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Significance and Vision of Nutrient Recovery for Sustainable City Food Systems in Germany by 2050

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Citation: Keuter, V.; Deck, S.; Giesenkamp, H.; Gonglach, D.; Katayama, V.T.; Liesegang, S.; Petersen, F.; Schwindenhammer, S.; Steinmetz, H.; Ulbrich, A. Significance and Vision of Nutrient Recovery for Sustainable City Food Systems in Germany by 2050. *Sustainability* **2021**, *13*, 10772. https://doi.org/10.3390/su131910772

Academic Editor: Sabine O'hara

Received: 13 August 2021
Accepted: 24 September 2021
Published: 28 September 2021

Abstract: Within this paper, the authors explain their transdisciplinary vision of nutrient recovery for sustainable urban plant cultivation in Germany from different but complementary perspectives (SUSKULT vision). Nowadays, the demand for fresh, healthy, locally and sustainably produced food in German urban areas is constantly increasing. At the same time, current agricultural systems contribute significantly to exceeding the planetary boundaries. The disruption of the phosphorus and nitrogen cycles in particular stands out from the manifold effects of modern food production on the Earth system. One central issue that will have to be faced in the future is how increased yields in agriculture will be achieved with high-energy requirements in fertilizer production and pollution of water and soil by phosphorus and reactive nitrogen. City region food systems (CRFS) can be a solution to overcome these issues. Nevertheless, to ensure sustainable CRFS, innovative technologies and methods need to be developed, including nutrient and energy recovery and adapted horticultural cultivation methods that fit complex urban dynamics. Such new strategies need to be integrated in long-term social and political transformation processes to enhance acceptance of food produced by recyclates. The joint contribution of experts from the wastewater, horticultural, and political sciences, together with industrial and societal sector actors, is critical to reach these objectives. The overarching goal of SUSKULT's vision is the establishment of the field of urban circular agricultural production as an innovative sector of the bio-based economy in Germany.

Keywords: CRFS; circular economy; transformation; nutrient recovery; treated wastewater; Germany

1. Introduction

Food supply chain resilience is being severely tested in the last years with disruptions caused by the climate effects in Europe as in 2017, the European drought and heat wave in 2018 or the COVID-19 pandemic in 2020. Besides these effects, the climate change and the energy transition in Germany pose major challenges for German cities and hence the main market for fresh products. Given that risks to municipal infrastructures will continue to increase due to the negative effects of climate change, it is urgent to promote policy, planning and actions for mobilizing the existing local and national resources to accelerate urban food systems inclusive transformation [1]. This requires considerable adjustments not only in the operation and in expansion of the infrastructure, but also in concepts for the sustainable production of food close to the consumer. In the literature on regional food systems there is an ongoing debate what circle to draw around an urban region to define 'regional', which ranges from 30 to 300 km [2]. We define a production site within close proximity to the urban consumers within a distance of 2–10 km to reach a majority of 50–80% of the urban inhabitants. Metropolitan areas offer the chance to consequently use the potentials of wastewater, heat and CO_2 resources for sustainable food production [3].

By 2050, 68.4 % of the world's population is expected to live in cities [4]. As hubs for creative ideas and technology innovation cities owe "transformative power" [5]. The current Global Environmental Outlook identifies urbanization as a critical factor for the implementation of the sustainable development goals (SDGs) [6]. Current empirical evidence suggests that urban and peri-urban agriculture will play a key role in providing a stable and sustainable food supply for the cities of the future [7,8]. These forms of agriculture are part of the so-called "city region food systems" (CRFS), a planning approach developed by the Food and Agriculture Organization of the United Nations (FAO) that is considered to be a key element for the implementation of the Agenda 2030 and the New Urban Agenda (NUA) [7]. The CRFS approach assumes that the city region has the potential to leverage impacts that are tailored to specific local challenges. CRFS interlink rural and urban communities in a region within a country, across regions, and sometimes even between continents [9]. They recognize the central role of the private sector in the food system, but are simultaneously based on the understanding that public goods will not be delivered by market forces alone, and that greater transparency and democratic participation are prerequisites [3]. One of the cornerstones of the contribution that CRFS can make to global sustainability transformation is the production of food at or near the place where it is most likely to be consumed—the city.

CRFS can integrate agricultural food supply chains into urban infrastructures by means of vertical and building-integrated approaches [10,11]. They are spreading globally and play an important role in the urban food revolution [12,13]. A key element of CRFS is circular production (circular production in means of circularity of the resources, as nutrients (human excrements-wastewater-fertilizer-plants-human excrements), water, (CO_2 and heat), which interlinks different sectoral systems, e.g., plant cultivation and animal husbandry (aquaponics) or plant cultivation, and urban nutrient flows (building-integrated agriculture).

The spread of CRFS links to ongoing political debates about new, sustainable and inclusive economic growth strategies and agricultural practices. As an integral part of the European Green Deal—setting out how to make Europe the first climate-neutral continent by 2050—the "Farm to Fork Strategy" (F2F) of the European Commission published in May 2020 promotes extended application of precise fertilization techniques and sustainable agricultural practices. By 2030, the F2F aims at reducing "nutrient losses by at least 50%, while ensuring that there is no deterioration in soil fertility. This will reduce the use of fertilizers by at least 20% by 2030" [14]. The strategy has been developed by the European Commission with involvement of the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions with the aim of implementing a fair, healthy and environmentally-friendly food system in Europe. According to [15], the F2F's potential of serving as a game changer in European food policy depends on four challenges: (i) answering the open question of what is meant by food sustainability, (ii) addressing the mismatch between the F2F's policy objectives and legal actions in the EU Common Agricultural Policy (CAP), (iii) complex institutional integration in different affected policy areas, e.g., health, food safety, agriculture and environment, and (iv) solving problems of vertical coordination between the EU level and the governments of the member states.

In Germany, the Nationale Bioökonomiestrategie (National Bioeconomy Strategy) adopted by the Federal Government in January 2020 promotes the use of biological resources, processes and systems to provide products, processes and services that "unite biological knowledge with technological solutions and utilize the inherent properties of biogenic raw materials such as their natural cycles, renewability and adaptability" [16]. The strategy targets "novel cycles for the production, processing and recycling of biogenic resources, for instance in urban areas" [16], places special focus on waste streams (e.g., municipal or industrial wastewater) and highlights the need for innovative methods and processes for efficient processing and recycling of important resources such as phosphorus [17]. Regarding agricultural production, the strategy highlights the need to develop "holistic agroecological systems with the help of key technologies and concepts that bring together existing agricultural techniques and ecological requirements in novel ways (i.e., from smart and organic farming approaches to (modular) high-tech production systems, and largely closed circulation systems such as vertical farming)" [17].

The overarching goal of this paper is to introduce a vision that sees urban agricultural production as a key component of sustainable, resilient and inclusive CRFS of the future-at least by 2050—(see Figure 1). The vision connects the urban wastewater treatment system and the agricultural production system in densely populated urban areas. It projects the transformation of a conventional waste water treatment plant (WWTP) into a "NEWtrient®-Center", which draws the essential resources of water, nitrogen, phosphorus, potassium, CO_2 and heat for urban plant cultivation from municipal wastewater. This includes the use of biogas, produced from anaerobic digesters in combined heat and power plants. The vision is currently being developed by 15 partner institutions in the joint research project "SUSKULT—Development of a Sustainable Cultivation System for Food in Resilient Metropolitan Regions". The SUSKULT vision is going to be implemented in a model plant at the WWTP "Emschermündung" in the model region Ruhr (German federal state of North Rhine-Westphalia).

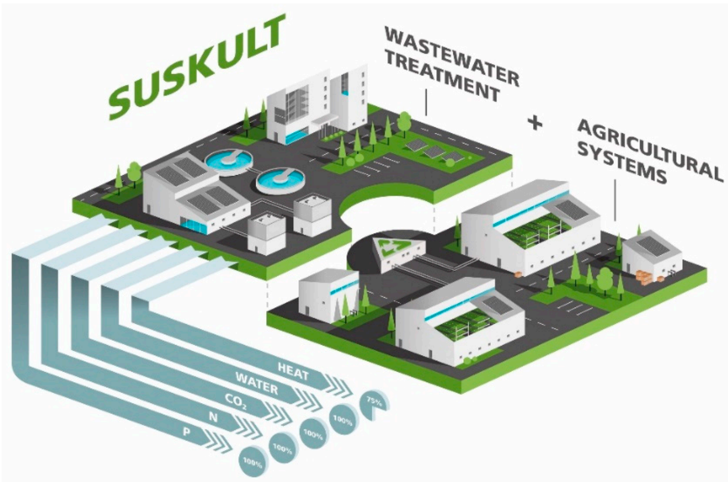

Figure 1. Concept of the SUSKULT circular urban economy of the future.

