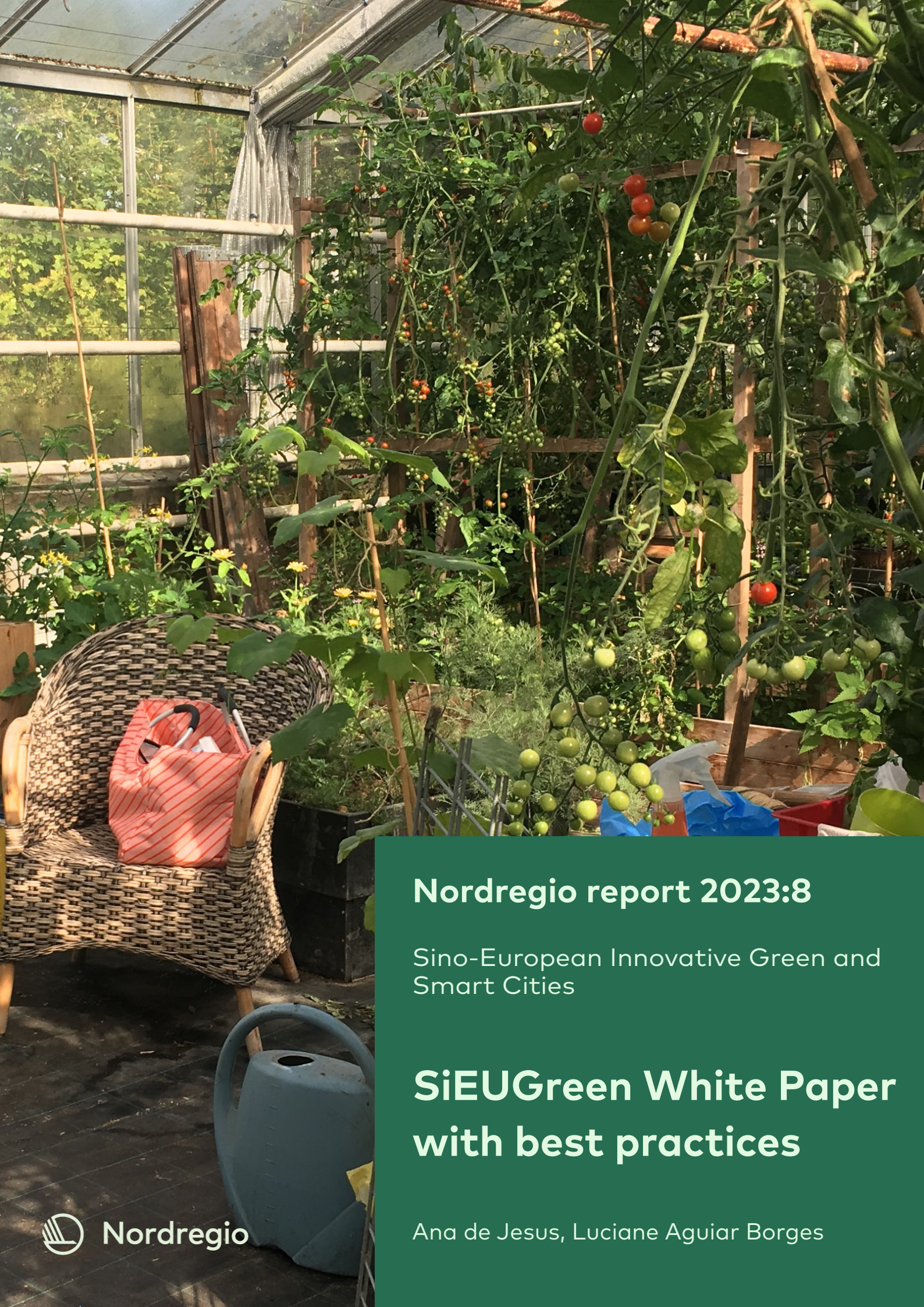




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Sino-European Innovative Green and Smart Cities

SiEUGreen White Paper with best practices

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Nordregio

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Shared tools for farming in Brabrand Fællesgartneriet, Aarhus, Denmark.

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Aquaponic and hydroponic system in Sanyuan Farm, Beijing, China.

Abstract

This report explores the potential of Urban Agriculture (UA) to enhance food security, improve resource efficiency, and promote smart, resilient, and circular cities. The discussion is framed within the scope of the Horizon 2020 project 'Sino-European Innovative Green and Smart Cities' (SiEUGreen) which explored different pathways to turn waste into resources for growing food in cities through the combination of different technologies. These technologies were tested in five showcases: Campus Ås, in Ås, Norway; World Gardens and Brabrand Fællesgartneriet community gardens in Aarhus, Denmark; Turunçlu greenhouse in Atakya, Turkey; Sanyuan Farm, in Beijing, and Futiancangjun residential area in Changsha, China. The insights and knowledge gained with these showcases were the basis to discuss the barriers and drivers of UA in the transition to more sustainable and resilient circular cities, across five aspects (1) environmental, (2) technological, (3) economic, (4) social and cultural and (5) regulatory and institutional issues. The results suggest that city food provision and UA systems can be designed considering circular economy regenerative cycles, but it is important to promote local research that can highlight policy solutions to address context-related barriers and limitations. Among the main lessons learned across the different aspects, we highlight:

- The need for more evidence-based research, clear monitoring tools and evaluation/assessment of the different UA typologies and their impact on the environment, society and economy;
- The implementation of innovative technological developments that support and promote UA for reduce; reuse, recycle/recover resources require more experimentation, large-scale tests and validation both concerning their efficiency, positive environmental impacts, as well as economic viability;
- The need for high investments, difficulties accessing financial support, underdeveloped business case for circular resource models, and limited recognition of the positive and indirect economic, environmental benefits of UA are among the main barriers that limit the uptake of agriculture in cities;
- Despite the significant role UA can play in advancing a circular economy (e.g., by supporting sustainable local food systems, promoting community resilience and reducing waste), behaviour and cultural barriers were found to have a deep impact when fostering a closed-loop approach to UA, especially concerning overcoming prejudice against waste as a resource,
- Local governance and public policy play a central role in framing and supporting UA (e.g., incentives, funding, regulatory frameworks) as a pathway that enables close loops in cities.



Urban farming in Brabrand Fællesgartneriet, Aarhus, Denmark.

1. Introduction

The last decade was marked by high volatility and different shocks, from the aftermath of a global financial crisis and its political and socio-economic fallout, to the more recent effects of the COVID-19 pandemic and the Russian aggression against Ukraine. The next 10 years are expected to be as (if not more) unpredictable, with several megatrends—demographic changes, technological developments, the transition towards climate neutrality that have accompanied this period expected to assume even greater importance.

As the main *loci* for the world's energy and resource consumption and carbon emissions, cities are in the centre of this discussion. With around 70% of the population expected to live in urban areas by 2050, cities have significant ecological impacts, operating as dysfunctional ecosystems in which natural resources are distributed, used, and disposed within the prevalent, linear “take-make-dispose” economy (IRP, 2018). In 2018, cities were already consuming around 70% of global resources and energy, producing over 70% of all greenhouse gases, and creating more than 70% of global waste (Paiho et al., 2020). These numbers are expected to rise, and since linear, industrial agri-food systems are at the centre of the socio-ecological crisis, food production systems need to shift considerably if we are to meet our global environmental goals (Pascucci, 2020). However, cities simultaneously have a high potential to address these negative impacts as they are dynamic innovation centres for technological development, new business models and fertile in resources that can close energy production-consumption loops.

In addition to growing urbanisation, the world faces other challenges spanning from climate change, biodiversity loss, and pollution to more recent risks related to health (COVID-19) and energy and food security (linked with the war in Ukraine). Due to the eminence of these threats, urban agriculture (UA) has been gaining importance as a strategy to tackle some of the social, economic, and environmental challenges cities face (Davies et al., 2021). Within this context, this white paper explores the potential of UA to enhance food security, improve resource efficiency, and promote smart, resilient, and circular cities. The discussion is framed within the scope of the Horizon 2020 project ‘Sino-European Innovative Green and Smart Cities’ (SiEUGreen) which explored different pathways to turn waste into resources for growing food in cities through the combination of different technologies. This white paper uses as data the insights and knowledge gained during the SiEUGreen project to discuss the barriers and drivers of UA in the transition to more sustainable and resilient circular cities. The questions at the heart of this discussion are: ***What are the lessons learned from the SiEUGreen showcases concerning the role of UA, and what are the drivers and barriers to applying resource circularity in cities?***



Bubble Greenhouse in Campus Ås, Norway

2. From a linear to a circular economy: What is the role of urban agriculture?

2.1 Urban agriculture

UA has been defined as the practice of food production within and around cities (D'Ostuni and Zaffi, 2021). This umbrella concept is used to describe a range of multifunctional and multi-purpose practices that involve different actors and imply a variety of development options. It can include commercial and non-commercial activities (D'Ostuni and Zaffi, 2021) and can be operated from intra-urban to peri-urban areas, on public or private land, employing a variety of more advanced (high-tech) to simpler (low-tech) technologies (Borges et al., 2019). UA includes, for example, community gardens, institutional gardens, guerrilla gardening, vertical farming, and zero-acreage farming (z-farming), among others.

The different SiEUGreen showcases demonstrate that **the impacts of UA are highly contextual** and country-specific, dependent on the actors involved, purpose, land use, property, technology, and production system (D'Ostuni and Zaffi, 2021; Nadal et al., 2018). In the Global South, UA is often seen as a means of survival and poverty alleviation, while in the Global North, motivations include reducing negative urban development impact on the environment, improving the quality of life of urban communities, as well as improving physical and mental well-being and social inclusion (Binimelis et al., 2014; Borges et al., 2019; Ferreira et al., 2018; Piore et al., 2018). However, recent global challenges, such as the coronavirus pandemic and the Ukraine war, emphasized the fragility of food supply chains and blurred some Global North/South distinctions, raising questions concerning the need for further knowledge on more efficient food production and distribution methods in cities (International Resource Panel, 2021).

If the conceptual debate on the definition of UA, as well as its purposes, functions, and overall impacts (positive/negative), is still ongoing, it is undeniable that UA directly influences environmental and social factors, in addition to food security in cities (Ferreira et al., 2018; Pascucci, 2020; Skar et al., 2019a). However, UA as an urban sustainability practice is "when urban agriculture is circular (using regenerative practices, eliminating pollutants, recycling waste and maximising exploitation of the inputs used) and is fair and equitable for producers and consumers" (International Resource Panel, 2021).

