage risk (Bianco et al., 2024; Meng et al., 2018; Poudel et al., 2023), and uneven growth patterns (Sdao et al., 2025). Moreover, these alternatives are still limited to small-scale experiments, and to the authors' knowledge, no implementation at the commercial level has been reported.

From a business perspective, this unpredictability may represent a risk for VFSs, which typically operate under high-volume needs and low-margin conditions (de Jong et al., 2024). This risk is further compounded by market requirements, especially from supermarkets that require strict uniformity in size and quality. Such requirements may hinder the implementation of by-products and highlight how power dynamics along the supply chain may influence the feasibility of symbiotic exchanges. A similar dynamic has been documented in Rosado and Kalmykova (2019).

The findings also indicate that the search for potential symbiotic partners occurs only after operational stability has been achieved. This suggests that the implementation of UrS is perceived as a secondary priority. This observation aligns with previous studies showing that implementation of synergies is not prioritized, mainly due to additional infrastructure and processing needs to transform by-products into feasible inputs (Aid et al., 2017; Martin, 2020; Taddeo et al., 2012). Moreover, virgin materials are often easier and cheaper to implement compared to by-products (Neves et al., 2019), further reducing the willingness to engage in UrS networks. This is illustrated by the cases of F1 and F5, who both engaged in circularity initiatives but discontinued them after organizational changes occurred and shifted their focus to core business operations.

Indeed, handling requirements associated with by-products can increase operational complexity and increase work demand for

employees. This is particularly relevant in VFSs, where labor costs constitute a significant share of operating expenditures (Monzini and Orsini, 2025). Without a standardized way of processing by-products, their integration into existing production workflows remains challenging. Further research is needed, as also stated by Turken and Geda (2020), who highlight the absence of empirical research on the implications of by-products handling on daily operations.

Lack of adequate infrastructure may also influence input choices. For example, one company considered switching to PLA (polylactic acid) packaging but continued using conventional plastic bags due to the lack of adequate recycling infrastructure in Sweden (Nordic Swan Ecolabel, 2018). This illustrates how conditions external to the system can also limit adoption of symbiotic strategies, even when commercially viable alternatives exist.

Moreover, findings suggest that output flows may represent a more feasible entry point for UrS implementation. Unlike input flows, output exchanges may represent low operational risk and generate immediate economic benefits, such as reduced disposal costs. Similar drivers have been identified by Patricio et al. (2018), who proposed output flows opportunities among food sector companies, but no viable options for using by-products as inputs. This further reinforces the challenge that food companies may face in integrating by-products as inputs.

Taken together, these findings suggest that not all symbiotic exchanges are equally feasible in the context of VFSs. Exchanges associated with lower business risks are more likely to be implemented.

### 5.2. Customer proximity versus symbiotic partner proximity

A recurrent pattern among the studied VFSs was the prioritization of customer proximity over proximity to potential symbiotic partners during site selection. This preference has been justified as more environmentally sustainable, especially due to the reduction of food miles. However, previous research suggests that final distribution has little contribution to the overall environmental impacts (Enthoven & Van den Broeck, 2021; Weber and Matthews, 2008), including in urban VFSs (Martin and Molin, 2019), whereas transportation of material inputs contributes more. Customer proximity was also associated with the increased capacity to better adapt to customer requests, a characteristic that has also been highlighted in Rosado and Kalmykova (2019). From the interviews, it emerged that closeness to customers and integration into a UrS network were perceived as difficult to fulfill simultaneously, as potential symbiotic partners may be located further from urban areas. However, this might be due to an underestimation of potential partners present within the urban environment. Previous studies have shown that VFSs have the potential to be integrated with several urban stakeholders (Blom et al., 2023; Martin et al., 2019, 2022). Moreover, Jensen et al. (2011) highlighted that within a radius of 28 km, sufficient diversity among potential donors and receivers can be found. Similarly, Patricio et al. (2018) identified a similar distance threshold when identifying potential synergies for Swedish mushroom and beer producers. In addition, from an environmental perspective, Velenturf and Jensen (2016) found that the benefits achieved through the repurposing of resources outweigh the impacts caused by transportation, further contrasting with the view of prioritizing food-mile reduction.

The type of resource flows that VFSs could exchange also has implications for the optimal location. For example, organic material, waste heat, and CO<sub>2</sub> exchanges may benefit from proximity to partners (Domenech et al., 2019; Marchi et al., 2018). From a business perspective, customer proximity may be sufficient at small-scale operations, but as farms scale up and the costs of sourcing inputs increase, proximity to potential donors and receivers could have more weight in siting decisions. This is supported by Pesch and Louw (2023) who found that prioritizing closeness to symbiotic partners during site selection can improve resource use efficiency and support the development of a strong symbiotic network.