2. Methodology

In this paper, the circular urban food cycle as the core vision of SUSKULT is explained as part of the three key elements of this novel food system for 2050: (i) recovery of urban resources from wastewater for cultivation, (ii) cultivation techniques and crop varieties complying with future needs and (iii) consumer demands and perceptions. Building on findings from ongoing transdisciplinary research in SUSKULT, the paper shows the resource potential of wastewater treatment plants (WWTP) for urban plant cultivation in detail. In order to evaluate the resource potential of water (Q), nitrogen (N), phosphorous (P), potassium (K), thermal energy (W) and carbon dioxide (CO_2) in different wastewater streams concentrations and loads of fictional model WWTPs were estimated by accounting resources with static calculating methods according to German standard-values (DWA-rules such as DWA A 131, DWA M-368, DWA 383, DWA M114, DWA M 366 E; more details see Table 1). The new cultivation techniques developed by the University of Applied Science Osnabrück are based on literature results [18,19], upscaled to larger production units, optimized to various environmental settings and examined with multiple experimental approaches and cultivars. The role of society in large transformation processes as targeted by the research project is examined in the third key element. The empirical focus is on the Ruhr area, which is similar to other major cities and megacities in terms of area and population [13]. As the largest German agglomeration, the Ruhr area is characterized by a polycentric structure as well as an industrial legacy that left behind a well-developed infrastructure now badly in need of renovation [13]. At the same time, the German Advisory Council on Global Change is rightly devising the Ruhr area as the emerging "post-mining model region" [13] that offers opportunity for drawing valuable lessons and sharing bottom-up experiences around how best to implement sustainable CRFS for the future. Based on reviews of literature on sustainable consumerism (e.g., [20,21]), consumer survey research (e.g., [22,23]) and our own participatory stakeholder research within the SUSKULT project, the status quo is analyzed and partly projected to future demands in German polycentric metropolitan areas (as defined by [24]).

3. Key Elements and Enabling Technologies Based on the SUSKULT Vision of a Circular Food Supply in Urban Areas

The overall assumption of the SUSKULT vision is that in 2050 there will no longer be WWTP in their current form as waste disposal facilities, but rather so-called "NEWtrient Centers®". Resource flows, which contain relevant amounts of nutrients (including, i.e., organic waste), will be traded. The consumer of food becomes at the same time the producer and supplier of his very own nutrients. This makes it possible to close, e.g., the phosphorus cycle and to shorten the natural cycle of nitrogen and potassium via a shift to soilless systems.

According to information provided by the Federal Ministry of Food and Agriculture (BMEL) in 2015/2016, about 94 kg of vegetables per inhabitant were consumed in Germany [25]. Tomatoes accounted for around 25 % of this. This corresponds to a quantity of about 2,000,000 t/a. Approximately 4 kg N and 0.7 kg P are released into the wastewater per person per year on average, resulting in about 400 t N/a and 66 t P/a for a city with a population of 100,000. That amount of nutrient would be sufficient to cultivate around 200,000 t/a of tomatoes (accounts for around 10 % of the German market needs), for instance. This rough estimation shows the production potential of further food products by the remaining nutrients of WWTPs. WWTPs also offer the potential to produce low-temperature heat from wastewater (total chemically-bound energy in the influent to the plant: approx. 150 kWh/(E*a)), for example via the recovery of heat from the plant's effluent (approx. 1 kW/(m^3*K) or from biogas (potential: 45 kWh/(E*a)). Additionally, CO_2 produced by sewage sludge digestion (2.5 m^3/(E*a) and contained in the exhaust air of the combined heat and power (CHP) plant (7.0 m^3/(E*a) would be available year-round for CO_2 enrichment in urban plant cultivations systems.

In order to realize this vision, key elements, enabling technologies and rural urban interfaces have to be developed so that the treatment plant output is directly converted into high quality, plant-available and harmless resources for utilization in intensive horticultural systems for sustainable urban food supply. SUSKULT's vision is to spatially integrate food production in hydroponic systems into a WWTP. Certain requirements for the components recovered from the resource flows of the WWTP, in particular the nutrients, with focus on P, N and K, are thus derived and defined based on this vision. Concentrated nutrient solutions on the other hand need to undercut critical concentrations of sodium and chloride content and conductivity, which could inhibit plant growth or quality.

The overarching goal of the SUSKULT vision is to introduce urban agricultural production as a component of the circular urban economy of the future (see Figure 2) as an innovative sector of a bio-based economy in Germany. We follow the consensus view of basic notions of the circular economy as an economic system that represents a change of paradigm in the way that human society is interrelated with nature and aims to prevent the depletion of resources, close energy and materials loops, and facilitate sustainable development through its implementation at the micro (enterprises and consumers), meso (economic agents integrated in symbiosis) and macro (city, regions and governments) levels [26]. The circular urban economy approach according to the SUSKULT vision is specifically developing a hydroponic-based sustainable and local food production system.

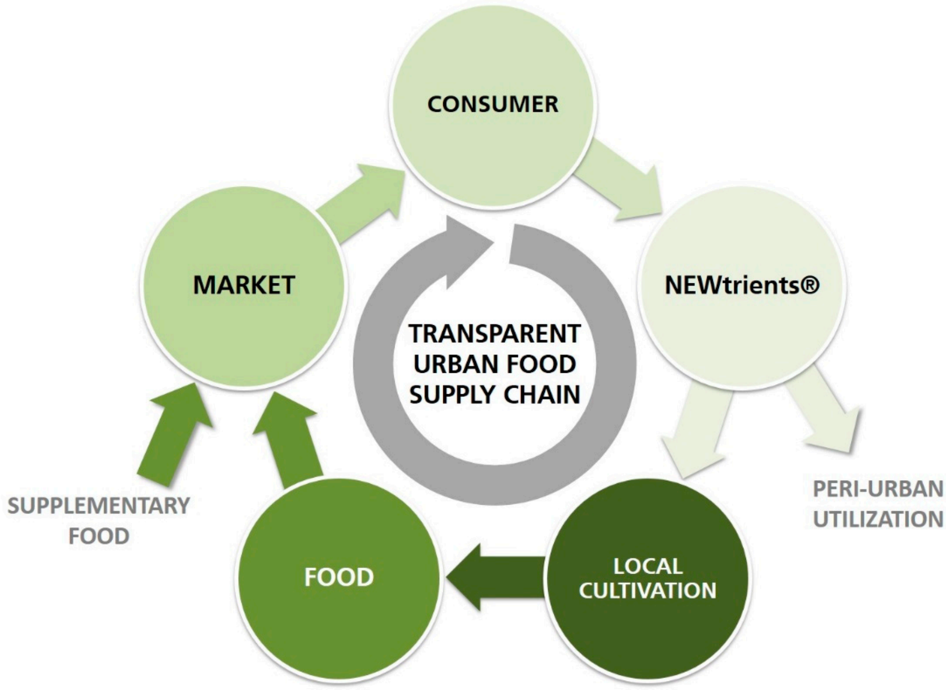

Figure 2. Circular urban economy according to the SUSKULT vision.