2.2 Urban agriculture in a circular economy

Circular economy is an "economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling, and recovering materials in production/distribution and consumption processes" (Kirchherr et al., 2017). Inspired by natural ecosystems, the concept conveys the need and possibilities to move away from the "linear" extraction, production, distribution, consumption, and disposal paradigm, towards a permanently regenerative economy, focusing on circular flows of reuse, restoration, and renewability and encompassing the entire value chain.

The circular economy approach has become a priority in the world policy agenda in the last decade. Countries and companies seeking to decouple economic growth and social development from resource use and waste production have adopted the circular economy approach as an operational strategy in the pathway to sustainability (WEF, 2014). However, there is some debate about the potential impact of circular economy. While some argue against its "revolutionary" potential by raising questions about its ability to deliver fundamental change (Hobson and Lynch, 2016; Skene, 2017), others stress the possible benefits of implementing circular economy strategies at different levels (e.g., macro, meso and micro levels) to achieve sustainable goals (Korhonen et al., 2018).

Despite differing opinions, the concept has received immense attention in sustainability discourse. Countries worldwide have embraced it, partly because it can help to concertize the process of setting long-term objectives and provides a framework for various regulatory initiatives (de Jesus et al., 2019). In Europe, the 2015 EU Circular Economy Action Plan included several legislative proposals "(...) establishing an ambitious long-term path leading towards waste prevention and recycling" (EC, 2017a, p. 3) which was reinforced in 2020 by the European New Green Deal. In China, there has been explicit circular economy legislation since the Cleaner Production Promotion Law of 2002, followed by the 2008 Circular Economy Promotion Law, mainly focusing on eco-industrial parks and cleaner production practices (de Jesus et al., 2018).

Even if circularity strategies vary substantially, the most common definitions encompass activities focused on the 3R principle—reducing waste, and reusing and recycling resources (Kirchherr et al., 2017; Reike et al., 2018). This principle focuses on input minimisation and efficient use of regenerative resources; life cycle extension and systems reconceptualisation (repair, re-conditioning, and re-manufacturing options); and output/waste reduction and valorisation, namely by recycling and valuing by-products and waste (de Jesus et al., 2018; Kirchherr et al., 2017; Manríquez-Altamirano et al., 2021). The 3R priorities are accepted in academia and in circular economy practices, and they have been employed in Chinese and European policy as well as in the discourse of the European Union (EU), United Nations (UN), and Organisation for Economic Co-operation and Development (OECD). This reinforces the potential of the circular economy framework when addressing global challenges (Reike et al., 2018).

Although circular economy objectives are straightforward—limit inputs, close loops/optimize resources, and avoid/transform waste—circular economy implementation is a complex endeavour. At an urban level, different cities, such as London and Paris, are already deploying urban circular roadmaps (Prendeville et al., 2018). Around 80% of the global GDP was generated in cities in 2018, but in a linear economy, cities are often "food deserts", utterly dependent on production from rural areas (WEForum, 2018). The separation between "places of production" and "places of consumption" affects not only food supply but also waste management. When food and organic waste are the endpoints of a linear production-consumption-waste system, cities must contend with an expensive waste management problem (Pascucci, 2020). Introducing the circular economy concept at a city level can address these challenges, making urban environments more resilient, less dependent on external supply chains, healthier, and more resource-efficient.

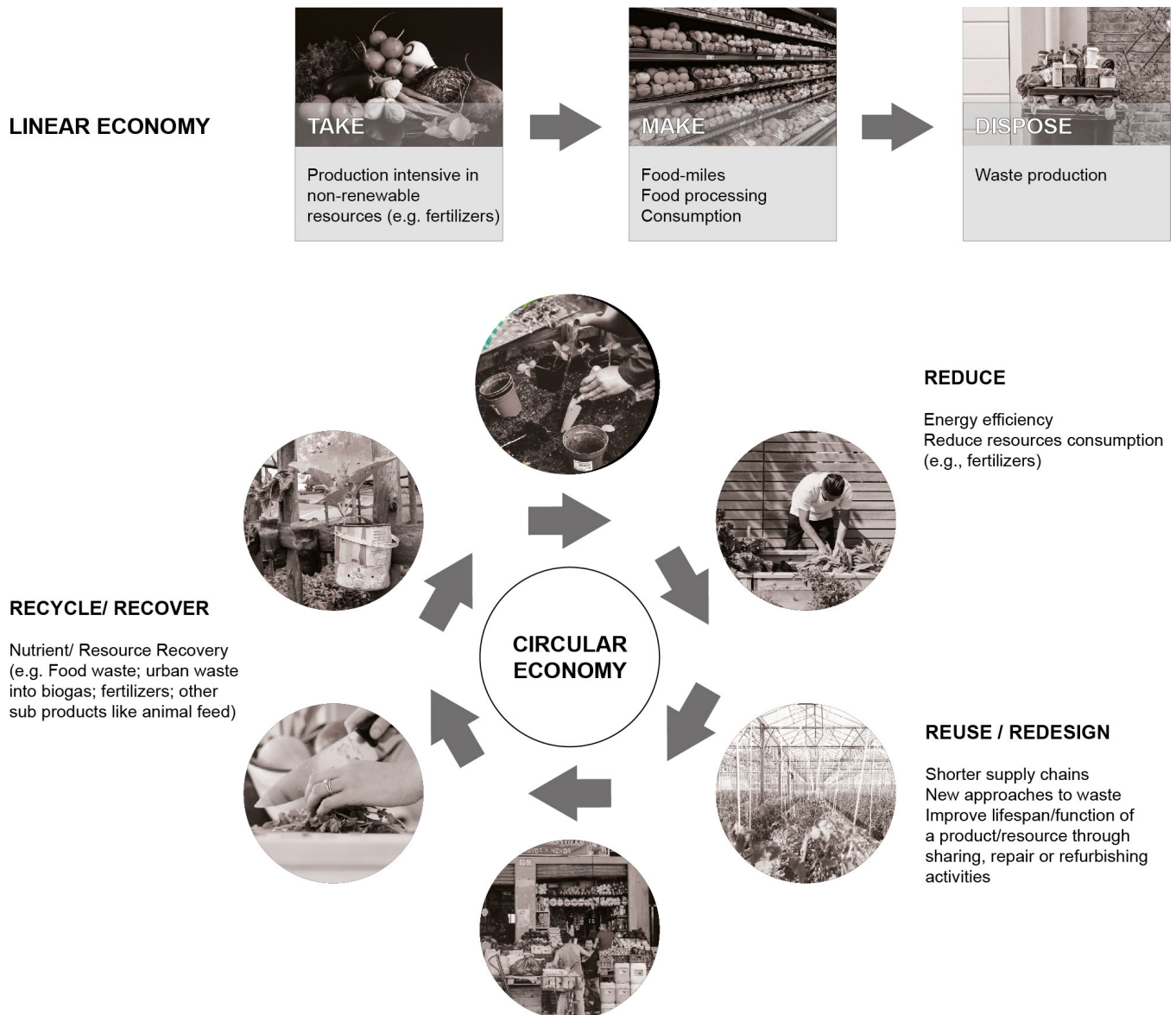


FIGURE 1: Linear and Circular Economy: Perspectives

Therefore, cities are ideal test beds for the implementation of circular economy strategies. Urban environments concentrate and combine resources, knowledge, and economic activity in a limited geographical area. Cities have the potential to supply the necessary inputs (e.g., waste, by-products) to develop circularity while simultaneously implementing strategies that close the loop by recycling such materials and waste (International Resource Panel, 2021; WEFForum, 2018).

There is, therefore, a case to make concerning cities' potential when implementing circular economy strategies (WEForum, 2018). Against this backdrop, **UA systems can be designed** considering regenerative cycles (Pascucci, 2020). UA has been found to contribute to resource-efficient food production through the application of circularity strategies such as reduced transport of food products, reduced food waste, reuse of nutrients, use of underutilised spaces, and smart water use (Artmann and Sartison, 2018; Thomaier et al., 2014). Transformative processes in UA systems can also enable circular resource flows, reincorporating resources that would otherwise be wasted (Ferreira et al., 2018).

3. SiEUGreen Project

The main activities of the project focused on knowledge production and dissemination, illustrating how UA can play a central role in a circular system that transforms urban waste into resources. The project was able to implement different technologies, from simple technologies (such as organic waste composting) to highly sophisticated technologies (recovery of nutrients from wastewater).

Box 1: SiEUGreen technologies

- Green technologies concern soil-based traditional plant growing, water-based hydroponic culture (soilless growing) and aquaponics (fish and plant growing systems), paper-based plant growing, and greenhouse technologies.
- Blue technologies concern water and waste management, production of fertiliser and soil amendment from waste, and water-based resource recycling.
- Yellow technologies concern biogas production from waste resources, seasonal solar storage, combined heat and power systems, and photovoltaic generation of electricity.
- Red technologies involve the development of an application for more active social engagement and an interactive platform and resource centre for raising awareness and sharing best practices.

The core of the project was on testing these technologies in urban environments with limited space and high residential density, and where social acceptance, health risks, and legislation may hinder the reuse of waste, especially for food production. Five selected European and Chinese urban and peri-urban areas provided the empirical basis for testing the variety of technologies: Campus Ås, Norway; community gardens in Aarhus, Denmark; Turunçlu greenhouse in Antakya, Turkey; a community farm in Beijing, China; and a new green urban development in Changsha Central China (see Box 2).

Box 2: SiEUGreen showcases

Campus Ås is a property of the Norwegian University of Life Science, NMBU. It is located in the peri-urban area of Ås Municipality, situated 30 km south of Oslo.