### 5.3. Network emergence and the role of trust

The findings suggest that facilitated networks might be the most suitable model for UrS development involving VFSs. Limited time and the lack of dedicated personnel and financial capacity make self-organized network development hard to pursue. This aligns with previous research highlighting how self-organized initiatives require significant organizational capacity (Domenech et al., 2019; Neves et al., 2020). Additionally, the delay in searching for potential partners until operations stabilize acts as a further constraint on network formation. In a facilitated network, municipalities and academic partners could actively identify potential partners and support the establishment of synergies (Harding et al., 2021; van Capelleveen et al., 2018). Notably, all interviewed companies are already engaged in research collaborations with academic partners, suggesting that a foundation for a facilitated network development may already be in place.

Interestingly, lack of trust did not emerge as a barrier in the interviews, despite being identified in the literature as a key factor in network formation (Chertow and Lombardi, 2005; Hewes and Lyons, 2008; Walls and Paquin, 2015). A possible explanation might be that only symbiotic output flows are currently in place, which might be perceived as low-risk and have not raised any resource dependency issues. This resonates with findings from Patricio et al. (2018), where trust issues did not emerge among companies involved in output-based exchanges. Another explanation could be that building trust might require resources like time and money (Hewes and Lyons, 2008; Velenturf and Jensen, 2016), which respondents identified as scarce. Hence, the absence of trust may reflect the fact that UrS exchanges are still too limited for trust to become a relevant factor. Trust is likely to become a salient factor as firms progress towards input-based exchanges, which involve resource dependency and higher operational risk. The present findings, therefore, cannot capture how trust would operate under such conditions, which remains a direction for future research.

### 5.4. Implications for practice

The findings offer several practical implications for advancing VFSs integration into UrS networks. First, a facilitator is needed to establish contacts and assess potential exchanges between companies that currently lack the time and resources to do so independently. This role can be taken on by different local actors, such as municipalities and academic partners. Given that all interviewed companies are already engaged in research collaborations with academic partners, these existing relationships could be leveraged to initiate a potential UrS network.

Second, an entry point for such a network would be to begin with low-hanging fruits and progressively build towards more complex integrations as trust and operational familiarity develop between partners. Output flows such as waste heat and organic waste might represent a viable starting point as they do not affect VFSs' core operations. This aligns with Patricio et al. (2018) who focused exclusively on output flows when identifying potential exchanges. In the Stockholm context, the municipal landscape management could act as a receiver of organic waste from VFSs, generating a double benefit: organic waste will be diverted from incineration, while the municipality will reduce its reliance on peat in urban greenery management, which is associated with significant GHG emissions (Savvas and Gruda, 2018). In this way, the municipality would not only act as a facilitator but also become an active participant in the symbiotic network. This aligns with Södergren and Palm (2025) who suggested procurement as a tool to be used for promoting UrS initiatives. Beyond this specific exchange, literature suggests other ways of valorizing organic waste from VFSs, including mushroom production (Fufa et al., 2021; Philippoussis et al., 2007), animal feed, and nutrient recovery (van Tuyl et al., 2022).

Finally, the findings suggest that integrating UrS exchanges at the design stage of new projects would be more feasible than retrofitting

existing facilities. Hence, future projects involving VFSs should consider symbiotic exchanges early in the planning stage.

### 5.5. Implications for policy

The findings suggest different policy interventions that could accelerate the integration of VFSs into UrS networks, including financial support, urban planning, and information tools. Grants or subsidies for implementing symbiotic exchanges could reduce the financial risk thresholds that currently discourage engagement. Furthermore, these instruments should be designed to ensure the long-term financial sustainability of such initiatives, which still remains insufficiently addressed, as highlighted by Marini et al. (2023).

Regarding urban planning, the findings also highlight that VFS companies were proactively seeking partnerships with real estate firms and landlords to access underutilized spaces at reduced costs. This suggests a lack of policy instruments that can facilitate such arrangements. Similar gaps have been identified in other European cities where UF activities (including VFSs) are not integrated into urban planning initiatives (Marini et al., 2023). Hence, more targeted policies are needed to support the expansion of such activities in urban areas. As the findings indicate that integrating UrS infrastructure is more feasible at the design stage, policy could promote the co-location of potential symbiotic partners (VFSs, mushroom farms, breweries, and wastewater treatment plants) in new development projects, which could create the conditions for the emergence of a UrS network.