3.1. Analysis of Urban Resource Potential

In the majority of countries of the OECD (Organization for Economic Co-operation and Development) more than 80% of the population is connected to municipal WWTPs, in some countries the connection rate is even close to 100 % [27]. For example in Germany 96.5 % of the population is connected to central WWTPs [28]. Thus, resources discharged in the sewer system are accumulated at the site of WWTPs. The objective of conventional wastewater treatment is to reduce contaminants in wastewater to a level that can be released into the environment without negative effects for the receiving waters. State of the art is degradation or precipitation of these substances and depollution of the wastewater during the treatment process, because otherwise discharges of wastewater containing relevant amounts of organic components and nutrients result in oxygen depletion and eutrophication of water bodies. Therefore, WWTPs have to comply binding limits for nitrogen, phosphorous and organic discharges in several countries such as member states of the EU [29] (for example, Germany [30]) USA [31,32] or China [33]). Besides setting emission standards, e.g., in Germany depending on the size of the WWTP [30], the state of the receiving water can be decisive for setting surveillance values for the effluent, e.g., in China intended use and type of water body [33]). Existing treatment technology is constructed to keep the limits. Other parameters are mostly only interesting, if they disturb operation or affect costs (for example energy consumption, demand of chemicals or sewage sludge disposal).

Nevertheless, the main objective of wastewater treatment is a safe and cost-effective purification of wastewater. Ingredients of wastewater are mainly considered whether they affect this objective and not according to their specific value for other purposes. However, phosphorous is an exception. Enhanced due the discussion on the so-called peak phosphorus and the European dependency from phosphorous imports a rethinking of phosphorous recycling has occurred. Since 2014, phosphorous rock is officially declared as a critical raw material by the European Commission [34]. In 2017 the list of critical raw materials in the EU was supplemented with phosphorous [35]. In Switzerland and Germany there are meanwhile obligations by law to recycle phosphorous from sewage sludge as of 2026 and 2029, respectively [36,37].

Recovery of one single nutrient does not satisfy the idea of comprehensive recycling. Wastewater contains several essential resources for agricultural cultivation, besides phosphorus also water, heat, nitrogen, potassium and through the treatment process carbon dioxide.

Successful plant cultivation needs adequate relations between nutrients (see Section 3.2). Deficiencies or excess of some nutrients affect optimal plant growth. The adequate relation between nutrients is dependent from plant species (see also Section 3.2) and in some cases from growth period. To produce variable nutrient solutions separation and recovery of individual nutrients or a specific combination of nutrients is necessary.

Efficiency of nutrient recovery is on the one hand dependent from process disturbing contaminants and on the other hand from the nutrient itself (load, concentration, chemical compound). Whenever possible coarse solids and disturbing contaminants should be removed before recovery. The load of nutrients in the starting wastewater stream affects the potential mass of recovered nutrients. The higher the concentration recoverable nutrients the smaller the volume flow that has to be treated for the same amount of recovered nutrients. Thus, a higher concentration of a nutrient in a recoverable compound under otherwise same process conditions reduces the specific demand of space for the recovery unit, energy for pumping and stirring, chemicals to adapt process conditions such as adequate pH and other operating material. For evaluation of the nutrient potential of a wastewater stream all these aspects such as load, concentration, type of chemical bond and disturbing substances have to be considered.

In order to evaluate the resource potential of water (Q), nitrogen (N), phosphorous (P), potassium (K), thermal energy (W) and carbon dioxide (CO_2) in different wastewater streams concentrations and loads of fictional model WWTPs were estimated by accounting resources with static calculating methods according to the DWA standards in Germany (see Table 1). Incoming loads were assumed according to literature data. Assumptions and calculations for balancing the resource potential at different points within a model WWTP (see Table 1).

An example for a resource balance on a model WWTP is given in Figures 3 and 4, where nitrogen load and concentration, divided into dissolved, solid and gaseous fraction, is pictured. The scale of the pictured diagrams depends on the maximum value, which occurs in the influent raw wastewater in case of load while the highest concentration occurs in the dewatered sludge. Resource potential of nitrogen and other resources on the same plant configuration are shown in Table 2.

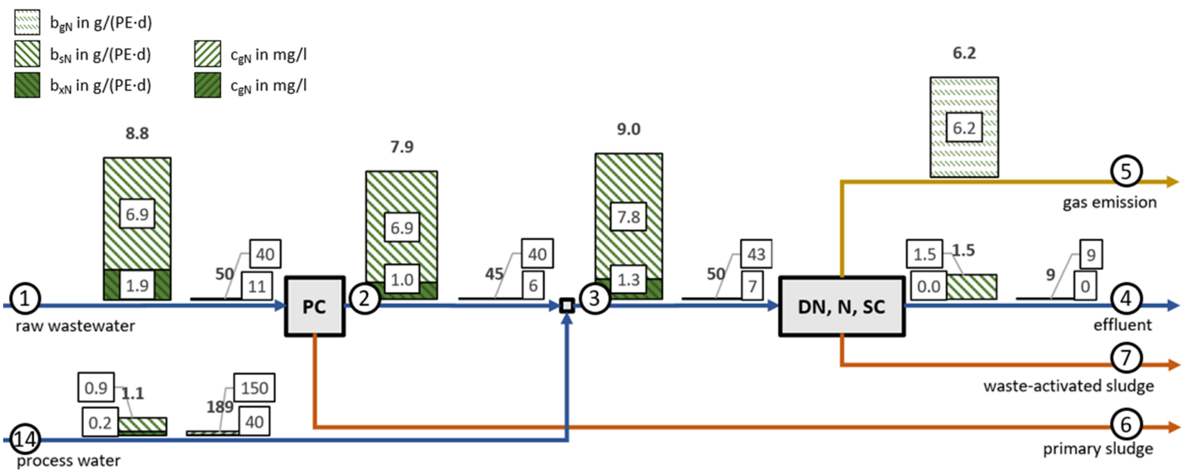

Figure 3. Load (b) and concentration (c) balance of nitrogen based on inhabitant specific values according to Table 1 for a model WWTP with chemical phosphorous removal and anaerobic sludge stabilization—Part 1 wastewater treatment, with: bgN gaseous nitrogen load; bsN dissolved nitrogen load; bxN solid nitrogen load; csN dissolved nitrogen concentration; cxN solid nitrogen concentration; PC primary clarifier; DN denitrification; N nitrogen removal; and SC secondary clarifier.

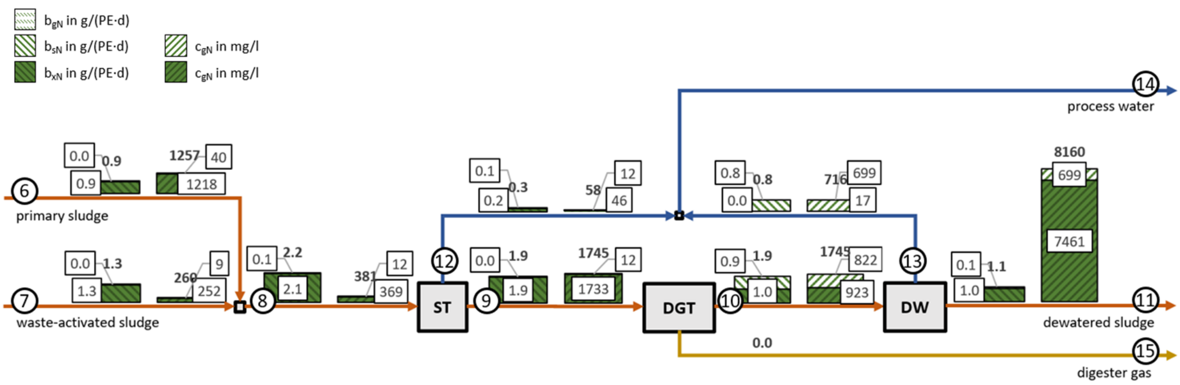

Figure 4. Load (b) and concentration (c) balance of nitrogen based on inhabitant specific values according to Table 1 for a model WWTP with chemical phosphorous removal and anaerobic sludge stabilization—Part 2 sludge treatment, with: bgN gaseous nitrogen load; bsN dissolved nitrogen load; bxN solid nitrogen load; csN dissolved nitrogen concentration; cxN solid nitrogen concentration; ST sludge thickener; DGT digester; DW de-watering.

Table 1. Assumptions and calculation methods used for balancing resource potential in Table.