Within the SiEUGreen project, Campus Ås demonstrated how different technologies are combined to turn waste into resources in a circular system. A bubble greenhouse lies at the core of the circular system and showcases how sub-products of wastewater and solid waste are transformed into fertilisers to grow food. The closed system is fed by various sources and uses a combination of technologies. For example, student housing and administrative buildings were equipped with vacuum toilets. The toilet wastewater is treated in a reactor that transforms it into a concentrated liquid fertiliser used to grow food in the bubble greenhouse. While vacuum toilets enable a reduction of 90% of water consumption, on-site treatment and recycling of blackwater into nutrients allow for an ecological and economically efficient system that saves resources. In addition, greywater from an administrative building is pre-treated in wetland/filter beds, processed in tanks, and used for irrigation and generation of bubbles in the greenhouse. These bubbles improve the greenhouse's insulation in the winter and cooling in the summer, thus extending the growing period within a cold climate.

Household waste is also transformed into vermicompost, which is used as a soil additive to grow food in the bubble greenhouse. Campus Ås also showcases a borehole thermal energy storage system (BTES). In this system, the heat from solar energy captured through PV panels is stored in rock sediment underground. This system allows the harvested heat in the summer to be used in the cold season to warm up the surrounding buildings.

Campus Ås also demonstrated the efficiency of green roofs for rainwater management and the potential of nature-based solutions such as a network of rain gardens, ponds, and open streams to drain stormwater while creating a diverse and attractive landscape. The interlinkages between these different systems aim to demonstrate how low and high technologies can be employed in urban environments contributing to urban sustainability and resilience.

In Aarhus Municipality (Denmark), the programme "Taste Aarhus" adopts an inclusive approach to facilitate different social groups (e.g., residents, businesses, and local institutions) to engage in urban agriculture. This case provides valuable lessons on how to engage diverse sectors of society (such as urban planning, social, health, and educational sectors) while capitalising on available resources (e.g., underutilised spaces in the city, human resources). The case also empowers residents to address the challenges of segregated communities, obesity, lack of access to green areas, and absence of physical activity. In the context of SiEUGreen, two gardens acted as testbeds for different technologies: Brabrand Fællesgartneriet and World Gardens.

- **Brabrand Fællesgartneriet** is one of the oldest gardens in Aarhus, established in 2014 in the peri-urban area of the city. The garden has an area of 11,000 m², which includes open land for cultivation and greenhouses where 100 families grow food. As part of the SiEUGreen project, a solar-driven toilet was implemented on the site in September 2019. This toilet does not use water to flush waste; instead, the waste is collected in the tank and exposed to thermal energy harnessed through solar panels to transform the waste into nutrient-rich biochar. This type of charcoal can be used as a soil additive and fertiliser for growing food. This technology aims to demonstrate alternative ways of dealing with human waste (faeces and urine) while addressing the scarcity of phosphorous, a non-renewable resource found in human waste and fundamental for growing food.
- **World Gardens** is an association that runs community gardens in the Gellerupparken and Toveshøj districts around Aarhus. As part of the SiEUGreen project, World Gardens has been allocated funding to build polytunnels made of recycled materials. The polytunnels showcase new means for the residents to grow vegetables and prolong the growing season.

The Turunçlu greenhouse in Antakya, Turkey, was built with the support of SiEUGreen and Hatay Municipality and has been in operation since May 2021. The purpose of the greenhouse is two-fold: to introduce new technologies to produce food in the region and to promote social integration of vulnerable groups. In the context of Antakya, agriculture plays a vital role in the region's economy; however, reliance on traditional soil-based modes of food cultivation and soil depletion due to unsustainable agricultural practices has led to a growing need for new technologies that can improve the region's resilience. In the greenhouse, aquaponics technology is adopted to grow food. Aquaponics combines aquaculture (fish farming) with hydroponics (cultivation of food in water) into a sustainable system that does not require soil, can save water usage by around 90%, and uses fish manure as a nutrient for the production of herbs and leafy greens to feed people.

Turunçlu greenhouse has approximately 1,500 m², about half of which is occupied by growing channels where lettuce and basil are cultivated. The aquaponics system includes six fish tanks, each with a capacity of five tons of water. These tanks are connected to a biofiltration pool that collects fish waste to produce a liquid fertiliser used in the hydroponic system.

Regarding social integration, the greenhouse became an educational centre offering training on aquaponics, hydroponics, and paper-based microgreen cultivation techniques to disadvantaged groups (specifically, Syrian refugees, low-income residents, and women). The collaboration with local universities is also an added value as it helps to anchor aquaponics technology as a feasible and efficient means of producing food that local entrepreneurs can embrace. Furthermore, the greenhouse functions as a centre for disseminating the value of urban agriculture to younger students from primary and secondary schools. In 2021, 148 people participated in six workshops held in the greenhouse providing information about the potential of aquaponics for food production in the region.

Unfortunately, in February 2023, Antakya was severely affected by earthquakes that left the region devastated, including the collapsing of the Turunçlu greenhouse.

Sanyuan Farm is a state-owned farm in Beijing, China, which has been in operation since 1949. It is located in the peri-urban area of Beijing and has an area of 667,000 m² divided into two equal halves. In the West District, several greenhouses produce fresh vegetables. This production significantly impacts Beijing's food resilience as it supplies the city with vegetables that previously came from South of China.

The East District consists of a cherry forest and flower fields managed by the government. In 2008, approximately 165,000 m², about half of the district, was divided into small plots (between 50 and 80 m²) and rented out to people who wanted to grow their own food. This area attracts around 1,300 middle-class, well-educated Beijing households. A large greenhouse was built in the East District and, since 2012, demonstrates hydroponics and aquaponics technologies. This greenhouse is a centre that combines urban agriculture with tourism, technology, and education and attracts a diverse group of stakeholders. The greenhouse advises companies on the potentialities of soilless and aquaponic technologies, hosts school kids that learn how to grow food, and gives tourists the opportunity to harvest the food produced in the greenhouse and open fields.

Sanyuan Farm's vision is to demonstrate resource-efficient UA and a healthy, happy lifestyle. Within SiEUGreen, the farm demonstrates the implementation of aquaponics technology to grow vegetables and focuses on recovering nutrients from organic waste. The farm tested organic fertiliser generated by biological processors that recycle household waste.

The Futiancangjun residential area in Changsha, China, demonstrates a resource-efficient, intelligent, and sustainable urban development with reduction, reuse, and recycling of waste, local supply of safe food, and effective utilisation of solar energy (Michailidis, 2021). Futiancangjun development covers an area of 320,000 m² with a total construction area of 700,000 m², which includes 35 high-rise buildings (18 floors) with around 100 apartments per building. The entire development accommodates 3,500 families. The buildings are similar to one another and offer apartments of 70, 100, 120, and 180 m² to attract families with different needs. In addition to the residential buildings, the development includes a kindergarten, primary school, junior school, and a park, and there are also plans to add a shopping mall (Borges et al., 2019).

Within the SiEUGreen project, 18 apartments were equipped with low-flush toilets. This technology reduces water usage and enables struvite precipitation from blackwater. In addition, 100 hydroponic devices that support growing vegetables, fruits and herbs on apartment balconies were donated to some of the residents to promote urban agriculture.

By strengthening EU-China collaboration in food security and sustainable UA, SiEUGreen sought to contribute to the implementation of a circular economy at a global level while improving the well-being and quality of life of urban residents. Throughout SiEUGreen's implementation, EU and China have shared technologies and experiences, thus contributing to the future developments of urban agriculture and urban resilience in both continents. This partnership resulted in some learnings that are highlighted in Box 3.

Box 3: Takeaways from the knowledge exchange between Chinese and European partners

Overall, the knowledge and technology sharing between the European and Chinese partners was successful, especially in the green and blue technologies. For example, the paper-based microgreen production (which involves growing edible sprouts in paper as an alternative to sowing them in the soil) used by the Chinese partner, Beijing Green Valley Sprout Ltd (BGVS) was also tested in Norwegian research institute NIBIO. Another example comes from the implementation of wastewater treatment technology which took place both in Changsha (by Hengkai and in collaboration with Scan Water) and at NMBU in Norway.

The main challenges encountered in the project originate from cultural differences and linguistic barriers. Strategies like the promotion of several scientific visits between China and Norway, specialists' exchanges, and regular online meetings and communications were employed to ease these shortcomings.

In regard to closing resource loops in cities, the SiEUGreen showcases offer insightful examples on the potential of implementing circular strategies in cities through UA (see Box 4).

Box 4: SiEUGreen examples of the impact of UA on cities' circularity

REDUCE: Input minimisation and efficient use of regenerative resources

This strategy focuses on the prevention and reduction of raw materials and energy consumption

Examples from SiEUGreen showcases:

- Reduced waste production and reduced energy inputs by implementing hydroponic and aquaponic systems within Turunçlu greenhouse in Hatay (Tapia et al., 2020)
- Reduced energy inputs by implementing aquaponics in Sanyuan Farm in Beijing (Moumtzi and Papadopoulou, 2022)
- Reduced use of artificial fertilisers by recycling nutrients in wastewater and food waste by making liquid and solid organic fertilisers in Campus Ås (Jenssen et al., 2022)
- Reduced use of tap water for irrigation by use of treated grey water and rainwater harvesting in Campus Ås (Jenssen et al., 2022)
- Reduced use of peat soil as growth media by making compost from food waste, bio residue in black water and garden waste in Campus Ås (Jenssen et al., 2022)
- Microgreen production without the use of fertilisers and soil media in Beijing (Moumtzi and Papadopoulou, 2022)

REUSE: Life cycle extension and systems reconceptualization

This strategy is related to expanding/optimising lifespans; reconceptualising products to greater lifecycles from the outset; facilitating maintenance, repair, reconditioning, and re-manufacturing options; and creating new business models

UA Examples/Examples from SiEUGreen cases:

- Extending the lifespan/function of a product/resource through sharing, repair or refurbishing with the elaboration of polytunnels with recycled materials in World Gardens in Aarhus (Borges and Oliveira e Costa, 2020).
- Reconfiguring unused public spaces for urban gardening in Aarhus Municipality (Borges et al., 2018; Tapia et al., 2020).
- Sharing of tools between the members of Brabrand Fællesgartneriet in Aarhus (Borges et al., 2018; Tapia et al., 2020).

RECYCLE/RECOVER: Waste reduction, valorisation and minimisation

This strategy relates to waste management and recycling of waste that cannot be reused or re-manufactured. It also involves using waste/by-products from one process as raw materials for another, thereby ascribing a higher value to waste materials as potential resources that can feed production.

