Water reuse in hydroponic systems: a realistic future scenario for Germany? Facts and evidence gained during a transdisciplinary research project

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ABSTRACT

The HypoWave transdisciplinary research project investigated the innovation of water reuse in a hydroponic system, focusing on its applicability in Germany. The methods applied were the operation of a pilot plant for the appropriate treatment and subsequent reuse of water in a hydroponic system, expert interviews, feasibility studies, an impact assessment and a stakeholder dialogue. To identify the concept's advantages and disadvantages, publications specialising in the various disciplines involved and meeting protocols were analysed and the results grouped together in a SWOT (strengths, weaknesses, opportunities and threats) analysis. This revealed that the system has potential for application in Germany subject to certain requirements being met, such as suitable local wastewater treatment conditions and actors looking for new business opportunities within agricultural production. This system is not recommended for the country as a whole, but it does offer an interesting alternative for locations that meet the appropriate conditions. Nevertheless, additional efforts and knowledge are required to promote and operate a new system of this kind. These include the reliable supply of irrigation water with guaranteed plant nutrition, comprehensive quality management to manage potential risks, a good understanding of the cooperation arrangements required and a more detailed examination of energy aspects.

Key words | governance, greenhouse, irrigation water, SWOT analysis, vegetable production, wastewater

HIGHLIGHTS

- Water reuse in hydroponic systems serves two aims: wastewater treatment and regional food production.
- The involvement of different sectors requires new cooperation arrangements between actors; forms of these already exist and can be applied here.
- It can be recommended if certain preconditions are met, e.g. local wastewater treatment facilities, farmers and organisations looking for new forms of agricultural production.

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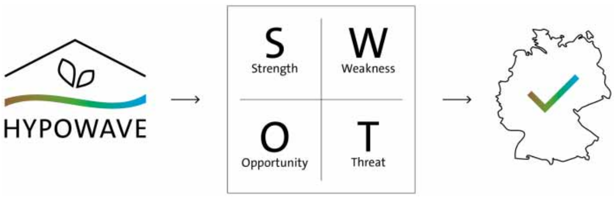
GRAPHICAL ABSTRACT



INTRODUCTION

Agriculture is the world's largest consumer of water, and consumption is rising due to increasing production and the effects of climate change (IPCC 2019). Hydroponic systems can contribute to tackling the global problem of water scarcity and an increasing demand for water in food production, because these systems require much less water (Sambo *et al.* 2019). Using treated wastewater for irrigation purposes not only saves drinking water resources, but also allows the nutrients contained in it to be reused for plant fertilisation. This would also help close the water and nutrient cycle. Hydroponic plant cultivation offers two advantages: the removal of nitrogen and phosphorus and an additional water treatment step (Fischer *et al.* 2019). However, the great challenge is to balance these advantages with the effluent quality required. There is also a requirement to meet plant quality standards for heavy metal and organic trace substances, as well as the additional commercial criteria of purchasers such as weight.

Even though Germany has a moderate climate, the hot, dry summers of 2018 and 2019 clearly point to an increasing need for irrigation in agriculture to ensure food security. At the same time, social concerns about globalisation and climate change appear to be stimulating growing interest in regionally produced food. In that regard, hydroponic systems used in conjunction with greenhouses have interesting potential for Central Europe. As well as requiring less water for food production, they also facilitate a higher production yield per area and year-round regional production of Mediterranean vegetables, for example (Hosseinzadeh *et al.* 2017).

Until now, there has not been a thorough investigation of whether the goals of both the wastewater treatment and plant production sectors in Germany can be achieved by this system, particularly the link between centralised wastewater treatment systems and food production. Technical and organisational issues need to be dealt with, as well as questions about product safety and market placement. Furthermore, the required cooperation between the wastewater and agricultural sectors does not yet exist except in the case of the reuse of sewage sludge in agriculture, a practice that is decreasing in Germany. There is a unique cooperation in Braunschweig and Wolfsburg, where treated wastewater is used as irrigation water in agriculture. Overall, this is a fairly typical situation when a socio-technical innovation is being introduced.

These aspects were investigated in the transdisciplinary research project 'HypoWave – Use of hydroponic systems for resource-efficient water reuse in agriculture'. Significant resources were required in the research undertaken to set up and run the largest pilot plant to date for water reuse in hydroponic systems in Central Europe. The plant provided the starting point for joint research. The research results are now available (for details see Bliedung *et al.* 2019, 2020; Ebert *et al.* 2019a; Mohr *et al.* 2019a; Dockhorn *et al.* 2020; Mohr *et al.* 2020; Zimmermann & Fischer 2020). An overall analysis was therefore undertaken that included the various research perspectives and disciplines. This analysis is now presented in this paper. Based on the preconditions outlined above, the research questions were whether it is feasible to apply water reuse in a hydroponic system in Germany and, if so, what key issues need to be addressed to promote a system of this kind.

METHODS

Methods used in the HypoWave research project

The research results analysed in this article were obtained by a team of researchers who have backgrounds in engineering and in natural, agricultural and social sciences. The team also comprised operators of wastewater treatment plants (WWTPs) practising water reuse, an engineering and landscaping office, a software development company, plant engineering companies and a producer of sustainable plastic. This transdisciplinary team was supported by external stakeholders as part of a stakeholder dialogue, as well as by additional external experts.