Material Flow/Process	Assumptions and Calculation Methods
Raw wastewater	
Nutrient loads:	N = 8.8 g/(PE·d) [38,39] **; xN = 1.9 g/(PE·d) calculated according to [40,41]; P = 1.4 g/(PE·d) [38,39] **; sP = 2/3·P [42]; K = 4.9 g/(PE·d) [43]; sK = 0.975·K [44]
Volume flows:	Q = 175 L/(PE·d) [41]; Q_{DW} = 130 L/(PE·d); [45]; Q_{HW} = 0.3·Q_{dw} [42]
Further parameters:	COD = 96 g/(PE·d) [38,39] **; xCOD = 62.7 g/(PE·d) calculated according to [41] with 1,6 gCOD/gVS; TS= 56 g/(PE·d) [38,39]; VS = 0.7·TS
Primary clarifier	
Clarifier:	Separation efficiency according to [41] with τ = 1 h: η_N = 10%; η_P = 10%; η_{TS} = 50%; η_{COD} = 30%; η_{xCOD} = 45%, K no enhanced separation assumed
Sludge parameters:	TS = 4% [39]; VS = 0.75·TS [39]; RBS = 0.7·VS [39]
Biological Treatment (denitrification, nitrification, phosphorous removal, secondary clarifier)	
Biological process:	Calculation for COD, N, P, TS, vs. according to [41] with T_{design} = 12 °C; SRT = 15 d and average influence factors; xK_{BM} = 0.3·P_{BM} [46]
Effluent:	sN_{inorg} = 6.5 mg/L; sP= 0.5 mg/L dissolved effluent concentrations of N and P were assumed 50% of permissible emission standards in Germany for a WWTP > 6.000 kg BOD_5/d; N_{org} = 2 mg/L [41]; TS= 12 mg/L [41,47]
Waste-activated sludge parameters:	TS= 0.7% [39]; RBS = 0.45·VS [39]
Sludge thickener	TS = 5% [39]; TS separation efficiency 90% [48]
Digestion	
Gas production:	T = 37 °C [39]; SRT = 20 d [39]; degradable rate of RBS = 85% [39]; gas yield primary sludge = 0.95 m^3 i.s.s./kg [39]; gas yield waste-activated sludge = 0.85 m^3 i.s.s./kg [39]; digester gas composition: 1/3 CO_2 and 2/3 CH_4 [39]
Dissolution:	Calculation of N, P and K dissolution according to [49]; assumed P refixation with xP = 0.95·P [50]
Dewatering	Centrifuge assumed: separation efficiency 98% [51,52]; TS = 26% [51]
Heat usage	
Water temperature:	Calculation according to [42] with T_{HW} = 35 °C [42]; T_{PW}= 10 °C [42]; T_{IW}= 10 °C [42]; no heat loss assumed;
Usable heat:	calculation according to [53] with $T_{min\ in}$ effluent = 5 °C and T_{min} previous to biological treatment = T_{design}; no heat usage in sludge treatment previous to digester assumed

BM (biomass); BOD_5 (5-day biochemical oxygen demand); COD (dissolved oxygen demand); inorg (inorganic); i.s.s. (in standard state); IW (infiltration water); K (potassium); N (nitrogen); org (organic); P (phosphorous); PW (potable water); Q_{DW} (domestic wastewater); Q_{HW} (hot water); RBS (readily biodegradable solids); s (dissolved); SRT (sludge retention time); TS (total solids); vs. (volatile solids); x (solid). ** According to [39] median values can be assumed with 80% of the in Germany commonly used 85th percentile values COD = 120 g/(PE·d), N = 11 g/(PE·d) and P = 1.8 g/(PE·d) [38].

Table 2. Mass and volume of resources in the streams of a model WWTP (process facilities see Figures 3 and 4: with x solid load and s dissolved load).

	CO_2 [1]	N [1]	xN [1]	sN [1]	P [1]	xP [1]	sP [1]	K [1]	xK [1]	sK [1]	Q [2]	W [3]
1	0.0	8.8	1.9	6.9	1.4	0.5	1.0	4.9	0.1	4.8	175	725
2	0.0	7.9	1.0	6.9	1.3	0.3	1.0	4.9	0.1	4.8	174	722
3	0.0	9.0	1.3	7.8	1.6	0.5	1.0	5.1	0.1	5.0	180	746
4	0,.0	1.5	0.0	1.5	0.1	0.0	0.1	4.8	0.0	4.8	175	2146
5 [4]	58.0	6.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0
6	0.0	0.9	0.9	0.0	0.1	0.1	0.0	0.1	0.1	0.0	1	0
7	0.0	1.3	1.3	0.0	1.5	1.5	0.0	0.3	0.2	0.1	5	0
8	0.0	2.2	2.1	0.1	1.6	1.6	0.0	0.4	0.2	0.2	6	0
9	0.0	1.9	1.9	0.0	1.4	1.4	0.0	0.2	0.2	0.0	1	0
10	0.0	1.9	1.0	0.9	1.4	1.2	0.3	0.2	0.1	0.1	1	32
11	0.0	1.1	1.0	0.1	1.3	1.3	0.0	0.1	0.1	0.0	0	5
12	0.0	0.3	0.2	0.1	0.2	0.2	0.0	0.2	0.0	0.1	5	19
13	0.0	0.8	0.0	0.8	0.1	0.0	0.1	0.1	0.0	0.1	1	34
14	0.0	1.1	0.2	0.9	0.3	0.2	0.1	0.3	0.0	0.2	6	53
15 [4]	11.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0

[1] Data in g/(PE·d); [2] data in l/(PE·d); [3] data in Wh/(PE·d); [4] gaseous stream.

Independent from chosen technology the most favorable location for water recovery is the effluent flow. The water amount equals 100 % of the influent water amount, while the contamination is quite low. Nevertheless, dependent from intended reuse purpose further wastewater treatment (e.g., filtration, disinfection, micropollutant removal) is necessary in most cases [54]. Through addition of chemicals during the treatment process (e.g., precipitants for phosphorous removal), the number of dissolved components might increase between influent and effluent of a WWTP. If $FeCl_2$ is used as phosphorous precipitant in the given example in Table 2 (assumed precipitant need β = 1.5 mole metal/kg precipitated P) the chloride load in the effluent increases by 3.2 g/(PE·d) which means a concentration of 17.9 mg/L. Solely this additional chlorine concentration corresponds to 30 % of the maximum tolerance of greenhouse grown strawberries [55]. For tomato cultivation in closed systems the limit value for chloride is 0.9 mmol/L, which corresponds to a value of 31.91 mg/L [56] (cf. Section 3.2). Thus, the type of wastewater treatment might have an influence on necessary purification and utilization options.

Nitrogen is intentional removed during biological wastewater treatment. Thus, the majority of incoming nitrogen load escapes as gas (see Figure 3, Stream 5). Nevertheless, there are streams suitable for recovery, such as process water (approximately 15 % of incoming load). The advantage of process water is that nitrogen is mainly dissolved and that concentrations are high compared with other water streams. The effects of an emission of the denitrification can be illustrated with Figure 3 and data from Table 2. Without denitrification, the gaseous nitrogen fraction would remain as dissolved nitrogen fraction in the water phase. For the example in Figure 3: the total dissolved nitrogen load in the effluent would be 7.5 g/(PE·d) (see (1)), which means that effluent would contain approximately 86 % of the incoming nitrogen load. However, with 43 mg/L the concentration would still be low compared to process water. Thus, recovery technologies that can treat large volumes with low concentration efficiently must be developed.

$$\begin{aligned} sN_{4,woDN}* &= (gN_5 + sN_4 + sN_7)\cdot Q_4/Q_3 \\ &= \left(6.2\left[\tfrac{g}{PE\cdot d}\right] + 1.5\left[\tfrac{g}{PE\cdot d}\right] + 0.0\left[\tfrac{g}{PE\cdot d}\right]\right)\cdot 175\left[\tfrac{L}{PE\cdot d}\right]/180\left[\tfrac{L}{PE\cdot d}\right] \\ &= 7.5\left[\tfrac{g}{PE\cdot d}\right] \end{aligned} \tag{1}$$

* dissolved nitrogen without denitrification.

At WWTPs with phosphorous removal the highest potential for P-Recovery with approximately 90 % of incoming phosphorous load is in the sewage sludge. There phosphorous is mostly in a particulate form. Process water contains only about 15 % of the incoming load—depending on the type of P-Removal—but due to higher concentration and proportion of dissolved phosphorous than in the mainstream the effort for recovery is reduced. With enhanced biological phosphorous removal and sludge disintegration the load of dissolved phosphorous in process water can be increased up to 50 % [57]. At WWTPs without systematic removal of phosphorous, the phosphorous amount in sludge is 20 to 50 %, the rest remains mostly dissolved in the effluent, which could be a starting point for recovery before discharge into the receiving water. As in the case of nitrogen, technologies, which can treat large volumes with low nutrient concentration, would be needed.