UA Examples/ Examples from SiEUGreen cases:

- Polytunnels made of recycled materials in World Gardens in Aarhus (Borges and Oliveira e Costa, 2020)
- Household waste turns into vermicompost, black water turns into fertilisers, and grey water is used to make the bubbles in the greenhouse at Campus Ås (Borges and Rohrer, 2022)
- On-site composting of food waste and garden waste at Campus Ås (Mæhlum et al., 2022).
- Reuse of wood waste for planters and vermicompost containers at Campus Ås (Mæhlum et al., 2022).
- Liquid and solid fertilisers (e.g. struvite) from biogas production based on black water at Campus Ås (Mæhlum et al., 2022).

Note: inspired and adapted from de Jesus et al., 2018; Kirchherr et al., 2017; Potting et al., 2017, and examples collected in the SiEUGreen showcases.

Interconnections and interdependencies between UA and the implementation of circularity strategies at the city level are therefore evident. Still, the conditions that can trigger or hamper the implementation of circular economy have until now been little explored (Pascucci, 2020). A roadmap that uses UA to achieve more circularity in cities needs to identify both enablers and obstacles of transition.

4. Pathways towards circular cities: Enablers and challenges of urban agriculture

Proponents of UA argue that it can promote agri-food sustainability and food security while delivering various ecosystem services with positive impacts ranging from health benefits to the promotion of social inclusion (Caputo et al., 2020; Menconi et al., 2020; Russo and Cirella, 2019). Nevertheless, the pathway is unclear, and different urban centres having difficulties transitioning to a more circular urban agriculture paradigm (International Resource Panel, 2021).

Derived and inspired by the literature on circular economy and UA (D'Ostuni and Zaffi, 2021; Ferreira et al., 2018; International Resource Panel, 2021), **five categories of drivers and challenges are defined to clarify the pathway to more circular cities through UA** (see Figure 2). These categories are not mutually exclusive, as each are interlinked with one another. "Drivers" are defined as factors that enable and encourage the transition to circular UA (what are the benefits?), and "barriers" are impediments or bottlenecks that obstruct and limit transitions (what are the disadvantages?). In the following sub-sections, these drivers and barriers are introduced, discussed, and exemplified through the SiEUGreen experiences.

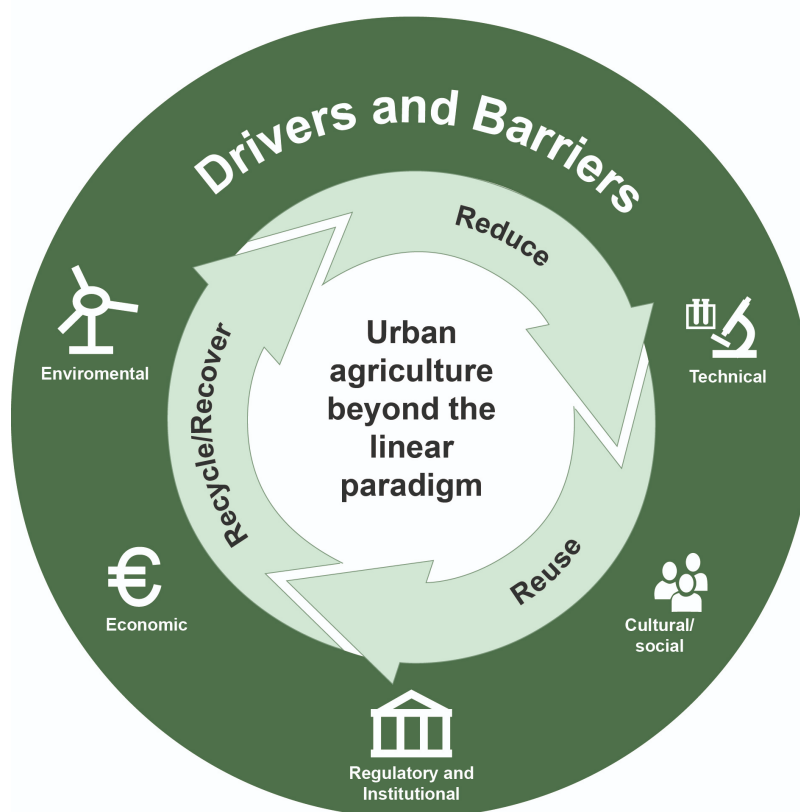


FIGURE 2: Drivers and barriers of UA to resource circularity in cities

4.1 Environmental impacts of UA and circularity of resources

There is a deep urban dimension to the world's environmental and climate challenges. With 52% of the global population living in urban areas and the expected increase of this share to 68% in the following decades (United Nations, 2018), urban areas greatly impact the environment while at the same time experiencing vulnerability to environmental issues (namely, extreme weather events, biodiversity loss, and pollution). Therefore, cities play a crucial role in the pursuit of an economically, socially, and environmentally sustainable future.

Sustainable agricultural practices in urban settings have the capacity to substantially **reduce environmental impacts and resource consumption**. Regarding energy savings, studies have shown that UA uses less energy when compared with long-distance supply chains, particularly in relation to transportation, cooling, and storage activities (International Resource Panel, 2021; Lwasa et al., 2014). On the other hand, recent technological developments, and

the integration of agriculture into existing buildings in the form of zero-acreage farming (rooftop gardens or greenhouses, edible green walls, and indoor farming operations), can provide significant **energy savings** and increase energy efficiency of buildings (Tapia et al., 2020; Wong et al., 2003). Research has also suggested that UA supports **resource efficiency**, especially concerning water and fertiliser usage (Armanda et al., 2019). Irrigation represents around 85% of global water consumption. Recovering wastewater and closed-loop systems by recirculating the irrigation water in hydroponics to produce food in cities can play a vital role in reducing global water demand (Pollard et al., 2018; Rufi-Salís et al., 2020). Some research has also found that UA can reduce resource consumption—for example, it can minimise the need for food packaging (Hallett et al., 2016)—and recycle waste as fertiliser, thereby closing the production-to-waste loop (Rudisill et al., 2015). Using organic waste as fertiliser can decrease the consumption and environmental impacts of mineral fertilisers and emissions from landfills (International Resource Panel, 2021).

Box 5: SiEUGreen experiences: Reduced resource consumption and improved efficiency

- The solar dry toilet in Brabrand Fællesgartneriet is an example of a circular and energy-efficient system. The toilet is powered by a PV panel that helps accelerate the decomposition of human faeces, which then becomes an input to the production of fertiliser to grow food (Borges and Oliveira e Costa, 2020).
- Sanyuan Farm implemented sustainable soil management while recycling waste. In 2019, approximately 100 tons of organic waste was recycled through vermicomposting, generating around 10 tons of organic fertiliser used for food production (Moumtzi and Papadopoulou, 2022)

UA can also foster different **climate change mitigation and adaptation strategies**, improve carbon capture, improve air and water quality, promote agricultural biodiversity, and maintain ecosystem services with positive environmental impacts (International Resource Panel, 2021; Nicholls et al., 2020). UA can indirectly improve urban adaptation capabilities, namely with water management, by mitigating the risk of floods and landslides caused by runoff from non-permeable surfaces in cities (e.g., streets, roofs, and car parks; Tapia et al., 2020). The expansion of urban green areas through UA can contribute to climate regulation by both reducing emissions and promoting the **additional capture of CO₂ emissions**. Furthermore, UA has the potential to shorten the distance between production and consumption, which reduces “food mile” emissions (Hallett et al., 2016). Worldwide, around 30 to 50% of food is lost, especially fruits and vegetables, due to inadequate infrastructure. UA improves food proximity to markets which can potentially reduce emissions as well as food loss (International Resource Panel, 2021). Another UA positive effect is on biodiversity as urban agricultural sites can become **ecological corridor habitats for fauna**, especially birds and insects (Clucas et al., 2018; International Resource Panel, 2021; Zhao et al., 2019).

Box 6: SiEUGreen experiences: Biodiversity and climate change mitigation

- Pier 2, a garden from Taste Aarhus, is a showcase of biodiversity gains coming from UA. The garden transformed an unattractive, previously industrial harbour space into a place for social interaction favourable to biodiversity. At the same time, it also acted as a climate change mitigation measure. The garden increased the permeable surface by implementing pallets in areas previously covered with gravel, minimising the flood risk in Aarhus (Tapia et al., 2020).
- In Brabrand Fællesgartneriet, the production and distribution of crops in the garden generated 65.3% less GHG emissions compared to conventional food supply systems. This estimation is based on the variety of vegetables, herbs, and fruits cultivated in the garden (Tapia et al., 2020)
- Sanyuan Farm contributes to reducing food miles by shortening the distance between food production and consumption, thus lessening carbon emissions. The farm provides a large amount of fresh food to Beijing, making available vegetables that otherwise would need to come from South China (Moumtzi and Papadopoulou, 2022)

The debate on the positive and negative environmental impacts of UA and the transition to resource circularity is still ongoing. While examples of positive environmental impacts of UA exist, these tend to be context sensitive (local context, business models, etc.). Some detrimental effects of UA, such as contaminating aquatic ecosystems, worsening water quality, and promoting health risks, are still being discussed (Graefe et al., 2019; International Resource Panel, 2021; Perrin et al., 2014; Taylor and Lovell, 2015). The effects of urban pollution on the quality of food produced in cities, especially due to heavy metals and organic chemicals, also raise concerns about health

risks. The impact of UA on, for example, the dissemination of vector diseases such as mosquito-borne illnesses caused by stagnant irrigation water, or on food waste reduction and transport emissions still lack further empirical research to clarify absolute UA gains (Armanda et al., 2019; International Resource Panel, 2021).

As most UA assessments focus on economic and social aspects, the environmental benefits or drawbacks remain ambiguous or lack empirical data. Therefore, there is a need to develop suitable methods, tools, and indicators to evaluate the contribution of UA to resource efficiency and to mitigate environmental externalities (Armanda et al., 2019; Mok et al., 2014; Pollard et al., 2018). The Life Cycle Assessment (LCA) method, which evaluates the environmental impact of a product from cradle to grave, seems a promising tool for assessing the environmental performance of UA (Armanda et al., 2019). Overall, further evidence-based research on UA's actual environmental impact and health risks is necessary, as well as a deeper understanding of technology's role in fostering sounder (or at least neutral) ecological impacts.