Within the HypoWave research project, the team undertook different research activities to investigate the concept of water reuse in hydroponic systems in Germany. An overview of the key working steps is provided below. The results and conclusions were sorted in an additional assessment step to provide an overview of the concept's advantages and disadvantages. This methodological step, a SWOT analysis, is presented at the end of this section.

Establishment of a pilot plant to investigate the interaction between wastewater treatment and plant production

For the investigations during the HypoWave project, a pilot plant was implemented and operated over a 3-year period on the site of the Wolfsburg–Hattorf WWTP in Germany (Bliedung *et al.* 2019). The setting covered a total area of 396 m^2 and included a greenhouse measuring 116 m^2. Pretreated municipal wastewater was continuously processed in an existing activated sludge treatment plant at the Wolfsburg–Hattorf WWTP and also on a technical scale in an anaerobic expanded granular sludge bed (EGSB) reactor and an aerobic sequencing batch reactor (SBR) to eliminate organic compounds and nitrification. Other advanced treatment steps were also undertaken using a biological activated carbon filter or ozonation to reduce organic trace substances and pathogens. Due to the different treatment technologies and steps, various combinations of these were possible to provide treated waters of different qualities, for example with regard to nutrients, trace substances or pathogens. These waters were used for the irrigation of lettuce in eight separate hydroponic lines operated using a slightly modified deep-flow technique. Five lines were used for the main investigations: four hydroponic lines with treated wastewater and one with a reference nutrient solution. The other three lines were used as borderlines and for subordinate investigations. The hydroponic lines consisted of pipes with an inner diameter of 10 cm without any slope. A water level of 7–8 cm was maintained in the pipes.

In this working package, the central scientific and technical task was to establish the steps that are required in wastewater treatment in order to produce high-quality agricultural products within the hydroponic system.

The hydroponic system was operated either as a flow-through system (23.5 L/h) or as an adapted recirculation system (also called 'feed & deplete' with approximately 185 L per exchange; for details, see Bliedung *et al.* 2020c). The differently treated wastewater used as irrigation water had varying compositions. For example, the average concentration of nitrogen ranged from 1.6 to 42 mg/L. Other nutrients were not added to the irrigation water. During a second test period, a recirculation system was used in the hydroponic plant production. Here, the irrigation water had a high initial nitrate concentration (42 mg NO_3-N/L) and was circulated in the system until the nitrate concentration dropped below a defined threshold. The water was then replaced with freshly treated water. This process was repeated until the plants reached a target weight of 275 g FM (fresh matter, FM).

Expert interviews to acquire an understanding of the institutional framework

In the context of this socio-technical innovation, guideline-based expert interviews were used to generate knowledge with the actors involved in this cross-sectoral cooperation. There were three parts to the qualitative expert interviews. The first questions focused on knowledge about the individual and regional challenges faced by the sectors and intersectoral relationships related to the issue of irrigation in agriculture (see also Witzel & Reiter (2012)). Based on this, a second section dealt with perceptions about the technical novelty, enabling the challenges and adaptation requirements to be pointed out, as well as an assessment of whether they matched the problem frames previously articulated. The third and final part highlighted potential cooperation arrangements, responsibilities for certain roles and the challenges of interacting with state agencies and sales structures. Overall, nearly 50 interviews were undertaken.

The experts were identified on the basis of a desktop study. They came from the water and agricultural sectors and their respective consultants and associations, representatives of retailers, NGOs and environmental and consumer protection, as well as governmental institutions and research institutes. The actors' analysis was verified with the project partners, especially practitioners, and at a later point also with the participants of the stakeholder dialogue too. The expert interviews were analysed using a qualitative content analytical method with MaxQDA to identify the key issues.

Feasibility studies to gain knowledge about the concept's adaptability for other locations

Options for implementing the concept were investigated in feasibility studies at four different sites in Germany, Belgium and Portugal (Mohr *et al.* 2019a, 2019b). The aim was to identify beneficial and inhibitory factors in the use of treated wastewater in the hydroponic system. For each feasibility study, a transdisciplinary team was assembled with expertise in wastewater management, plant production, social sciences and landscape design. The team analysed the local framework conditions regarding water supply and wastewater infrastructure, agricultural production and demand for irrigation, marketing of agricultural products and interaction between stakeholders from the water and agricultural sectors through desktop research, literature analysis and on-site visits. Semi-structured interviews with the relevant local experts were conducted to co-create and evaluate the knowledge available at each site. The resulting concept was discussed during a workshop with local stakeholders in order to obtain their evaluation and develop a final local concept for water reuse in hydroponic systems. The concept was then published in a brochure for each study (for details, see the list of references). The transdisciplinary results obtained indicated whether and under which conditions this concept could be implemented locally. During this process, an overall analysis of the feasibility studies was undertaken at a workshop in which all project partners participated. The analysis identified the factors that promoted and impeded the concepts, as well as any similarity in patterns. These overall results can contribute to identifying the concept's advantages and disadvantages, improving them and determining the appropriate framing conditions for the establishment of such systems.

Impact assessment to understand potential niches for the concept

To evaluate the overall sustainability of the concept, a probabilistic graphical model called a Bayesian belief network (BBN) was used to investigate the potential social, ecological and economic implications of the investigated concept and then to identify beneficial system characteristics and supportive measures for the implementation of crop production systems as investigated in the HypoWave project (Zimmermann & Fischer 2020). Qualitative and quantitative data were combined in the BBN (Chen & Pollino 2012), and expert knowledge as well as calculations and project results were included. The various system elements (variables) and their relationships were developed with different members of the HypoWave project team. In a next step, experts evaluated the likelihood of certain social and ecological implications using standardised questionnaires. Economic implications were considered in a model with illustrative calculations for costs and revenues (Wageningen University & Research 2020).