For the case of treatment plants with P-removal several technologies for phosphorus recovery with different degrees of technological maturity have been developed during the last years, using different flows within the WWTP or subsequent sewage sludge incineration [58,59]. P and N-recovery from process water is the most promising due to high concentrations with low solid content although the highest potential is in the sewage sludge. Developments for nutrient recovery on municipal WWTP focus mostly on phosphorus, nitrogen might be a by-product as in the case of magnesium-ammonium-phosphate precipitation. Egle et al. calculated that the production costs differ significantly in dependence of the chosen process between around 2 to 28 €/kg recovered phosphorus, which is in the best case between 0.8 and 2 €/(PE*a). However, the technological breakthrough has hardly been achieved, so that projects for P-recovery are currently being supported with EU or national or federal state funding. Most projects at WWTP aim to produce a solid fertilizer such as magnesium-ammonium-phosphate, while SUSKULT aims to produce a liquid fertilizer from process water considering P, N and K.

Containing approx. 95 % of the incoming potassium load the effluent stream might be a good potassium source, but with low concentrations. Thus, appropriate technologies must be developed. According to the potassium balances in Table 1, process water contains a much lower amount of less than 10 %. The percentage is based on the potassium load in raw wastewater before returning the process water. However, as there are no limit values for potassium discharges, the used DWA regulations for calculating the nutrient amount do not include specific information for potassium. Analyses of process water samplings of four wastewater treatment plants in the Ruhr area in Germany (measurements from Fraunhofer UMSICHT in summer 2019, sampling size 12) indicate higher potassium loads of up to 20 % of the inflow load in process water (having an average concentration of 137 mg/L). For a more precise statement, the effects of different wastewater treatment processes on potassium fate must be further investigated.

The heat values in Table 1 are the amount of usable heat, considering limitations of heat extraction due to subsequent processes. Direct use of sewage heat is possible for example in the effluent stream, as there is no impairment of subsequent processes. Additional at plants with anaerobic digestion, digester gas can be used for heating or thermal energy from cogeneration can be used.

Plants need carbon in form of carbon dioxide [60] for growth. Digester gas contains approximately 33 % carbon dioxide [52]. Carbon dioxide produced while biological treatment is irrecoverable with the currently standard open construction. Another source (not included in Table 1) is exhaust gas from combustion engines.

A schematic overview on promising starting points for recovery of individual resources is given in Figure 5. The balances in Table 1 relate only to the plant configuration in Figures 3 and 4. In further investigations, balances of different plant configurations were compared to show the influence of existing technology (e.g., different methods for phosphorous removal and sludge stabilization) on potential of resource recovery.

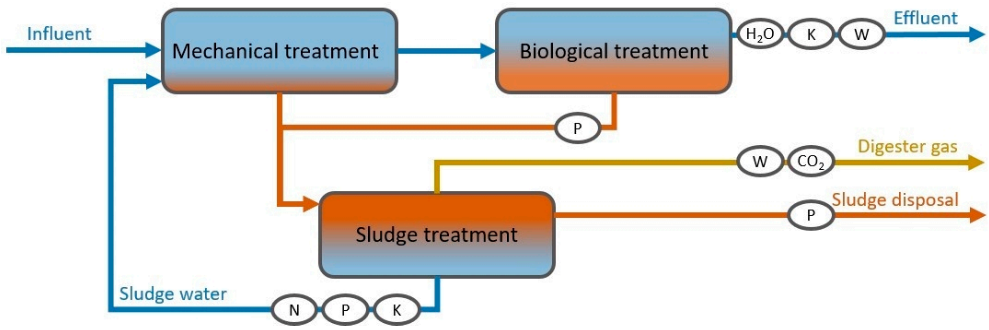

Figure 5. Schematic overview of conventional wastewater treatment plants with important water (blue), sludge (brown) streams, and potential starting points for resource recovery.

The accounting of average loads provides valuable indications about the potential of different resources on the wastewater treatment plant. For information on other macronutrients and micronutrients, this estimation has to be supplemented. When thinking of implementation of technologies for recovery, it has to be considered that influent composition and amount of wastewater varies widely with daytime, season, weather condition etc. In addition, availability of recovered nutrients for plant uptake has to be considered in further studies.

3.2. Cultivation Systems and Crop Varieties for Circular Food Supply in Urban Areas

Consumers are placing increased importance on aspects such as nutritious, healthy and regionally produced food. A broader acceptance of plant-based food from climate-friendly and sustainable, even if no longer traditional agricultural production can be expected. A major reason for the acceptance will be that the production in controlled environment agriculture (CEA) systems as e.g., indoor vertical farms (IVFs) will largely avoid the use of pesticides. This is confirmed by a survey of 500 consumers, of whom approx. 50% would be willing to buy fresh products produced in vertical farming systems. The participants of the survey laid a particular focus on the sustainability of the systems [61].

The goal of operating an IVF as sustainable as possible can be reached by using hydroponic or aeroponic systems. It is defined as the soilless cultivation of plants using mineral nutrient solutions. In case of hydroponic systems the roots are in contact with a liquid nutrient solution, while in aeroponics the solution is dispersed in the form of a fine mist [62]. The use of this hydroponic growth system in combination with a controlled atmosphere offers the possibility to use the resources water and nutrients highly efficiently, through closed nutrient- and water cycles, as well as a demand-oriented and plant specific supply, adjustable for each plant development stage. Nutrient leaching into the groundwater after nutrient application on or into the soil is avoided [63]. Highly polluted areas have been designated and further measures have been introduced to reduce or prevent nitrate inputs from agriculture into the environment [63]. The development, optimization and use of IVFs in these regions and metropolitan areas thus further contribute to the preservation and improvement of the protected goods soil and water. Redundant areas of arable land can thus be afforested in the future and ensure further ecosystem services and fresh air supply to metropolitan areas [64]. Another benefit of IVFs is the possibility to grow crops with high nitrogen requirements. Through intensive and optimized lightning high nitrite levels in vegetables can be avoided, which occasionally occur during low light seasons. This includes, but is not limited to certain cabbage varieties, leek, cucumber, eggplant and tomatoes [65].

The high added value of the SUSKULT vision is thereby the production of nutrient-rich and dietetically valuable plant species and varieties, which, by current production standards, takes place far from the consumer. By means of IVFs it is possible to simulate the environmental conditions, of e.g., southern countries and even optimize them to the plant-specific needs.

Therefore, SUSKULT's core approach is the safe recovery of secondary nutrients as liquid fertilizer solutions (see Section 3.1) for the plant-specific use in hydroponic or aeroponic IVFs. Shorter transport distances and the use of additional resources accompany the approach from WWTPs as water, heat, energy or CO_2. The low level of self-sufficiency for fruit and vegetables [66] in Germany illustrates the necessity.

Own research on globally established commercial indoor farms suggests that the production is yet limited to leafy greens, salad and herbs. These cultures are macronutrient poor plants, and thus barely contribute to the global food security concerning carbohydrates, proteins and fats. Reasons are, among others, the high field efficiency, low environmental demands of the crops, lower energy requirements (especially light) and very short cultivation cycles [67]. With current technological standard of IVFs, the exclusion of other species or cultivars is caused by high production costs and lack of profitability.

Contemporary an IVF requires an input of 7–9 kWh of electric energy to produce 1 kg curled lettuce (fresh mass) [68]. For macronutrient-rich and thus energy-rich plant species such as potatoes, the demand would be much higher. To produce more economically, the demand of energy to produce one-kilogram curled lettuce has to be reduced significantly.

Besides the production cost reduction of an IVF optimized for SUSKULT in comparison to normal IVFs (e.g., through a decreasing energy demand), the increase of high added value plays an important role for the profitability analysis. This can be reached by adjusting the following factors:

- Use of the total biomass produced;
- Increase of valuable plants substances (primary and secondary plant constituents);
- Process engineering approaches (production system);
- A regionally differentiated or usage related species and varieties selection.