Urban farming in Campus Ås, Norway

4.2 Technological developments in UA

Technical solutions are essential to fully take advantage of the potential of UA for closing the resource loop in cities. Many non-renewable resources are becoming scarce, such as phosphorous, which is critical in the production of soil additives to optimise agricultural production (Zamparas, 2021). Additionally, water scarcity affects 40% of the world's population (World Bank, 2022), highlighting the need to adopt sustainable water management systems. These trends, combined with increasing waste production and the consequent challenges of managing waste, indicate the need for technological developments and their urgent implementation. Regarding **waste management and sanitation** in a circular economy, UA finds value in untapped resources within the urban waste sector, mainly organic waste and wastewater. Annual production of food in Europe demands about 11 Mt of nitrogen, 2.9 Mt of phosphorus, and 2.5 Mt of potassium of manufactured fertilisers (Fertilizers Europe, 2018). At the same time, Europeans produce 3.6 Mt of N, 1.7 Mt of phosphorus, and 1.3 Mt of potassium as part of human excrement each year (Kisser et al., 2020). Considering that more than 75% of the European population lives in urban settings, the potential to generate nutrients from human excrement in cities is vast. Nevertheless, with the conventional linear sanitation management system, most of these nutrients are lost to the environment, causing or adding to pollution downstream. The linear sanitation system involves the transportation of resources far from the sources of origin, with intensive use of water and energy, causing inefficient and untenable recovery of resources. **Redesigning the waste management system from a linear to circular** resource flow is paramount. There are already several innovative technological solutions to address these problems, especially through nature-based solutions which enable the recovery and reuse of resources and reduce environmental degradation, health risks, and overall costs (United Nations, 2017). Several of these solutions have been tested in the SiEUGreen showcases.

Combined with integrated post-treatment systems, **anaerobic digestion** of source-separated blackwater and food waste is one promising technology that facilitates bioenergy production, nutrient recovery, and pathogen/micropollutant removals (Eshetu, 2019). The organic matter in waste (such as blackwater, organic household waste, and garden waste) can be used as the primary resource input. For example, the anaerobic treatment of blackwater in anaerobic bioreactors enables energy recovery from organics which can be used to generate heat and electricity in the form of **biogas**. This treatment also retains most of the nutrients available in the solid and liquid phases of the digestate, which is a reliable feedstock for producing **organic fertiliser**. This fertiliser can supplement or replace chemical fertiliser.

However, anaerobic digestion alone is not enough to remove pathogens and pharmaceutical residues to the level that meets the required reuse or discharge limits; therefore, the waste must undergo post-treatment. For a reliable operation of the nutrient recovery processes and improved quality of the recovered nutrients, the effluent of anaerobically treated blackwater should be free of organic, particulate, and colloidal material and, as low as possible, in soluble micropollutants (Moges et al., 2020; Todt et al., 2015). The recovery of ammonium and phosphates as struvite is an example of turning waste streams (anaerobically treated blackwater effluent and urine) into fertilisers (De Graaff et al., 2011; Günther et al., 2018). Another promising circular approach for sewage sludge management or excess sludge from anaerobic digestion (the solid digestate) is its conversion into **biochar**. This process requires the combination of the excess sludge with waste wood biomass and spent coffee grounds which allows for recovering nutrients and energy, contributes to carbon sequestration, and reduces GHG emissions (Opoku and Boateng, 2021).

Urine is also a rich resource as it has a high nitrogen-phosphorus ratio, and thus, it can be an excellent supplement to many organic fertilisers and composts with a lower ratio (Hellström, 1998). Nevertheless, the urine must be separated from faeces through devices such as urinals or urine-diversion toilets to be used as fertiliser. A disadvantage of this process is the unpleasant odour (especially from stored urine) and social resistance to its use for growing crops. The nitrification of urine in the anaerobic digestion **bioreactors** is a possible alternative to overcome these shortcomings. This process can reduce smell, stabilise the liquid in storage, and provide a better plant nutrient solution. The nitrification process is different depending on the purpose: to increase storability, it should be performed on high-strength solutions, and to improve plants' nutrients, it can be performed on diluted solutions just before watering plants (Jenssen et al. 2022). Additional treatment as UV and active coal filtration, can also be used to obtain a fertiliser product that is free of infectious agents and pharmaceuticals (Mæhlum et al., 2022).

Urine and source-separated blackwater can also be a substrate for growing microalgae. **Microalgal**-based processes produce biomass as a secondary raw material for purposes such as **bio-fertiliser**, **biofuel**, or other applications like **animal/fish feed** (depending on the quality and composition of the algae biomass). Microalgae have a high growth rate where it takes only a few days to complete the entire growth cycle, and high photosynthetic abilities compared to plants (Brányiková et al., 2011).

Box 7: SiEUGreen experiences: Waste stream loops for urban agriculture

- Campus Ås successfully demonstrated blackwater management by using **upflow sludge blanket anaerobic baffled reactors** for anaerobic digestion. Students' flats located on the campus are equipped with vacuum toilets that allow the separation of blackwater from greywater. In this process, the blackwater is pumped into the biogas reactor. The outputs are: (a) energy in the form of **biogas**; (b) **biochar** produced from the excess solids from the bioreactor; and (c) a **nutrient-rich liquid** (digestate) that is processed into hygienically safe liquid and solid **fertilisers** after further treatment. Moreover, a two-stage **algae photobioreactor** was developed in Campus Ås for cultivation and up-concentrated nutrient-rich green biomass production and production of improved effluent quality (Mæhlum et al., 2022; Moges et al., 2019)
- In the Futiancangjun community (Changsha), the anaerobic treatment of blackwater from 18 low-flush toilets enabled the recovery of 96% of total phosphorus and 80% of total nitrogen. Nutrient recovery is partly based on the production of struvite for soil fertiliser. This process demonstrates the feasibility of implementing and scaling up decentralised integrated sewage treatment systems (Weijie, 2021)
- A **solar dry composting toilet** was tested in Brabrand Fællesgartneriet in Aarhus Municipality. The toilet demonstrated the possibility of recovering nutrients from human faeces. The compost from the toilet resulted in a nutrient-rich compost (Mæhlum et al., 2022)
- The German SiEUGreen partner IGZ produces urine-based recycling fertilisers for horticultural production called **Aurin CROP**. Compared to synthetic fertilisers in hydroponic cultivation, this fertiliser performs equally efficiently in total biomass shoot fresh matter and uptake of nitrogen, phosphorus and potassium. Therefore, nitrified urine with low ammonium nitrate has high potential as a recycling fertiliser in a nutrient film technique system for tomato cultivation (Halbert-Howard et al. 2020).

Composting is another sustainable resource recovery technique. The main process of composting involves transforming organic household waste into organic fertiliser, which can increase the self-sufficiency of urban farming systems while lessening the volumes of waste disposal in landfills. This technique has great potential to replace the reliance on peat. A non-renewable resource, peat is also one of the most efficient carbon sinks on the planet, making its preservation an important goal (Aurdal et al., 2022; Jenssen et al., 2022; Mæhlum et al., 2022). Composting can take place on different scales, from industrial applications using different composting technologies to small-scale composting in individual gardens. Therefore, it can easily be implemented and adapted to urban farming systems.

There are different processes for decomposing organic matter. For example, **vermicomposting** uses different species of earthworms to accelerate the decomposition process of food waste. Vermicomposting begins with providing the worms with a bedding material (e.g., a mixture of decomposing food waste). Gradually, one adds small portions of food waste into the worm bin. Earthworms will eat through the food waste and excrete waste in the bottom layers of the bedding. This organic material which has been "treated" by the earthworms, generally makes nutrients more available for plant uptake and gives the soil a better structure. Leachate compost (i.e., the liquid that drains from the compost) and vermicomposting have high nutrient content and can be collected and used as fertiliser (Jenssen et al., 2022). Furthermore, the worms from vermicomposting systems can feed fish within aquaponic systems (Jenssen et al., 2022).

Box 8: SiEUGreen experiences: Closing the loop on organic waste

- A **biological processor** that converts kitchen waste into fertiliser was implemented in a residential building in the Dongcheng District of Beijing. This processor is an electrical device controlled automatically (stirring, deodorisation, drying) that uses microbial anaerobic fermentation technology. After 30 hours of treatment, the kitchen waste is decomposed and ready for use. The compost was used in the Sanyuan Farm vegetable garden (Jenssen et al., 2019; Weijie, 2021).
- In Campus Ås, researchers tested **alternative growth media** such as food waste compost, vermicompost, and garden compost mixed with tree fibre. Results showed that these types of fertilisers are suitable to replace peat. Nevertheless, some precautions need to be taken. As food waste is often rich in nutrients and other salts, it must be diluted with different composts (Mæhlum et al., 2022). Another study compared the use of peat and sewage digestate-based compost to grow tomatoes. Results showed that sewage digestate-based compost is as efficient as peat, with no differences in the tomato yield or quality (Aurdal et al., 2022).
- In Campus Ås, bokashi containers were tested for temporary storage and pre-treatment of kitchen waste before using insulated tumbler composters. A mixture of food waste and other waste products (e.g., garden waste, wood chips) assisted in improving the aeration of the mix. This mixture resulted in a better carbon-to-nitrogen ratio, which benefits the composting process (Mæhlum et al., 2022). This technique is suitable for small-scale food waste treatment in cities due to the ease of operation, low cost, and efficiency in reducing flies, odours, and unwanted runoff.

As UA requires large amounts of water, technologies that minimise water usage are also relevant. The **treatment of greywater and capturing rainwater** can significantly reduce stress on urban water supplies. If treated, it is possible to reduce water consumption by more than 90% by reusing greywater for in-house applications. Biofiltration in **filter beds** or **constructed wetlands** is suitable for treating greywater. The combination of both types of filters results in the removal of phosphorus and nitrogen. The use of single-pass **biofiltration** in porous media and intermittent loading is a well-known, and widely used technology in Nordic countries for small wastewater flows in houses and cabins (Jenssen and Vraale, 2003). Constructed wetlands and **green walls** also act as a biofilter and/or can remove a range of pollutants such as organic matter, nutrients, pathogens, and heavy metals from the greywater (Mæhlum et al., 2022). The challenge has been to make biofiltration systems more compact for urban and peri-urban areas and implement an irrigation system that efficiently reuses water. Nonetheless, fixed-film or fluidised filter beds are efficient as they deliver highly hygienic water with low energy consumption and a small carbon footprint (Mæhlum et al., 2022). After treatment, which includes UV-filtration for hygienisation, the water is stored in a tank and is ready to be used for irrigation. Surplus water can be infiltrated on the ground if the soil is suitable. Otherwise, it can be channelled to a drainage network or another appropriate recipient.