Stakeholder dialogue for additional feedback and guidance

The stakeholder dialogue (Ebert *et al.* 2020) involved practitioners from various state authorities, local NGOs, farmers, other environmental, social and agricultural representatives, wastewater experts and scientists. The dialogue accompanied the project from the outset and was concentrated into three workshops that included a field trip to the pilot plant. A final conference to present the research results was also arranged that was open to the public. The research team presented the HypoWave concept and the intermediate results of the current research process.

During the workshops, stakeholders commented on these inputs but also actively contributed in work phases to identifying relevant actors and framing conditions (first workshop), key topics and issues to be addressed (second workshop), and options for cooperation between the different actors involved (third workshop). The final conference, which offered generous time slots for exchange and discussion, focused on an assessment of the results achieved and general questions to be addressed in future research.

SWOT analysis

An overall assessment of the available research results was undertaken using a SWOT analysis. SWOT stands for strengths, weaknesses, opportunities and threats. 'SWOT analysis is a widely used tool for analysing internal and external environments in order to attain a systematic approach and support for decision situations' (Ghazinoory *et al.* 2011, p. 24). The internal environment, which can be influenced by the system operators themselves (in the analytical framing called 'controllable'), is reflected in the strengths and weaknesses, while the external environment ('incontrollable') is reflected in the opportunities and threats. The methodology was developed in the field of strategic management to provide managers with an analytical tool for developing new business strategies. SWOT analyses have also been applied in research, with agriculture being a prominent field of application (Ghazinoory *et al.* 2011). The SWOT approach selected for the analysis of HypoWave results goes back to Novicevic *et al.* (2004). It merges knowledge (the authors refer to 'intelligence') and planning perspectives and introduces the criteria of controllable and uncontrollable factors, while intelligence is divided into desirable and undesirable factors.

The analysis evaluated the (water) technology, plant production, institutional/organisational settings, and legal, economic and social/societal aspects insofar as these were addressed in the research. The analysis was undertaken using existing project publications and further project outputs, such as the feasibility studies (Fischer *et al.* 2018; Mohr *et al.* 2018; Ebert *et al.* 2019b). It considered the recommendations for practitioners (pre-version) as well as internal documents arising from the project and stakeholder meetings. In addition, there was an overall process of knowledge integration with discussions, (intermediate) results and conclusions regarding the advantages and disadvantages of the HypoWave concept. The process was documented in the protocols of the working groups and project and stakeholder meetings. These documents were also included in the analysis.

RESULTS AND DISCUSSION

Results of the wastewater-driven hydroponic system

To provide a general impression of the developed concept of water reuse in hydroponic systems, a broad overview of the most promising treatment technology, hydroponic management, plant production and governance aspects is given below. The results do not go into great detail because this has been done in different papers published by the researchers and references to these are given in the text. Here, the broad overview is designed to provide guidance on the key issues and clarify the findings of the SWOT analysis. It should also be noted that the text does not discuss the general advantages and disadvantages of wastewater reuse in agriculture. There are many standard textbooks on this subject (e.g. Asano *et al.* 2007; Lazarova *et al.* 2013), and the authors consider the knowledge contained within them as a prerequisite to understanding water reuse in agriculture.

From wastewater to irrigation water

The HypoWave project is the first to investigate the appropriate treatment of municipal wastewater in order to provide irrigation water and its subsequent reuse in a hydroponic system for the production of high-quality products. The most important step in this direction is to identify the suitable combination of treatment steps required.

Based on the results of the pilot tests in HypoWave, a combination of an SBR reactor and a biological activated carbon filter proved to be very efficient in terms of producing high-quality irrigation water. Nitrogen, phosphorus and the required nutrients remained in the treated water, while there was an effective reduction in the chemical oxygen demand (COD), micropollutants and heavy metals

(Bliedung *et al.* 2019, 2020a, 2020b, 2020c; Dockhorn *et al.* 2020; Mohr *et al.* 2020).

Based on the results, the following recommendations can be made. During biological pre-treatment, organic compounds must be significantly reduced in order to avoid biofilm formation or anaerobic conditions in the hydroponic system and not impair plant growth. For this purpose, an anaerobic treatment (e.g. EGSB reactor) can be applied as a first step. However, since temperatures in Central Europe do not allow COD to degrade sufficiently under anaerobic conditions (Urban 2009), a subsequent aerobic treatment for further COD removal is strongly recommended. At the same time, nitrification can take place in this aerobic treatment step since nitrate is the preferred nitrogen source for lettuce and many other plants. To provide the optimal nutrient supply for the plants, the wastewater treatment should not aim to achieve denitrification or eliminate phosphorous in order to maintain the level of water-borne nitrogen and phosphorus nutrients as much as possible.

To reduce pathogens and organic trace substances, ozonation or biologically activated carbon filtration can be used (Bliedung *et al.* 2020b, 2020c; Dockhorn *et al.* 2020; Mohr *et al.* 2020). In the case of ozonation, it is important to adjust the specific ozone doses to minimise the transformation products of organic trace substances and achieve the appropriate elimination of pathogens. However, the combination of both ozonation and biologically activated carbon filtration is also an option. Although this setting involves two treatment steps, the advantage is that transformation products produced during ozonation can be eliminated by subsequent bio-filtration (Knopp *et al.* 2016; DWA-Fachausschuss KA-8.6 2019). However, despite a further reduction of pathogens during water treatment, regrowth can occur in the hydroponic system itself. If necessary, continuous UV disinfection of the (circulated) irrigation water should also be provided.