To make metropolitan areas more resilient as it is a focus of CRFS regarding food sufficiency with local horticulture production systems, the production system development in the SUSKULT vision focuses on a wider range of plant species, which, in addition to the production of secondary metabolites such as flavors, bitter compounds and colorants, is also representing the primaries (carbohydrates, proteins, fats). For these reasons, the following four model plants were selected.

3.2.1. Tomatoes (*Solanum lycopersicum*)

Of all vegetable varieties, tomatoes are the most popular in Germany [58]. A major part of the consumed tomatoes and tomato products in Germany at present are imported from neighboring countries. The annual self-sufficiency of tomatoes in Germany has increased since 2010 with an increased harvest from around 73,000 to 107,000 tons in 2018. This meets a self-sufficiency level of only four percent for marketed tomatoes [66]. High-energy consumption is expected in an overall year production in greenhouses, especially in wintertime due to additional lightning and heating of the growing areas. This accounts for a footprint of around 9.3 kg CO_2 per kg tomatoes [69]. The main focus within SUSKULT is on an optimized cultivation environment for enhanced secondary plant metabolite concentration of lycopene, anthocyanin and flavors in tomatoes. Besides our developments look on further important flavorings as rutin and tomatoine, which have an astringent effect, and polyphenols, which can influence the sweet taste (e.g., naringeninchalcone, e-riodictoylchacone and phloretin) [70].

Tomatoes have not been successfully cultivated in IVFs until now, due to predominant cultivation systems. Therefore, production did not seem economically feasible. The approach in SUSKULT thus faces unresolved technical, plant-physiological and economically challenges. One aspect concerns a possible exceeding of the limit concentration of chloride in the targeted fertilizer composition (cf. Section 3.1). In an established growing system, tomatoes are grown in inert substrate such as rockwool. An adaptation and advancement of the established growing system into IVFs, therefore, needs to significantly increase the area use efficiency respectively space utilization efficiency. A horizontal cultivation management on several levels of an IVF seems to be a promising solution to overcome the economical challenge (see Figure 6). The plants are positioned horizontally on wire constructs and exposed from three sides (top, bottom and front) with different light intensities. Through a specific light control, gravitropism is superimposed by long-term impulses with 450 nm of blue light.

Figure 6. Newly developed horizontal cultivation system for tomatoes in IVFs.

3.2.2. Duckweed (Lemna and Wolffiella)

In the future, the supply of protein can possibly be ensured by domestically produced duckweed as an alternative to soya in human and animal nutrition. The innovative aspect of this approach lies in the special nature and composition of the genera *Lemna* and *Wolfiella* studied in the SUSKULT project. Both are characterized by high multiplication rates and doubling of biomass within 2–5 days. The nutritional potential of duckweed can be illustrated by protein levels between 20 to 35 %, lipid levels between 4 to 7 % and starch levels between 4 to 10 % per gram of dry mater. The nutritional composition will be further optimized by varying abiotic factors. A specific nutrient supply, especially the nitrate-N to ammonium-N ratio [71] and control of secondary fertilizers as well as control of light intensity, spectrum and climate in the IVF will affect *Lemna* and *Wolffiella* quality and quantity. The "amino acid composition of these species is very close to the WHO recommendations with, for example, 4.8 % lysine, 2.7 % methionine + cysteine and 7.7 % phenylalanine and tyrosine" [72].

Among the previous culture approaches, duckweed was characterized. Fresh consumption or further product development by food processing of fresh or dried duckweed will have great market opportunities. The nutrient requirements of duckweed cultivated this way (see Figure 7) are fulfilled by the integrated system approach of nutrient recovery from WWTPs and offers a particularly innovative possibility for the increase of high added value.

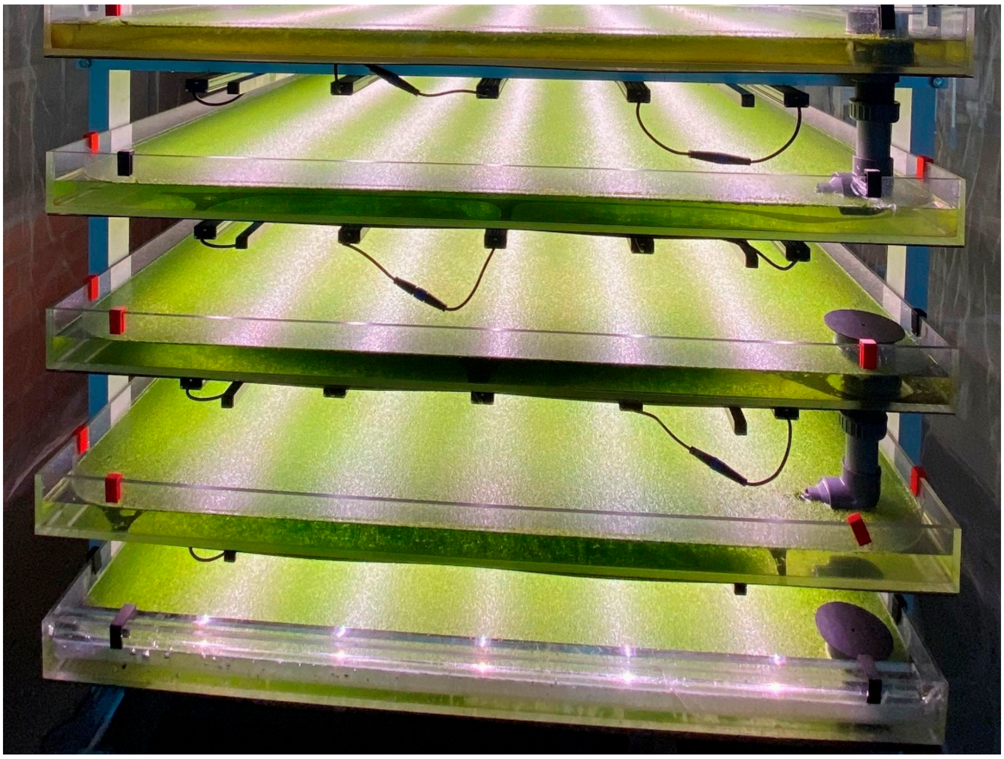

Figure 7. Detail of the vertical cultivation system for Duckweed.

3.2.3. Sweet Potato (*Ipomoea batatas*)

The sweet potato is no longer a niche product in Germany with annually increasing consumption and consumer spending of 43 million Euro in 2016 (increase of 42 % over the previous year) [73]. *Ipomoea batatas* plays an important role as basic foodstuffs in many developing countries due to their nutritional importance [74]. They are grown in open field cultivation in the tropical and subtropical countries of Asia, America and Africa. The nutritional profile of sweet potatoes is characterized by sugar, starch, a high content of dietary fiber and secondary plant metabolites.

The health benefits in particular have led to sweet potatoes being considered the healthiest vegetable in the world [74] and demand in Europe has increased significantly in recent years. Compared with potatoes, the sweet potato contains higher nutrient levels. This becomes evident for example by high contents of carotenoids, as well as vitamins C, E, B2, B6 and biotin. Anthocyanin has an anti-oxidative effect and is present in abundance in many sweet potato varieties. Noteworthy are also high values of potassium and magnesium [75] and the high quality of carbohydrates for human nutrition.

The import volumes to Germany has increased from 1817 metric tons in 2009 to 28,984 metric tons in 2018 (and approx. 31,000 tons in 2019) [76]. Germany has recently become the sixth-largest importer of sweet potatoes worldwide.

The focus on developing a new cultivation system for sweet potato within SUSKULT is based on previous results by the Tuskegee university in collaboration with NASA as well as Japanese scientists [18,19] worked on hydroponic growing systems for sweet potatoes, and showed promising findings by the use of nutrition film-techniques (NFT). Implementation of these findings to a successful production in IVFs, however, requires further developments and optimizations, e.g., of the storage root formation. In our own research, however, it was possible to show that aeroponic culture methods (see Figure 8), compared to NFT technology, and are better suited for the cultivation of sweet potatoes.

Figure 8. Newly developed aeroponic cultivation system for *Ipomoea batatas* in IVFs.