Using **blue-green infrastructures for stormwater retention** is suitable for preventing flooding and leaching from UA, improving water quality, increasing biodiversity, and minimising water scarcity. These alternatives include green roofs, biofiltration systems, rain gardens, wetlands, ponds, and open channels, which also have the potential to create pleasant urban environments. Stormwater systems can be designed to harvest and treat rainwater for the irrigation of UA and other green areas (Eiter et al., 2022). Urban runoff systems can also be a source of irrigation for UA. Nevertheless, the water must be treated to avoid chemical compounds and infectious substances that can damage crops and the health of those who consume them. Risks of infection depend on the distribution of the water on the ground and the period between harvesting and using the water for irrigation. As urban stormwater runoffs are irregular, other water sources are needed to provide reliable irrigation systems that can cope with dry periods while delivering good water quality throughout the growing season (Eiter et al., 2022).

Regarding water management, **hydroponics and aquaponics** are very effective as they contribute to waste reduction, nutrient recycling, and water reuse. These closed-loop systems can save 40% of irrigation water and 35-54% of nutrients daily compared with linear systems (Rufí-Salís et al., 2020). Nevertheless, technical barriers such as the lack of waste segregation infrastructure and metrics to measure circularity need to be addressed. Further research is also needed to assess the economic feasibility of these systems (International Resource Panel, 2021).

Box 9: SiEUGreen experiences: Water efficiency and recycling

- In Campus Ås, biofilters were introduced to treat greywater in an office building. After being collected in a settling tank, the greywater is sprayed by a high-pressure nozzle in a biofilter tank containing lightweight aggregates (LECA). The biofilters remove the organic matter and phosphorus, thereby enabling the use of recycled greywater for irrigation and producing bubbles that insulate the greenhouse. This process saves up to 50% of water (Michailidis, 2021).
- Aquaponics technology has been successfully implemented in the Turunçlu greenhouse (Antakya) and in a greenhouse in Sanyuan Farm (Beijing). This technology is very efficient as it enables food production with 90% less water than traditional agriculture (Tapia, et al. 2022).

Despite the advantages mentioned above and the demonstration of many of the technologies in the SiEUGreen showcases (see Box 7-9), implementing these solutions requires more experimentation and large-scale tests. The security concerns with treating waste streams, particularly the handling and processing of blackwater locally, are critical. The biogas produced by an anaerobic digestion plant is composed of methane (50-75%), carbon dioxide (25-50%), water, nitrogen, oxygen, hydrogen sulfide, and ammonia. Methane is highly combustible, and hydrogen sulfide and ammonia are poisonous; therefore, **health and safety precautions are needed** (Chrebet and Martinka, 2012; Salvi et al., 2012). Additionally, **social acceptance and awareness towards these technologies** require effective engagement strategies that can reshape social behaviours and negative perceptions of waste. Finally, it is also necessary to further research the environmental impacts and **economic potential** of these technical solutions in order to build a **business case for up-scaling in urban settings**.



Polytunnels with recycled materials, World Gardens, Aarhus, Denmark.

4.3 Economic dimension: the business case of UA & circularity

Driven by global demographic trends, increasing and rapid urbanisation, and limited accessibility to land, UA is expected to play a crucial role in food production in the coming decades. UA enables short and resilient food supply chains (e.g., lower transportation costs), high-quality and environmentally friendly food (e.g., no use of pesticides or herbicides; lower resource requirements concerning land, water, and fertilisers; lower carbon footprint) and a stable production all year round (DRAXIS, 2021). Additionally, the COVID-19 pandemic and the Russia-Ukraine war have revealed the vulnerability of global and regional food supply chains (Levi and Molnar, 2022). Localising food production through UA initiatives has the potential to lessen the risk of logistics system breakdowns, reduce costs, and create more resilient supply chains. In times of crisis and economic hardship, including rising energy costs and inflation uncertainty, growing one's own food can help alleviate poverty and reduce living costs while granting access to healthy food (Armanda et al., 2019; Poulsen et al., 2015).

Nevertheless, the economic benefits of UA differ widely depending on the type and process of UA implementation, with different challenges and opportunities arising from the spatial location, functional focus, origin, market

orientation, and even farmer income level (Poulsen et al., 2015). Recent market research shows significant potential for the global urban farming market, which was already worth US\$137.5 billion in 2021 and is expected to reach US\$281.9 billion by 2030 (Market Watch, 2022). In particular, the market potential of vertical farming is expected to reach US\$9.7 billion globally by 2026 (Markets and Markets, 2020, 2021). Vertical farming is defined as a soilless cultivation method in a controlled indoor environment (Benke and Tomkins, 2017). It usually includes aquaponics, hydroponics, and aeroponics technologies, with hydroponics having the largest market share (Despommier, 2020; DRAXIS, 2021). Recent innovative and efficient technologies such as light-emitting diodes (LED), heat pumps, and active heat storage, as well as the use of 5G for automation and smart urban farming, have improved the potential of vertical farming to feed cities (Despommier, 2020; DRAXIS, 2021).

Several commercial exploitation possibilities were identified in SiEUGreen as one of the main objectives of the project was the demonstration of how technological and social innovation in urban agriculture can have successful economic impacts with different technological solutions, concepts, and products successfully demonstrated through the different project showcases (Box 10).

Box 10: SiEUGreen experiences: examples of potential exploitation

- **GREENergy:** Scandinavian Water Technology AS (ScanWater), the Norwegian Institute of Bioeconomy Research (NIBIO), and the Norwegian University of Life Sciences (NMBU) developed and deployed the concept of GREENergy at the SiEUGreen showcase site of Campus Ås. The concept is based on the principle of circular economy and is an innovative, integrated solution for water, sanitation, stormwater management, energy supply, and nutrient management in cities based on the principle of resource recovery and safe reuse. GREENergy aims to improve the management of organic household/domestic waste. It is a circular decentralised treatment system with near-zero emissions to water and air through the conversion of resources into fertilisers, bioenergy, and soil amendment. By doing so, GREENergy aims to increase cities' resilience and make urban development more climate neutral and human-friendly.
- **Commurban:** Developed by Draxis Environmental SA, this mobile application enhances people's engagement in UA. The app encourages users to explore new ideas, share knowledge about cultivation practices by posting Do-It-Yourself (DIY) UA projects, and actively participate in a virtual community through gamification features. The Commurban App has attracted the attention of users worldwide, with more than 840 downloads and 655 active users.
- **Garbage Processor:** Developed by Chinese company PHOTON, this home appliance uses microbial anaerobic fermentation technology and drying recovery technology to reduce the amount of food waste in a composting process. The garbage processor easily transforms kitchen waste into organic fertiliser that can be used by urban dwellers to grow healthy, organic vegetables.
- Fruit and vegetable/mushroom/succulent **planters** are home-growing devices produced by PHOTON as well. These devices can be used in limited spaces (e.g., balconies and kitchen banks) and automatically adjust humidity, brightness, and water replenishment for efficient cultivation. The planter facilitates the production of organic vegetables by urban dwellers and reduces, in part, the demand for market supplies (DRAXIS, 2022).
- **Biomass Estimation App:** This mobile app was developed and tested by NIBIO and NMBU with the aim of predicting vegetable biomass (yield) easily and quickly. Compared to traditional approaches, this app is very efficient as it demands less time and input of information while delivering accurate results (SEECON, 2022).

Less commercially driven types of UA, such as community gardens, also play a crucial role in the economy, despite focusing on self-supply or small-scale production oriented for local markets. Community gardens provide social services with the potential to generate employment related to the maintenance and governance of the gardens. Therefore, they can boost the local economy or even raise property values by enabling access to green areas. In the long term, this can be an advantage to property owners and municipalities collecting property taxes (Hallett et al., 2016; International Resource Panel, 2021).

Box 11: SiEUGreen experiences: Business models with a social focus

- Turunçlu greenhouse in Hatay and Sanyuan Farm in Beijing demonstrate interesting business models. In both cases, local authorities embrace food provision as part of urban infrastructure challenging usual, large-scale UA models, which are typically driven by the private sector (Borges and Rohrer, 2022).
- The women's cooperative in Hatay engages 250 women in financial and social vulnerability in UA. The municipality provides the women with the material to build a medium-sized polytunnel (6 m x 30 m) in their backyard. The cooperative owns half of the floor area of the polytunnel, which cultivates flowers used by the municipality to maintain public urban areas. The other half belongs to the women who cultivate vegetables for their own consumption and/or commercialisation in local markets (Borges et al., 2019).

There are several factors that can hinder the growth of UA markets. Access to private financing is still a barrier as banks remain hesitant to grant loans to private investors in this new and uncertain market (Cong and Thomsen, 2021). The significant initial capital investment necessary for establishing highly productive agriculture in cities, such as vertical farming, is another issue that may hamper UA markets (Armanda et al., 2019). Depending on the size and level of automation (from predominantly manual irrigation and harvesting operations to semi-automatic processes), the capital costs for planning and setting up UA facilities and operations are high. Furthermore, vertical farming is largely non-mechanised and thus dependent on highly skilled manual labour, adding higher operational costs than food production costs in rural areas.

Another set of barriers is linked to the **economic viability and competitiveness of UA products**. This relates to linear economy lock-ins. For example, chemical fertilisers are generally less expensive than bio fertilisers (Cong and Thomsen, 2021). The limited variety of crops grown with UA techniques can also reduce its marketability (Armanda et al., 2019; Ferreira et al., 2018). In addition, there are limitations related to the incompatibility of land costs versus financial returns of UA, which links directly with the small size of plots available to urban farmers (Ferreira et al., 2018) as well as the lack of access to land/competitive land use, especially when competing with residential and commercial interests (Armanda et al., 2019). Furthermore, costs to adhere to national and international standards concerning, for instance, organic certification can also be a hindrance (International Resource Panel, 2021).

The ongoing energy crisis and the increased prices of gas and electricity are likely to worsen these economic barriers, thereby negatively impacting UA initiatives. This affects not only commercial greenhouses and vertical indoor farms but also small-scale household operations. Here, the role of innovation in UA technology and recycling of organic waste for energy production (e.g., biogas) is essential to overcome these obstacles.