Plant production

Lettuce plants grown in the hydroponic system and irrigated and fertilised with the irrigation water were produced in comparable quantity and quality to those produced with mineral nutrient solution. Nevertheless, it was evident that nutrient concentrations in the irrigation water were at the lower end of plant requirements, with certain micronutrients in particular being limited (Bliedung *et al.* 2020c). Careful management of the nutrient solution, e.g. the volume and/or addition of the nutrient in deficit, was key for the production of a competitive yield. The nutrient content in the plants was largely comparable with the average found in current data in the literature. Where heavy metals were detected, they were at very low concentrations or below threshold values (Bliedung *et al.* 2020c). The plant quality with regard to organic trace substances and pathogens was also comparable with that of commercially available products (Bliedung *et al.* 2020b; Dockhorn *et al.* 2020).

An investigation of other vegetable varieties and crops in addition to lettuce was undertaken in the feasibility studies, the impact assessment and in additional literature research. Greenhouse crops for the system in question are those suitable for hydroponic systems with a deep-flow technique. Alongside lettuce, tomatoes, aubergines, courgettes and peppers (Mohr *et al.* 2018), as well as cut flowers like chrysanthemums (Fischer *et al.* 2018), have been identified as crops that could potentially be grown in the investigated concept.

There are recent examples in Germany where agricultural cropland has been covered with greenhouses (Kliebisch *et al.* 2009; Moninger *et al.* 2017), and the greenhouse sector in Germany is growing (BMEL 2019). Access to financial resources and limited access to land are currently leading to the establishment of more greenhouses. Another reason is growing customer demand for regional products in supermarkets (Moninger *et al.* 2017). Due to increasing quantities and customer interest, in addition to farmers' markets that were originally supplied, there has been a rise in the distribution of regional products through supermarkets.

An increase in greenhouse crop production supports self-sufficiency, especially since the demand for year-round, regionally produced agricultural products is growing as a result of consumer awareness (BMEL 2017; Meyerding *et al.* 2019). This rise in greenhouse crop production therefore boosts food security and has the potential to also increase farmers' income with the supply of high-value products (Stanghellini 2014). As shown by the results of the impact assessment, compensatory measures should be introduced when greenhouses are constructed on agricultural cropland in order to minimise or mitigate their negative effects on the environment (Zimmermann & Fischer 2020).

Key actors and their cooperation

Agronomic and technical decision-making takes place in a societal context. In social reality, not every apparently rational choice is valued as an appropriate solution (for differentiation, see Ebert *et al.* 2019a). Therefore, it is important to have knowledge of the norms and values as well as the logics and desires relevant to decision-making in both the wastewater and farming sectors. The newly established production system involves heterogeneous actors who were either socialised in the service-orientated public sector or operate within the logic of competition prevailing in small- and medium-sized private entities. Whereas the former, here operators of WWTPs, understands and frames problems by taking collective matters into account, such as preserving water bodies in this case, the expert interviews with farmers showed that their farm's continued existence and their identification with their products and production practices (e.g. plant production in soil) are very salient issues for them. In this context, nature plays a role when it comes to long-term perspectives for securing the existence of farms as private entities.

With this as the starting point, both sectors need to adapt the system to suit their own needs. The key actors involved at an early stage were the wastewater associations, their supervisory authorities and (organised) farmers. Horticultural producers and farmers had also expressed an interest in the system as an additional production branch. They should now search for advisors and potential purchasers. The system can be operated on the basis of individual private-law contracts. With regard to the above-mentioned rural applications of water reuse in hydroponic systems, the project showed that established enterprises are willing to establish complementary branches within their companies and become water service providers. Furthermore, regional organisations, such as irrigation associations and cooperatives, are a major group for creating opportunities and establishing such a concept by integrating it into their institutions or establishing new ones (Mohr *et al.* 2018; Ebert *et al.* 2019b). Cooperatives, in particular, contributed to sectorial and cross-sectorial understanding. The cooperation of actors in such heterogeneous sectors as wastewater treatment and plant production depends on mutual recognition and a basic understanding of belief systems behind the apparently rational choices of actors (e.g. pluralistic core beliefs on precaution, and distributional or intergenerational justice) (Jenkins-Smith & Sabatier 1994; Shinn 2004). Awareness of this was particularly relevant in order to secure joint quality management (Mohr *et al.* 2020; Schramm *et al.* 2019). For the actors, this might even justify the establishment of specialist water and nutrient management services (e.g. new independent service providers for irrigation water) (Ebert *et al.* 2019a).

Despite exceptional cases in decentralised continental European applications, the operation of water reuse in hydroponic systems requires collective action. Maintaining autonomy is an important rationale articulated in the expert interviews with farmers. Nevertheless, farmers are confronted with new dependencies involving other actors once more collective belief systems enter the picture. This process of establishing new modes of cooperation is accompanied by the ambiguous positions of other stakeholders such as NGOs, the large supermarket chains, government agencies, the scientific community and financial providers (Ebert *et al.* 2017). Hence, water reuse in hydroponic greenhouses takes place in a societal context in which collective actors, as well as individuals, make decisions in a situation of uncertainty. Contracts, organisational arrangements and (quality) management plans agreed between organisations can contribute to reducing this uncertainty and create signalling effects for decision-makers, e.g. with respect to responsibility and trustworthiness.