The high added-value potential will be increased in particular by using the entire plant (storage root and leaves can be consumed as spinach). By improving the cultivation systems, multiple harvesting of the aboveground fresh mass will be possible. Since sweet potatoes and tomatoes share demands on environmental parameters, a combined cultivation is conceivable.

3.3. Consumer Demands and Perceptions of the SUSKULT Vision

Plant cultivation systems for healthy vegetable varieties, such as tomatoes, duckweed or sweet potatoes combined with innovative technologies for nutrient recovery can contribute to the development of sustainable, resilient and inclusive CRFS. The SUSKULT project adds to the key objectives of CRFS to build short food supply chains, to allow for remaining local markets open even in times of global crises, to strengthen rural urban linkages [77] and to ensure urban food and nutrition security taking into account the environmental, economic, and social dimension of sustainability [78]. SUSKULT integrates and addresses consumer demands directly in the processes of research and development. Empirical data are derived from participatory stakeholder research based on written surveys, online-surveys and stakeholder workshops and discussions between September 2019 and July 2021 (see Table 3). The sample of people involved in (virtual) participatory research is n = 914. Data assessment was carried out using the statistical software SPSS. The sample size is the sum of all respondents who as yet have participated in the research process. The empirical findings apply only to this sample and not to the whole population.

Table 3. Overview of participatory stakeholder research in SUSKULT.

Date	Type of Survey	Tool	Real-Time Interaction between Researchers and Stakeholders	Format	Participants	Sample (n)
2–16 September 2019	stakeholder survey	Lime Survey	/	online	internal and external stakeholders	29
10 December 2019	student survey	written survey	√	on-site	students from Justus Liebig-University Giessen	75
September 2019 March 2020	five expert interviews	semi-structured interview	√	on-site and by telephone	representatives from the public sector and private companies	5
September 2020	stakeholder survey	Twitter	/	online	Twitter users	526
12 September 2020	stakeholder survey	Mentimeter	√	on-site	audience of a public panel discussion	17
11 November 2020	student survey	Sli.do	√	online	students from Justus Liebig University Gießen	143
26 November–3 December 2020	student survey	Lime Survey	/	online	students from Bauhaus-Universität Weimar	18
17 December 2020	stakeholder discussion	group discussion	√	online	students from Bauhaus-Universität Weimar	43
4 December 2020	three integrated stakeholder workshops	group discussion	√	online	internal and external stakeholders	39
2 July 2021	focus group workshop	group discussion	√	online	internal and external stakeholders from the food retailing and agricultural sectors	19
						914

3.3.1. Consumer Awareness and Information Demands Regarding SUSKULT

The literature on political and sustainable consumerism has demonstrated that consumers have become more aware of food issues and are interested in how foodstuff is produced [21,79]. In Germany and Western Europe, the basic supply of affordable food appears to be secured. "Consumers increasingly live alone in single households in cities, spending less time on food preparation, and the population is aging" [4]. At a very basic level, consumers rely on the fact that their food is safe and harmless to their health [80]. Food safety demands of stakeholders refer to potential risks to human health resulting from the presence of unwanted substances in food products, e.g., pathogenic organisms, toxic substances (e.g., pesticides and heavy metals), and contaminants [81]. In the European Union, food safety issues are covered by European Food Law, especially by regulations (EC) 178/2002 [82] and (EU) 2017/625 [83]. The European General Food Law Regulation ([EC] No. 178/2002) lays down general principles and requirements of food law, establishes the European Food Safety Authority (EFSA), and specifies procedures in matters of food safety [82]. According to Controls Regulation (EU) 2017/625 (replacing Regulation [EC] No. 882/2004), national enforcement authorities are to monitor compliance with food and feed law, rules on animal health and welfare, plant health, and plant protection products [83]. The main components of European food safety are the responsibility of entrepreneurs, traceability in the entire food chain, official food control, the precautionary principle, and independent scientific risk assessment, risk management and transparent risk communication to consumers [84]. Implementation of food safety addresses the entire food chain and connects different policy issues, e.g., contaminants, animal welfare, plant protection, food production and distribution, and food sector innovation [85]. The Nutrition

Report 2021 (BMEL-Ernährungsreport 2021) of the German Federal Ministry of Food and Agriculture (BMEL) [86] further reveals that, especially during the COVID-19 pandemic, consumers in Germany have paid increased attention to regional food production and local food supply chains. There is growing interest regarding the issues of urban food system resilience, e.g., via vertical farming systems, and individual food self-supply. A total of 70% of the respondents agree that political support should be provided to further enhance urban agricultural production systems in Germany [86]. During the COVID-19 pandemic, consumers' eating and cooking habits in Germany also have changed [22]. Consumers cooked more often for themselves and used more fresh ingredients when cooking [22]. As a short-term impact of the COVID-19 pandemic, higher consumer awareness and demand for environmentally and socially sound products facilitate local food consumption patterns and boost the diffusion of proximity production and local distribution systems [87]. Long-term impacts involve an increase in the online demand for foods and beverages and stakeholders growing understanding of the importance of strategic and local partnerships and networks, both to increase their value and improve their ability to cope with possible future crises [87].

Findings from consumer survey research also point to the high significance of food supply chain transparency. For consumers in Germany, information on the origin and ingredients of food products is most important, followed by details on production and processing methods, and sustainability aspects [23]. When buying food, consumers in Germany increasingly consider the aspects of animal welfare, sustainability, transparency, and regional origin [88]. Our own research findings unveil a general interest of stakeholders in the SUSKULT vision and specific consumer information demands regarding the SUSKULT food production process, the safety of food products, risk control and management approaches, and benefits compared to conventional agricultural production. Seven information demands stand out regarding health, sustainability, economic and social issues:

(1) Food security of vegetables cultivated in SUSKULT,
(2) Nutritional value of vegetables cultivated in SUSKULT,
(3) Sustainability of the SUSKULT approach compared to conventional agricultural cultivation systems,
(4) Energy consumption and energy costs of the SUSKULT approach,
(5) Consumers prices regarding final SUSKULT products,
(6) Interaction of the SUSKULT approach with established agricultural production and distribution systems,
(7) Impact of the SUSKULT approach on farmers near to SUSKULT cultivation systems.

The information demands regarding food safety (1) and the nutritional value of vegetables cultivated in SUSKULT (2) refer to human health concerns and the growing importance of ensuring healthy diets. Respondents are especially interested in the vitamin content of the vegetables produced in SUSKULT. At the same time, respondents raise questions regarding microcontaminants in wastewater, such as heavy metals or pharmaceuticals. In SUSKULT, significant risks regarding trace substances and organic trace compounds are closely monitored. Regarding heavy metals, own findings from ongoing laboratory tests reveal that the SUSKULT nutrient solution clearly falls below the limits of the Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on making available on the market of EU fertilizing products (European Union 2019). Moreover, nutrient recovery in SUSKULT achieves an average reduction of relevant organic trace compounds of 90 %. However, the information demands regarding food safety point to the relevance of dealing with societal risk perceptions of nutrient recovery from wastewater and necessitate adaptive risk governance and communication [89].

Information demands addressing the sustainability of the SUSKULT approach (3) refer to the relative performance of the hydroponic plant cultivation compared to conventional agricultural cultivation systems, especially regarding agricultural inputs, water consumption and climate impacts. The relevance of sustainability information is further substantiated by interview data from five expert interviews conducted between September 2019 and March 2020 with representatives from public administration and private companies. A food-marketing expert underlined the importance of informing consumers about the emerging SUSKULT technology to create acceptance of the production process and potentially higher food prices. Since consumers are especially attracted to foods, they can feel good about eating, the emerging SUSKULT technology should produce "food products with a story", telling consumers why food from the new production process is more sustainable than that from conventional agricultural production.

Stakeholders are also interested in economic aspects related to the SUSKULT approach and ask for information regarding energy consumption and energy costs (4) and consumers prices of the final products (5). Since SUSKULT is still in an early phase of technological development, it is yet not possible to provide exhaustive statements about final pricing. Stakeholders also raise information demands regarding the interaction of the SUSKULT approach with established agricultural production and distribution systems (6) and the impact on farmers near to SUSKULT cultivation systems (7). They are interested in the integrability of the SUSKULT approach in the local context and potential competition and crowding-out effects. Results from a focus group workshop involving experts from the food retailing and the agricultural sector in Germany in July 2021 indicate that the SUSKULT approach has huge potential to add value and to complement established agricultural production systems.