The significant **knowledge gap concerning the diversity and characteristics of circular business models** for valorising agro-waste and by-products is still significant (Dagevos and Lauwere, 2021; Donner et al., 2020). UA-based business models are distinct from standard ones as UA products are likely to face difficulties competing within mainstream commodity markets and against global prices. Nevertheless, UA can benefit from market niches linked with the demand for "circular", "fresh", "ethnic", and "tasteful" products that rely on short food supply chains and producer/consumer relationships, especially in developed countries. These conditions can be enablers for marketing both agricultural products and services associated with UA (Skar et al., 2019b).

Finally, the passive economic impacts of UA are poorly recognised. Public authorities often overlook the passive financial gains of UA (e.g. ecosystem services) as well as other social impacts, namely on health benefits, alleviating poverty, and improving lifestyles (International Resource Panel, 2021).



A greenhouse from Women Cooperative in Antakya, Turkey.

4.4 The social and cultural dimensions of UA

Several studies have pointed out how UA can promote social inclusion (Davidson, 2017), reduce poverty and crime (Ferreira et al., 2018; Zeunert, 2020), dismantle social barriers (Corcoran and Kettle, 2015), empower women (Hovorka, 2006), maintain traditional knowledge and cultural connections (Barthel et al., 2010; Shostak and Guscott, 2017), support human health and well-being (Brown and Jameton, 2000; Zeunert, 2020) and improve environmental education (Barthel et al., 2010; Hovorka, 2006).

Box 12: SiEUGreen experiences: Social inclusion

- The primary purpose of the Turunçlu greenhouse (Hatay) was to encourage social integration through its role as an educational centre. The educational programme was designed to instruct disadvantaged groups, including Syrian refugees and low-income women, on new growing techniques such as aquaponics, hydroponics, and paper-based plant growing (Borges and Oliveira e Costa, 2020). Participants found the greenhouse workshops highly valuable as a source of social interaction that enabled the exchange of knowledge and experiences while improving their skills to grow food (Borges and Rohrer, 2022; Tapia et al., 2020).
- The Taste Aarhus programme employed different strategies to explore the question, "How can cities create more socially inclusive places and communities when focusing on edible nature and urban farming?" The programme used UA as a tool to bring people together, activate underutilised spaces around the city and engage people in the practice of growing their own food (Borges et al., 2018).

Another potential social benefit of UA is the connection to **culture**, especially food culture. UA supports communities to maintain and nurture cultural identity while sharing values and customs with others. For emigrant communities, it can represent a continuation of cultural practices and traditional agroecological knowledge associated with their home country (Tapia et al., 2020; Taylor and Lovell, 2015).

UA's **physical and mental health benefits** have also been documented. UA can decrease risk factors for poor health, such as obesity, by expanding the supply of fresh and healthy food at reasonable prices. Studies report that UA increases fruit and vegetable intake and food diversity (Audate et al., 2019; International Resource Panel, 2021). Impacts on mental health are often attributed to the opportunities UA creates for people to meet and socialise and the associated effects of these encounters, such as increased life satisfaction, reduced loneliness, improved

happiness, and less stress. (Cong and Thomsen, 2021; International Resource Panel, 2021; Zeunert, 2020). Some potential but less empirically studied benefits are the improvement of environmental awareness among people and the dissemination of circular economy practices that are a byproduct of UA implementation (Barthel et al., 2010; Cong and Thomsen, 2021; Hovorka, 2006; International Resource Panel, 2021).

Box 13: SiEUGreen experiences: Healthy food

- The Taste Aarhus programme demonstrates the potential of UA to deliver fresh and healthy food. The programme identifies with signs edible resources available in urban public spaces and encourages the production of pesticide-free food (Borges et al., 2018; Tapia et al., 2020).
- Within six months of operation, Turunçlu greenhouse in Antakya produced approximately 4000 kg of lettuce and 2780 kg of basil. The food was donated to the social market, providing access to fresh and healthy food for low-income people. (Tapia et al., 2020)

Despite the potential benefits, social and cultural barriers can also hinder the implementation of circular strategies within UA. **Users' perceptions and misgivings concerning waste can limit a closed-loop approach to UA** (International Resource Panel, 2021). As Antić et al. (2020) highlight, the use of human waste as a fertiliser in UA needs further research to clarify the implications it could have on human health and the benefits it can bring to the environment and food security. Users for whom agricultural practices are not a custom or interest may also become disengaged with UA projects. Additionally, users' apathy or unwillingness to participate in recycling efforts, especially those involving technologies with high maintenance requirements or demanding lifestyle changes, can also cause obstacles in generating a functional and sustainable circular economy.

Box 14: SiEUGreen experiences: Social awareness and acceptance— behaviour, cultural, and social barriers

- Lab analysis showed that nutrients recovered from the human waste collected in the solar dry toilet in Brabrand Fællesgartneriet could be safely used as an additive for food production (Mæhlum et al., 2022). Despite this evidence, exchanges with the garden members revealed their unwillingness to use it. The aversion to using human excreta in food production relates to fears of chemical contaminants passing from the fertiliser to food production and its possible impacts on human health and soil quality (Borges and Rohrer, 2022).
- In the Dongcheng District of Beijing, a campaign to raise awareness of the use of kitchen waste as a resource for growing food involved 300 households. This strategy resulted in the reduction of 80% of household waste in the district (Borges and Rohrer, 2022).

Alongside these social hesitations towards UA, inadequate incentives to reuse bio-based materials (Pascucci, 2020) and the potential to exacerbate processes of gentrification (Horst et al., 2017; Safransky, 2014; Sbicca, 2019) are also pinpointed in the literature as adverse effects of UA. In fact, UA may reinforce and deepen societal inequities by benefitting privileged communities and resourced organisations and contributing to marginalisation and even displacement of socioeconomically disadvantaged households.

Local governance and public policies have a central role in supporting and promoting UA as a method for overcoming social barriers and anchoring circular practices that use waste streams to grow food in cities. Since local governments are responsible for a wide range of local infrastructure (e.g., water supply, waste management, sewerage treatment), they have a pivotal role in enabling practices and mechanisms (e.g., financial incentives, regulations) that encourage closing loops in cities and optimising food supply chains.



Solar-driven toilet and the janitor taking care of the compost in Brabrand Fællesgartneriet, Aarhus, Denmark.

4.5 Regulatory and institutional issues: governance for a more circular UA

European policy frameworks and strategies recognise the importance and necessity of integration of food, energy and water sectors—also known as the F-E-W nexus—to address global challenges such as climate change and economic, environmental, and social security. Food, energy, and water are recognised as human rights and are strongly represented in the UN SDGs as access to these resources are essential to people's life (United Nations, n.d.). In the **European Green Deal** (European Commission, 2019), the EU emphasised that a more sustainable EU economy relies on the efficient use of resources, moving to a clean, circular economy while restoring biodiversity and cutting pollution in the pursuit of climate neutrality by 2050. As part of the European Green Deal, the **Farm to Fork Strategy** aims to accelerate the shift to fair, healthy, and environmentally friendly food systems. This strategy acknowledges the intertwined connections between healthy people, healthy societies, and a healthy planet (European Commission, 2020a) and addresses challenges and opportunities in all food system phases (production, distribution, consumption, and disposal). But even in 2015, the EU Circular Economy Action Plan already highlighted the need to "(...) establish a concrete and ambitious programme of action, with measures covering the whole cycle: from production and consumption to waste management and the market for secondary raw materials" (EC, 2015: 2). The action plan covers not only legislative efforts but also funding tools in a significant policy push committing €222.7 million to support Europe's transition to a more "closed-loop" future (EC, 2015, 2017, 2019).

The importance of local governments to achieve these goals is stressed in international and national agendas, such as the **New Leipzig Charter 2020**, which emphasises the pursuit of the common good using the transformative power of cities. The charter provides a policy framework to envision and realise European and global agreements, such as the Paris Agreement and the European Green Deal at the urban scale, and it emphasises the need for inclusive and affordable urban policy that ensures safe services and infrastructure (European Commission, 2020b). Specifically related to food, the FAO initiative Food for the Cities (2011) was a pioneer programme for highlighting the role of cities as drivers for making food systems more sustainable and resilient (FAO, 2016). A further stepping stone was the Milan Urban Food Policy Pact in 2015 that pushed forward the development of holistic strategies integrating food, social economy, environment, and health at the local level in more than 240 cities and towns around the world. Most recently, the EU's Food 2030 framework pledged that solutions driving the transformation of current food systems towards sustainability could be achieved through a well-governed and more systemic research and innovation (European Commission et al., 2020). This document outlines that "governance and systems change" is an important element for delivering solutions to improve nutrition, the climate, circularity, and innovation.

The policy landscape suggests the importance of UA in strengthening the connection between the food, energy, and water sectors. The role of public policies coordination enabling framework conditions measures (e.g. legal frameworks, taxes, incentives, infrastructure development) in addressing market failures, technological limitations and socio/cultural difficulties is paramount in improving the circularity of resources in cities. Nevertheless, despite the gains that could be made by linking F-E-W policy areas, several limitations still hamper that development.

Specifically, regulatory frameworks can diminish the use of waste streams, as national regulations vary somewhat between countries and are generally quite restrictive. Further research on the hygienic risk of local use of waste resources and thorough routines for waste treatment, as well as coherent regulations, are still necessary (Jenssen et al., 2022). At the same time, upscaling the use of waste as a resource for food production in cities challenges current management structures and requires transformative governance models, new technical skills and tools, and reshaping the roles of civil servants and consultants within transformative processes as well as addressing social/cultural challenges and foster the diffusion of UA and circular economy information for both UA enterprises and civil society.