Potential locations for implementation

The feasibility studies, stakeholder discussions, expert interviews and impact assessment showed that it is possible to implement HypoWave, especially in rural areas where the wastewater infrastructure needs to be adapted and land for setting up greenhouses is more readily available (Fischer *et al.* 2018; Mohr *et al.* 2018). At the same time, settlements are usually smaller and produce less wastewater. This means that the amount of irrigation water and available nutrients is lower, and thus the space requirements for greenhouses are smaller. Moreover, industrial wastewater is less likely to be found and easier to identify in the wastewater of small settlements. As nutrients are not very expensive (<0.5% of the operational costs of the greenhouse production system) and water for agriculture is still cheap in many parts of Germany (e.g. Lower Saxony: € 0.007/m^3 for groundwater used in irrigation; Niedersächsisches Ministerium für Umwelt Energie Bauen und Klimaschutz 2020), the economic feasibility greatly depends on the synergies between advanced wastewater treatment (reducing nutrient concentrations) and the production of marketable products. Thus, the concept is interesting in areas that have a need to limit further the discharge of nutrients (nitrogen and phosphorous) into the environment to prevent eutrophication in receiving water bodies.

Furthermore, in peri-urban contexts, water reuse in hydroponic systems can be established for WWTPs that plan to add a fourth treatment stage due to administrative requirements, e.g. the removal of pharmaceutical residues. If this kind of additional treatment is implemented, the water quality of the effluent can become suitable for irrigation purposes. Being located in areas with a growing agricultural irrigation demand as well as an increasing drinking water demand (for example, expanding metropolitan regions such as Rhine Main), this concept offers opportunities to substitute the groundwater currently being used for irrigation purposes (Ebert *et al.* 2019b). Established local structures in horticulture as well as the demand for regional food strongly support this approach on a regional level. However, the need to integrate the demands of several farmers as well as requirements regarding irrigation water quality can lead to the decoupling of nutrient reuse (Ebert *et al.* 2019b). In this regional approach, reused water of high quality can contribute to structural policy, for example by keeping agricultural production attractive, to services of general interest, such as regional food supply, and to precautionary measures, for example preventing trace substances from entering the water cycle. The amount of water that can be used for irrigation greatly depends on the minimum ecological flow required by the receiving waters.

Results of the SWOT analysis

The results of the disciplinary research and the transdisciplinary integration process are presented here using the logic of a SWOT analysis. A summary of the results is provided in Table 1, which shows the topics identified during the SWOT analysis. The table also locates the topics within the analysis. As an additional measure, additional guidance is provided by the categories 'material' and 'immaterial'. Both categories provide thematic subcategories: 'material' includes the subcategories 'water treatment', 'plant production' and 'environment', while 'immaterial' comprises 'operation and management', 'economy', 'actors and institutions (law)' and 'values and standards (sustainability)'.

The analysis of the HypoWave material also highlighted additional topics and issues that could not be grouped into one of the four SWOT fields. These aspects are presented and discussed in the text below the respective tables.

The concept focuses on two aims at the same time: the treatment of wastewater and the service provision of irrigation water. The system provides a dual service and addresses the need for resource-efficient handling of water and nutrients, as well as a secure water source for agriculture, especially in situations with water shortages. As the results show (see also Table 2), both objectives can be achieved. However, a profound knowledge of wastewater treatment and agricultural production and understanding among the actors involved is crucial to its success. Required forms of cooperation exist, of which the actors are aware, and can be implemented. This is a huge asset because it implies security within the establishment of such a sociotechnical innovation, which by its nature involves numerous insecurities because there is no experience of it to date. The environmental benefits of the system are also due to its resource efficiency, the reuse of already extracted water, and being sealed off from the environment, thus minimising risks such as groundwater pollution.

A sensitive point in water reuse is always the handling of the risks originating from raw wastewater containing heavy metals, pathogens and pharmaceutical residues. As the results showed, all three of them were successfully eliminated by the chosen wastewater treatment and agricultural production process (Table 2). Nevertheless, the safe

Table 1 | Summary of the location of the identified topics within the SWOT analysis

Analytical framing		Desirable		Undesirable	
		Strength		**Weaknesses**	
		Material	**Immaterial**	**Material**	**Immaterial**
Internal aspects	Controllable	Water treatment – Water quality – Phosphorus recovery – Pharmaceutical residues, heavy metals, pathogens – Measurement and control technology	Economy – Profitability – Circular economy	Water treatment – Contamination – Salinity – Pharmaceutical residues, heavy metals, pathogens – Wastewater quality	Operation and management – System approach (2) – Staff – Existing experience (2)
		Plant production – System configuration – System approach – Weather-independent production	Actors and institutions – Forms of cooperation – Secure water supply	Plant production – Control systems – Nutrient supply	Economy – Economic incentives – Barriers to entry
		Environment: – Closed production system – Discharge water quality		Environment – Conversion of land	Values and standards (sustainability) – Change of perspective
		Opportunities		**Threats**	
		Material	**Immaterial**	**Material**	**Immaterial**
External aspects	Uncontrollable	Water treatment – Protection of water resources – Wastewater quality	Operation and management – Knowledge	Environment – Discharge water quality	Operation and management – Existing horticulture sector – Marketing experience
		Plant production – Regional food production (2) – Water scarcity – Use of artificial intelligence	Economy – Income and employment – Competition in resource efficiency		Economy – Market competition – Entry point to market
		Environment – Usable land	Actors and institutions – Experience (2) – Regional food production – Political will (2)		Actors and institutions – Reaction of media – Permits – Certifications
					Values and standards (sustainability) – Public acceptance

Only subcategories that provide information are listed. Where topics are addressed more than once, this is indicated in brackets.