Finally, policy could support the development of urban resource flow mapping tools and matchmaking platforms, which have been highlighted as effective mechanisms for facilitating symbiotic exchanges (Aid et al., 2017; Fraccascia, 2018; Patricio et al., 2018; Zhang et al., 2021). Such tools might help uncover potential exchange opportunities that remain invisible to both farms and municipal actors.

### 5.6. Limitations and further research

The limitations of the study point to areas for future research. First, the study is based on a sample of five commercial VFSs located in the City of Stockholm. While this sample reflects the limited number of commercial VFSs operating in the area at the time of the study, the findings may not be generalized to other urban contexts. Future research could expand the analysis and include a larger number of farms across different cities and regions.

Second, the findings are based on interviews with farm owners and managers. While the respondents provided valuable insights into operational practices and decision-making criteria, industrial and urban symbiosis typically involves a wide range of stakeholders, including municipalities, universities, research institutes, property owners, and utility providers. A future study could adopt a multi-stakeholder perspective to better understand drivers and barriers for UrS implementation.

Third, mapping potential urban symbiosis opportunities was beyond the scope of this study. Mapping urban resource flows could provide further understanding of feasible exchanges and help identify potential matches between VFSs and other urban actors.

Finally, further experimental research is needed to test the feasibility of integrating urban residual flows as inputs in VFSs, as well as exploring potential use for VFSs outputs. The results of this study highlighted how organic waste is generated in stable quantities, suggesting its potential use as a resource in a symbiotic exchange. Experimental research could explore ways of valorizing organic waste and help identify suitable receivers and assess technical and economic feasibility.

## 6. Conclusions

The study investigated the potential for implementing UrS in commercial VFSs located in the City of Stockholm. By combining semi-

structured interviews, on-site visits, and secondary data analysis, it examined the resource flows of five commercial VFSs, assessed the current status of UrS, and identified the main barriers and drivers influencing UrS implementation.

The findings reveal that while VFSs are promoted as strategies for increasing urban food self-sufficiency, they remain heavily dependent on imported production inputs, including growing media, fertilizers, packaging materials, and CO<sub>2</sub>. UrS could contribute to addressing this tension by shortening supply chains and increasing reliance on domestically available resources.

Although respondents demonstrate familiarity with the concept of symbiosis and identified potential partners (e.g., breweries, mushroom farms, wastewater treatment plants), the implementation of UrS remains limited in practice. Four main themes were identified as influencing its adoption: resource compatibility and availability, business strategy, infrastructure, and economic feasibility. The findings reveal that input-based exchanges are constrained by the limited compatibility of by-products with high standards required by commercial soilless production, while output-based exchanges, such as heat recovery, shared waste management, and the use of underutilized urban spaces, represent more feasible entry points due to their lower operational risk. The recent establishment of the studied VFSs, combined with organizational restructuring in some cases, makes them prioritize core business consolidation over UrS engagement. Moreover, the tendency to prioritize proximity to customers over proximity to potential symbiotic partners, combined with high investment costs and long payback periods, further limits implementation.

The findings suggest that facilitated urban symbiosis networks may be the most suitable development model for VFSs. Municipalities and academic partners could play an important role in identifying suitable partners and facilitating the establishment of synergies. Policies that better recognize urban farming initiatives could further support the integration of VFSs in symbiotic networks.

Overall, the study highlights that while VFSs have the potential to be integrated with urban resource flows, their implementation is still in an early stage. Future research should expand the analysis to include a wider range of stakeholders, develop a mapping of residual flows to identify feasible symbiotic opportunities, and conduct experimental studies to evaluate the feasibility of integrating urban residual flows in VFSs operations.

#### CRedit authorship contribution statement

**L. Mazzaferro:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **M.J. Bustamante:** Writing – review & editing, Supervision, Methodology, Data curation. **R. Milestad:** Writing – review & editing, Supervision, Methodology, Conceptualization. **F. Orsini:** Writing – review & editing, Supervision. **M. Martin:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

#### Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this manuscript, the corresponding author used Claude to improve the readability and language of the text. After using this tool, the authors carefully reviewed and edited the manuscript, taking full responsibility for the final version's content.

#### Declaration of competing interests

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.

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#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.clrc.2026.100490>.

#### Data availability

Data will be made available on request.

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