3.3.2. Risk Assessment and Transparency Related to SUSKULT

Stakeholders also raise the issues of risk assessment and management. When food is grown using nutrients from treated wastewater, quality requirements have to be suitably high, especially regarding limit values for contaminants of emerging concern. Potential risks of contaminants of emerging concern are topical issues regarding water reuse in agricultural production [90]. In Germany, different groups of substances have been detected in state of the art treated wastewater, such as pharmaceuticals, pesticides, or biocides, which need to be reduced in any case, but even more so when wastewater is used in agriculture [91]. In April 2020, the German Federal Institute for Risk Assessment (BfR), which is mandated to conduct independent scientific risk assessments for the BMEL, published a joint statement with the Federal Research Centre for Cultivated Plants (JKI) and Max Rubner-Institut (MRI) on the risks of treated wastewater for fruit and vegetables for raw consumption. The research organizations propose a new directive setting minimum quality requirements for treated wastewater for use in agricultural irrigation [92]. Our own survey results further substantiate the relevance of transparency regarding potential risks and minimum quality requirements. Responding to the question, which risks stakeholders perceive as most significant regarding the emerging SUSKULT technology, they name risks to human health first, followed by technological, environmental, economic, and social risks.

Retailers and other food value chain actors have responded to growing consumer transparency demands with an increasingly differentiated set of food standards and labels [79,93]. However, despite consumers' growing demands for food transparency, yet, there is no labelling requirement for food irrigated and produced with treated wastewater. As a consequence, it is not transparent to consumers whether food has been produced or irrigated with treated wastewater, although this is a common agricultural production practice in several European countries [94].

Consumers' growing attentiveness to (local) food issues is reinforced by digital approaches to enhance transparency in food supply chains, e.g., digital food tracking and tracing measures, online food blogs and food assessment portals [95]. There is especially an ongoing debate on the potential of blockchain technology and artificial intelligence to further enhance food supply chain transparency [96]. According to a survey by Bitkom [97], digital approaches offer advantages for improving food production efficiency, sustainability, product quality and transparency as well as for promoting proximity between producers and consumers. Corporate partners in the SUSKULT project already implement digital initiatives and pilot projects to increase food supply chain transparency. In 2019, REWE introduced so-called "self-scanners" at a store in Cologne with which customers are able to scan their products directly while taking them off the shelves. When paying, customers do not have to take the goods out of the bag again, but simply pay the amount determined on their smartphone [98]. In 2019, METRO conducted a six-week testing of the app "FreshIndex" that deals with the subject of best before date for pork to reduce food waste [99]. The app was developed by the start-up tsenso GmbH in a project funded by the German Federal Ministry of Education and Research [100,101]. Using precise individual data on hygiene and logistics as well as transport time to the next refrigerator and the own refrigerator temperature, the app calculates a dynamic best before date, which is often far behind the printed consumption date [99]. Moreover, METRO engages in the project "Intelli-Pack" funded by the German Federal Ministry of Food and Agriculture since September 2021, which aims developing an intelligent and smart packaging system to indicate the remaining shelf life of a product at any point in the supply chain based on temperature information [102,103].

Overall, consumer behavior, demands and perceptions play a critical role in the future development of sustainable, resilient and inclusive urban food supply chains. However, consumer behavior highly depends on the context in which it takes place. Environmentally unsustainable patterns of consumption have much to do with the collective development of what we take to be normal ways of life–such as meat-heavy diets [20]. To exploit their full potential for sustainable urban food supply, new solutions rely on institutional conditions that assist individual sustainable consumption and at the same time allow for the inclusion of stakeholders in urban food governance. As research on urban food democracy reveals, new food models can create dynamic spaces of social interaction also "beyond the market" [104,105] that allow stakeholders to shape urban food systems themselves in a way that takes into account specific information demands and perceptions as well as the issues of cultural diversity, social inequalities, and power imbalances [106].

4. Conclusions

The authors are convinced that sustainable, resilient and inclusive CRFS would benefit from putting the SUSKULT vision into practice. With the help of the innovative plant cultivation systems currently developed within the SUSKULT project, agricultural production of the future in resilient metropolitan areas will be significantly strengthened in its sustainability performance by closing material cycles. Such hydroponic systems will use water, nutrients, carbon dioxide, and waste heat from the "sewage plant of the future" (NEWtrient®-Center) and thus reduce the need for additional external resources to a minimum. With the research and subsequent establishment of the novel cultivation systems in practice, a considerable gain in knowledge is achieved both in applied plant science and in the field of technology development for IVFs. System-relevant developments include technical innovations for energy saving, automatic control systems for crop management, digitalization, e.g., for remote monitoring of IVF, hygiene concepts for high-quality food production, and quality optimization of the fruits and vegetables by adjusting environmental parameters. These developments indicate the sustainability of the innovations pursued under the SUSKULT vision.

Balancing the behavior of valuable materials within the wastewater treatment process allows for localizing the best starting points for recovery to supply the IVF. It could be shown that the operation process influences the recovery potential. In the future, improvements and adoptions of the treatment process are needed to use the full nutrient potential. The development of corresponding concepts and technologies is one of the next key innovation steps within the SUSKULT project.

The development of the new plant cultivation systems and nutrient recovery technologies under the SUSKULT vision are necessary but not sufficient for sustainable, resilient and inclusive CRFS. Our own findings from social and participatory research reveal that the SUSKULT vision also fuels new sector interlinkages between water and food and stimulates new stakeholder demands that substantiate the need for more integrated policymaking [107]. These findings correspond to studies on governing CRFS [108]. CRFS do not only enhance local environmental, economic, and social sustainability, they also involve the risk of expanding urban "food deserts" which compound deprivation and social exclusion resulting in spatial and socio-economic inequality [108]. Citizens with lower incomes particularly rely on supply of nutritious and healthy yet affordable food. Hence, CRFS need to enable the involvement of local stakeholders and to ensure coordination and collaboration across horizontal (different government departments and sectors) as well as vertical governance (across local, provincial, national and supranational authorities) levels [9]. Governing CRFS implies addressing poverty, hunger, malnutrition and inequalities in ways that improve health, address climate change, protect biodiversity, while supplying nutritious, sustainably produced foods for all [109]. To avoid social exclusion, there is a need for more integrated urban governance and planning [77]. A promising approach is to collect information at local and municipal level to provide policy guidance [77]. Urban governance arrangements such as food policy councils and other multistakeholder platforms can play an important role in securing stakeholder engagement as a mechanism for participatory definition and co-production of future CRFS food policies [9]. By enhancing transdisciplinary and participatory knowledge, research projects such as SUSKULT also contribute to inclusive CRFS development. By means of directly involving policymakers, consumers, local wastewater associations, as well as food and agribusiness actors in the research process, SUSKULT advances cross-sector research and development, allows ongoing feedback loops between theory and practice, and the participation of stakeholders in the development of research questions, concepts, and innovative technologies [107]. We are confident that the SUSKULT vision will offer guidance for both agri-food and nutrient recovery innovation for food supply chains in urban areas and future-oriented and integrated governance that will pave the way for more sustainable, resilient and inclusive CRFS.

Author Contributions: Conceptualization, V.K., S.Sch., H.S., A.U.; writing—original draft preparation, V.K., S.Sch., S.L., H.G., S.D., D.G., V.T.K., F.P.; writing—review and editing, V.K., S.Sch., H.S., A.U.; supervision, V.K. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by the Federal Ministry of Education and Research (BMBF) through the program Agricultural Systems of the Future in the framework of the "National Research Strategy BioEconomy 2030" under Grant No. 031B0728 "SUSKULT–Development of a Sustainable Cultivation System for Food in Resilient Metropolitan Regions" (https://www.suskult.de, accessed on 25 September 2021).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: Our sincere thanks to the members of the SUSKULT Advisory Board for the fruitful discussions and their input in our ambitious way for a sustainable food production. Furthermore, we thank all stakeholders, civil-society actors and professionals, for their valuable contributions and insights.

Conflicts of Interest: The authors declare that the research has been conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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