Table 2 | SWOT analysis of water reuse in hydroponic systems for German conditions: Strengths

Strengths	
Material	**Immaterial**
Water treatment • Treatment of wastewater to gain irrigation water is possible in qualities up to DIN 19650, even for the irrigation of vegetables eaten raw. • The concept can also address upcoming requirements of phosphorus recovery. • Pharmaceutical residues, heavy metals and pathogens can be reduced sufficiently within wastewater treatment or in the case of pathogens by implementing additional hygienic barriers. • Parts of the necessary instrumentation and control infrastructure already exist. For instance, most WWTPs are equipped with online measuring devices to detect ammonium, nitrate and phosphorus. ***Plant production*** • Plant growth functions in hydroponic systems fed with this irrigation water. Moreover, the supply of irrigation water via a tube includes an additional barrier regarding microbial risks as the water is only touching plant roots. • Depending on the design of the irrigation system, two goals can be achieved: nutrient efficiency (flow-through system) and water efficiency (recirculating nutrient solution). • Different greenhouse crops like fruits/vegetables and ornamental flowers can be produced, while the high-yield production is not exposed to seasonal weather patterns like droughts in summer or frost in winter as long as illumination and heating is provided. ***Environment*** • The system reduces environmental risks, such as groundwater pollution, as the hydroponic system itself is closed to the environment. • The hydroponic system can be balanced in a way that its effluent flow contains very low concentrations of nutrients. Thus, it can be discharged into sensitive water bodies without further treatment.	***Operation and management*** • First economic studies indicate that hydroponic greenhouses can be operated economically (Fischer *et al.* 2018; Mohr *et al.* 2018; Zimmermann & Fischer 2020). • As nutrients recycled from wastewater are used, this concept is an example of a circular economy. It helps to reduce the dependency on artificial fertilisers and reduces the need of nutrient elimination and therefore the cost of sewage treatment (Fischer *et al.* 2019) ***Actors and institutions (law)*** • There are forms of cooperation that can be used to organise and manage such a system among the involved actors: (a) private contracts and (b) regional organisations. The categories such as liability, obligations and quality assurance, requiring special care in the respective agreements, are known. • Quantitatively, the system contributes to secure supply streams that mitigate groundwater competition and reduce the risk of illegal overextraction, which is not currently monitored or measured. ***Values and standards (sustainability)*** –

production and high quality of the products (water and plants) have to be guaranteed at all times. As the system is complex, many aspects have to be considered (for details, see Table 3) and different actors are involved, a risk management concept is highly recommended for the whole wastewater processing and plant production process that addresses these weaknesses and how they are dealt with.

A minimisation of the risks mentioned, such as pathogenic contamination of plants or pharmaceutical residues contained in the products (for details, see Table 3), can also be achieved by further processing of the vegetables produced (e.g. cooking), when this is economically justifiable and the expense and workload involved in processing remains manageable. Where this is possible, the farmer gains greater independence from fresh food contractors. This provides leeway with regard to other market segments and contracts, as well as marketing channels.

Additionally, there needs to be clarification that the absolute dependency of the two coupled subsystems, wastewater treatment and agricultural production, only exists in cases where an optimum in water and/or nutrient efficiency is to be achieved. Otherwise, water reuse in hydroponic systems can be designed in such a way

Table 3 | SWOT analysis of water reuse in hydroponic systems for German conditions: Weaknesses

Weaknesses

Material	Immaterial
Water treatment • Proximity of plant production to the area of wastewater treatment/irrigation water preparation can cause an additional airborne loading of plants with pathogens via aerosols. • Salinity of treated wastewater should not exceed the plant requirements. Removal of excess salinity, for example by reverse osmosis, could be advisable. In such cases, the management of residues might also be necessary. • The additional treatment of wastewater also cannot guarantee that there are no pharmaceutical residues in the products because there are too many of them and their range is continually changing, making holistic analyses impossible. • Technical challenges presented by a wide range of influent water situations (dry weather and heavy rainfall). ***Plant production*** • Adequate plant nutrition on a minimum feeding level needs close attention and control systems. • Certain nutrients need to be added artificially to secure adequate plant nutrition. ***Environment*** • If a conversion of agricultural cropland to a greenhouse area takes place in an uncontrolled way, there will be negative ecological impacts such as the reduction of biodiversity and groundwater recharge, if no countermeasures are undertaken. Moreover, the landscape quality might decrease (Bürgow *et al.* 2019).	***Operation and management:*** • The system is highly complex as two goals have to be achieved: wastewater treatment and plant production. This requires a high level of competence and monitoring. • Due to this complexity, quality assurance plays a major role and requires competent and dedicated staff in a field where untrained staff are often employed. • So far, there is no comprehensive reference and therefore no experience of a combined system like this. • The conversion of traditional farming to greenhouse production requires new knowledge and experience, and also needs the establishment of new professional networks, including sales structures. • There is a dependency between wastewater treatment/irrigation water production and plant production. At the moment, the two systems are combined; individual decisions in one of the two subsystems always have an influence on the other and need to be coordinated. ***Economy*** • Synthetic fertilisers are cheap and, in areas with sufficient freshwater resources, there is usually little economic incentive for water reuse. • Barriers to entry in this new business field are relatively high initial investment costs for the greenhouses and the dependency on partnerships with WWTPs. So far, there is no experience of such partnerships in Germany. ***Actors and institutions (law)*** – ***Values and standards (sustainability)*** • The operator of a WWTP has to change perspective from disposal to provision and deliver a product that meets qualitative standards and quantitative requirements.