Box 15: SiEUGreen experiences: Regulatory limitations for implementing circular approaches for UA

- Despite the successful demonstration of recovering nutrients from wastewater in Campus Ås and the potential savings with fertilisers, the Norwegian legislation limits and controls the use of wastewater for agriculture (Landbruksdepartementet, 2003; Regjeringen, 2021). This restriction relies upon fears that wastewater may contain harmful quantities of organic pollutants or heavy metals, which can enter the food chain directly through irrigation. More research and information are needed to demystify these issues and to enable necessary legislative adjustments that make UA possible and safe (Borges and Oliveira e Costa, 2020).
- Human excreta are a sustainable and economically viable source of nutrients as it can be used to produce recycling fertiliser for horticulture by collecting and processing the contents of dry toilets (Krause et al., 2021). Nevertheless, overcoming the stigma of consuming food grown with the use of human excreta as fertiliser is not easy. This is a subject that needs further research to corroborate and consolidate findings on food quality and safety. The redefinition of regulatory frameworks and norms concerning what 'waste' is, and the development of certification standards can also be beneficial for anchoring the use of this type of fertiliser in society. Such institutional changes could help shape consumer behaviours towards products/crops produced using these means (Borges and Rohrer, 2022).

Other institutional barriers related to managing bio-based systems include the lack of defined property rights for biological materials and the ambiguity about who has the ownership of food as well as organic waste resources and who is in charge (and is liable) for managing it (Pascucci, 2020). Other hurdles are related to planning, with many local authorities failing to integrate UA activities into urban plans (Ferreira et al., 2018). In fact, territorial planning instruments and urban land use regulations have an essential role in officially acknowledging UA as a viable and worthwhile use of urban space (International Resource Panel, 2021).

Box 16: SiEUGreen experiences: Urban development versus UA.

- The Brabrand Fællesgartneriet is one of the oldest and largest UA associations of the Taste Aarhus programme. The garden was established in 2014 in the peri-urban areas of Aarhus. Currently, more than 100 members cultivate vegetables in an open-air site and in two large greenhouses. Nevertheless, in 2020 changes in the local legislation appointed the area as a priority for housing development which is likely to lead to the displacement of the association (Tapia et al., 2020).
- Gallerup (World Gardens) is a multicultural neighbourhood on the outskirts of Aarhus, and it is home to people from 80 different nationalities. The Danish legislation supported the revitalisation of the area as a strategy to counteract the negative socioeconomic trends (e.g., low income and high unemployment rates). The revitalisation included several interventions, such as the construction of an administrative public building, the reshaping of public spaces, and the renovation of several residential buildings with the demolition of some apartments. The spatial changes, however, triggered gentrification and eviction of some residents, and many gardens established more than 30 years ago were razed with the revitalisation of the area (Borges and Rohrer, 2022)

A significant challenge is the lack of mechanisms to anchor UA in the socioeconomic fabric of the city. This reflects the siloed development of planning policies, such as food and enterprise policies. This hints towards the importance of strategic governance towards UA implementation within a circular approach: a coherent roadmap to align policies at several levels and areas - not isolated initiatives. Therefore, looping resources through UA requires the development of urban transformative capacities (UTC). UTC encompasses the "collective ability of all actors in an

urban innovation ecosystem to conceive of, prepare for, initiate, and perform" transformative change at social, organisational and ecosystem levels, thus enabling sustainable future development (Wolfram, 2016).

Box 17: SiEUGreen experiences: Importance of governance at the urban level; recommendations for implementation of circular approaches for UA

- The "Green Embassy" is the headquarters of the Taste Aarhus programme. Located in the main public square of Aarhus, the embassy provides information to the public related to UA, such as the location of edible sources in the city or how to get support to initiate an urban garden. With a small but qualified civil service capacity (manager, communication, and garden expert) the programme has been successful in bridging gaps between different sectors of the municipality as UA is integrated into healthcare schemes, educational, and social programmes (Borges et al., 2018).
- The SiEUGreen showcases uncovered the need to develop new capacities to support the successful implementation and management of sustainable and circular solutions. For instance, one of the success factors attributed to the implementation and management of the solar dry toilet in Brabrand Fællesgartneriet was the employment of a janitor who took care of the waste (Borges and Rohrer, 2022). These learnings help to define necessary transformative capacities for future UA initiatives that will require local level governance support.

5. Looking to the future of UA in a circular economy

UA could play a critical role in ensuring food security, closing the loop on urban resources, and reducing pressure on agricultural land in the forthcoming decades. The experiences of the SiEUGreen project addressed throughout this white paper were used to feature some of the most recent research on these themes. The learnings can be seen as a springboard for broader debate concerning the future of UA within a circular economy approach (Figure 3).

When considering UA, context matters. The type of technology used or business model pursued may need to be adapted according to the social/historical factors of the local setting. Different UA typologies benefit specific populations, which means that UA implementation will take on distinct forms in different countries and even in different cities within the same country. Therefore, it is important to promote local research and case study analysis that can highlight **policy solutions to address context-related barriers and limitations**. In SiEUGreen, this diversity was noted in the different showcases across the various geographical location of the case studies, which has contributed to the broad viewpoint of advantages and hindrances hampering UA and urban circularity described in this white paper.

Another key takeaway is the importance of reconceptualising cities' food provision role under the inspiration of circular and regenerative principles and practices. **City food provision and UA systems can be designed considering circular economy** regenerative cycles, with evidence pointing to the many advantages of closing the urban resource loop, but this is not a given. There are several components of the linear, take-make-disposal economy that are structurally in place, many of which reinforce systematic barriers and limitations (environmental, technological, economic, cultural/social) to achieving urban food provision through UA.

From an environmental perspective, UA suffers from a polarisation of opinions and results regarding its impacts on resource consumption and efficiency in closing the loop. The discrepancies around how well UA can contribute to biodiversity and climate change adaptation reveal the need for more evidence-based research, clear monitoring tools, and **evaluation/assessment of the different UA typologies and their impact on the environment**.

As new (circular enabling) technologies and UA innovation and business model potential drive the development of UA activities, these are other building blocks that need to be addressed in this discussion. **Innovative technological developments** are enablers that can support and promote UA activities in all R's, from water reduction consumption enabled by aquaponic technology; to composting techniques to reuse organic household waste as organic fertiliser reducing waste disposal in landfills; and especially on recycling and recovering of materials and energy from the urban waste sector (e.g. Anaerobic Digestion). Nevertheless, **implementing these solutions requires more experimentation, large-scale tests and validation both concerning their efficiency, positive environmental impacts, as well as economic viability**. There are also several **regulatory challenges** concerning waste and waste management that need to be addressed, as well as social acceptance and awareness concerning the value of "waste".

On the economic side, high investment costs for some agricultural technologies and difficulties accessing financial support limit UA implementation. Other obstacles are related to competitive prices of food produced in larger supply chains and the **underdevelopment of a business case for circular resource models**. Lastly, there is limited recognition of the positive and indirect economic impacts of UA's social and environmental benefits. To address these challenges, researchers in relevant fields could construct a holistic cost-benefit analysis of these impacts to test the economic soundness of UA. Without such tools, public authorities may continue to neglect the broader economic impact that UA might offer through its social benefits, namely on health, boosting the local economy, enabling social inclusion, and alleviating poverty.

Even when the direct economic potential is limited, UA has the potential to trigger valuable gains. **Empowering groups at risk of social exclusion, lessening poverty, ameliorating human health and well-being, and improving environmental education—all of these are side effects commonly reported of UA**. While technological progress, innovation, and developing a business case for UA are all important, the deep societal impact these activities can offer should not go unnoticed. Several other societal benefits can be stressed as potential gains in the transition to a circular economy. However, it is also important to note that behaviour and cultural barriers have a deep impact when fostering a closed-loop approach to UA (especially concerning **overcoming prejudice against waste as a resource**).

Existing research, as well as the SiEUGreen showcases, point towards the central **role of local governance and public policy in fostering closed loops in cities** through various mechanisms (e.g., financial incentives, regulations) that support and promote UA as a pathway to address urban challenges. One of the main challenges is the need to overcome the siloed development of planning policies and, instead, enable collaborations within the urban innovation ecosystem to foster cities' sustainable future development. The transition to a circular urban agriculture needs structural change and the establishment of framing conditions that governments, both at local and national levels, can encourage. This can include the development of **tools to monitor environmental impacts, a sound regulatory framework, knowledge exchange and demystification of circular economy processes, collaboration among urban and regional actors, and showcasing successful examples that can lend themselves to the development of a business case for UA.**

The different SiEUGreen showcase examples allowed for interesting viewpoints on UA activities and pointed to several important questions that need to be addressed. What seems certain is that cities play a fundamental role (both positive and negative) in leading the global transition towards more sustainable food production, consumption, and waste systems. As this role will only increase in forthcoming years, it is important to foster discussions and stimulate debates on how to re-conceptualise urban food provision through the lens of a circular economy.

Table 1: Summary of drivers and barriers

	Drivers	Barriers
Environmental	• Positive impacts on resource consumption and efficiency and in climate change mitigation and adaptation • Potential to shorten food supply chains and contribute to biodiversity preservation in cities • The emergence of environmental sound technologies and plant growth techniques • Support from EU legislation that focuses on circularity of resources	• Need for more research on tools and methods to assess the environmental impact of UA • Limited evidence-based research on UA impacts on resource consumption and efficiency, health risk and UA products, sanitation, etc.
Technological development	• Increased food demand and the need to ensure food security • The emergence of innovative and efficient technologies • The outgrow of viable business models for high-tech types of UA	• Challenges with waste and waste management regulatory frameworks • Infrastructure lock-ins • Limitations concerning the economic potential, financing and business case for large-scale implementation of technical solutions
Economic	• Growing demand for food due to demographic drivers and food security (especially during shocks/ economic crises) • Potential to generate employment and improve the local economy • Beneficial economic indirect benefits (social/ health)	• High investments for some types of UA • Competition with linear economy product prices • Insufficient economic recognition of social and environmental benefits
Social/ Cultural	• Potential in the promotion of : - social inclusion, crime reduction and gender equality - mental and physical health - food culture and environmental education	• Cultural and behaviour barriers limit a closed-loop approach to UA (using waste as a resource) • Lack of participation in recycling schemes • Weak incentives to reuse bio-based materials
Institutional/ Regulatory	• Growing international policy focus on the role of cities in contributing to more sustainable and resilient food systems and climate change adaptation and mitigation • Increasing public/citizen demand/need for green areas and UA initiatives in urban space	• Limited focus on the business case as UA circular solutions depends on public funding with limited longevity after it • Local authorities still fail to integrate UA into urban plans • Regulatory limitations (e.g., access to finance, access to certification)

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This White paper is a part of the project **Sino-European innovative green and smart cities (SiEUGreen)**.

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