that only parts of the treated water are used as irrigation water in hydroponic production and the rest is discharged, for example. By designing the wastewater treatment in this way, a more adaptive and robust management of the whole system can be achieved. This might also be important in periods when hydroponic production is halted for cleaning or other maintenance activities.

Developments in the field of digitalisation and artificial intelligence are an additional driver, as listed in Table 4. The newly evolving field between water provision and agricultural production might be an interesting business area for companies in this sector. Closer cooperation between the (waste)water and agricultural sector is just a matter of time due to the already ongoing changes in water availability and requirements. At the same time, new tools might greatly alleviate the coordination and interaction between the two sectors, especially when it is developed as a learning system that helps to steer the overall processes with real-time interpretation of the recorded data.

New systems like this will not only advance sustainable development in agriculture and increase competition for more resource-efficient production (Table 4), but could be implemented as a wastewater-driven hydroponic system for urban areas too. Developing areas like this are often located on the border between urban and rural areas where agricultural land becomes part of an urban region and farmers have to leave. Water reuse in a hydroponic system could be

Table 4 | SWOT analysis of water reuse in hydroponic systems for German conditions: Opportunities

Opportunities

Material	Immaterial
Water treatment • The (re)cycling of water in smaller loops lowers the impact on nature as water withdrawal is minimised, while increasing resource efficiency. Natural water resources remain unspoiled or are available for uses other than the ones for which treated wastewater is used. • Wastewater that does not contain industrial influences and water collection in a separated sewer system are good starting points for setting up such a system. ***Plant production*** • Demand for regionally produced vegetables/fruits, also outside their seasons, is often higher than the production. • Water scarcity will become more severe due to climate change; thus, the demand for water reuse and water-efficient agriculture will increase in the coming years. This is especially true as the limits of current agricultural irrigation using mostly groundwater and surface water sources will be reached. • Rapid developments in artificial intelligence help to regulate and coordinate the two aims of plant production and nutrient reduction in the water. ***Environment*** • Due to the system being closed, any area can be used to set up the production system, including unpopular areas such as industrial wastelands. In such cases, the system can upgrade the landscape and additional efforts be made to improve its ecological characteristics.	***Operation and management*** • There is already knowledge around managing hydroponic systems in Germany, and this can be obtained in the form of consultancy by interested operators. ***Economy*** • Farmers' income increases compared with that from traditional agriculture. Jobs are also created since horticulture production is more labour-intensive. The HypoWave concept can offer new business options. • New systems like this can advance sustainable development in agriculture and increase competition for more resource-efficient production. ***Actors and institutions (law)*** • The experience and knowledge of water reuse in agriculture among actors and institutions might also spill over to new fields of water reuse. • The existence of regional organisations such as irrigation associations and cooperatives are an asset as they can be a starting point for setting up the cooperation required for such a system. A major advantage is that they know how to mediate between collective and individual interests. • Food retailers and supermarket chains might be interested in supporting new regional production systems due to existing demand for regionally produced food. • Preservation of nature and precaution can be positively influenced through political will and an executive habitus. • Political will can support a sustainable transformation of plant production by taking responsibility for structural planning and policy. ***Values and standards (sustainability)*** –

a way of farming continuing in areas like this and as a historical reference to the area's origins. It could, for example, also serve to integrate inhabitants through environmental education and joint social activities within farming.

One threat identified in the SWOT analysis (for details, see Table 5) is that consumers might be worried about the product safety of vegetables and fruits. Here, an additional potential option investigated in HypoWave is the production of ornamental flowers. A product like this could offer an alternative by implementing the system in the non-food sector. Nevertheless, it should be clear that by heading in the direction of cut flowers, market opportunities and competition with potentially international operators also have to be considered and parts of the SWOT analysis will have to be redone.

Key topics for further development of the innovation

It is striking how few *threats* there were in the 'material' category (Table 5). Nevertheless, this corresponds to the research questions targeted in the HypoWave project. Alongside the analysis of institutional aspects, the research addressed the key tasks of wastewater treatment and plant production. System configurations and processes were optimised during the 3-year project.

The HypoWave pilot testing proved that the combination of a nitrifying SBR reactor and a biologically activated carbon filter was very efficient in terms of producing high-quality irrigation water. Nevertheless, this combination was only tested on lettuce plants. Hence,

Table 5 | SWOT analysis of water reuse in hydroponic systems for German conditions: Threats

Threats

Material	Immaterial
Water treatment – ***Plant production*** – ***Environment*** • Water reuse can be critical for water bodies with low water levels. The reduction of the discharge can affect river ecosystems, especially in summer.	***Operation and management*** • The attitude of the horticultural sector towards the new production system is unclear regarding concerns or competition. • There is no experience of marketing production systems like this. ***Economy*** • The food sector is very sensitive about product quality and at the same time highly competitive. It might be difficult for single producers to receive binding and stable contracts for purchase. • The operator needs to identify a good and reliable entry point into marketing his products and relies on a respective partner in food trading if there are no plans for self-sale, e.g. farmers' markets. ***Actors and institutions (law)*** • Uncertainty and unpredictability about the media's views on the topic. There are different options for how the media will deal with it. This can range from promoting the positive image of regional food production and closed nutrient cycles to telling horror stories about product quality due to potential risks from the origin of the irrigation water. • The system is not fully subject to self-governance of public and private entities. Permits from local and regional state authorities are a necessity and might be difficult to get due to lack of experience and knowledge. This can present a challenge for the planning and implementation process. • It is not currently possible to receive organic certification for such crops, as organic products have to be produced in soil. Labelling as a regional product is possible, but dependent on the strength of the region's identity and integration. ***Values and standards (sustainability)*** • Consumers might be scared of the fact that the products are grown with irrigation water from wastewater and they might not accept the system or its products.

further development is required regarding the scaling-up of the technology, including treatment capacity, determining ideal operating parameters for various crops and therefore developing a robust technology for continuous irrigation water supply. Moreover, the integrated management of water treatment and plant production, including specific plant requirements, needs to be developed further.

The results also revealed a minimisation of risks resulting from heavy metals, trace substances and pathogens (Table 2). This is key to the successful promotion of the system (see Table 3, for example). The HypoWave results also indicated that this aim can be achieved and initial measures were identified (see Table 2, for example). At the same time, the analysis clearly showed the demand for high quality regarding irrigation water, discharge and the food produced. To address all these requirements, alongside the need for risk management and quality assurance, joint quality management is also required along the entire production chain to secure adequate quality of the water, discharge and food products. This will also help it to gain acceptance among consumers and address any criticism in the media (Table 5).

A clear asset of the system is existing forms of cooperation, such as irrigation associations and cooperatives, which can be used to establish water reuse in hydroponic systems (Table 2). However, cooperation experience regarding water reuse in hydroponic systems does not yet exist in Germany, and actors can only rely on experience transferred from adjacent subjects (Table 4). Therefore, the close support of actors entering this field is important to identify open questions and pitfalls, as well as develop ideas about how to design such cooperation. Municipal actors and civil servants cannot provide support with their existing knowledge and experience, but instead have to explore the innovation themselves to reach appropriate decisions (Table 5). An important measure in this regard can be the early involvement of the necessary stakeholders from the outset to identify any issues and concerns as early as possible and work together on solutions.

The energy consumption of water reuse in hydroponic systems was not a focus of this research project and therefore was only examined incidentally in two of the feasibility studies (Fischer *et al.* 2018; Mohr *et al.* 2018). However, energy aspects have an important impact, especially when the hydroponic system is combined with greenhouses. Fischer *et al.* (2018), for example, show that effluents in the hydroponic system could be treated in a short-rotation plantation, using fast-growing trees as one source for the required heating system.

Moreover, the production system will also be of great interest to many other countries where water scarcity is already more severe and the need for food production and economic development is high on the agenda. This was also shown in a feasibility study undertaken in Portugal (Germer *et al.* 2020). Hence, the concept also offers opportunities for the system, its technical components and the knowledge acquired to be exported.

Limitations of the analysis

A SWOT analysis offers overall guidance and supports decision-making. However, the aspects formulated in this paper might look different under specific local conditions, and the varying influence of local drivers, such as water shortage, demands on irrigation water or the role and influence of local institutions and actors. Due to the system's novelty, the decision about implementing water reuse in hydroponic systems currently involves uncertainty, especially when legislation is changing (e.g. EU legislation on water reuse) or certification processes are uncertain, such as organic certification of soil-less production systems.

Moreover, it is clear that the presented results depend a great deal on the specific knowledge and information made available by the project, contributed by the project partners, interview partners and stakeholders involved. A different selection of knowledge carriers might have had an effect on the results, since they contribute and act according to their own values, norms, motivations and reasoning in decision-making.

Last but not least, as mentioned above, a SWOT analysis provides overall orientation, which requires complex systems and their interactions to be presented in a less complex way. Nevertheless, this analysis provides guidance and can support decision-making. Especially when it comes to cases of (inter-)organisational cooperation, including institutional design, a SWOT analysis is not adequate for all the details to be shown. That is why the concept only has a limited explanatory force when explaining intersectoral cooperation based on collective action among heterogeneous actors.

CONCLUSIONS

This study revealed that water reuse in hydroponic systems is a realistic scenario for Germany in the future. The analysis showed that, on the basis of changing climate conditions and upcoming water shortages, Germany also needs to prepare and search for additional and new forms of food production – a position clearly shared by the stakeholders involved. Early promising results indicate the conditions and circumstances under which water reuse in hydroponic systems might be attractive. They also emphasise that this is no overall solution for everybody everywhere, but is an interesting innovation when considering certain preconditions such as the local wastewater treatment situation and interested farmers or organisations such as associations looking for new forms of agricultural production. Nevertheless, additional efforts have to be made to advance the system with regard to the robust preparation of irrigation water in combination with reliable plant nutrition, joint quality management to handle potential risks, good understanding of the cooperation and configurations required and a more detailed investigation of the energy aspect – all of which were at the heart of the overall analysis conducted by the HypoWave project.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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