

A critical assessment of the applicability of EU regulation 2020/741 for the development of a risk management plan for hydroponic water reuse

Marc Beckett^{a,*}, Marius Mohr^a, Martina Winker^b, Michaela Rohrbach^b, Antje Schwarzer^c, Tim Gebhardt^d and Thomas Dockhorn^d

^aInnovation Field Water Technologies, Resource Recovery and Scale-Up, Fraunhofer IGB, Nobelstr. 12, 70569 Stuttgart, Germany

^bInstitute for Social Ecological Research, Hamburger Allee 45, 60486 Frankfurt/Main, Germany

^cWasserverband Gifhorn, Nordhoffstraße 2A, 38518 Gifhorn, Germany

^dInstitute of Sanitary and Environmental Engineering, Technische Universität Braunschweig, Pockelsstr. 2a, 38106 Braunschweig, Germany

*Corresponding author. E-mail: marc.beckett@igb.fraunhofer.de

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ABSTRACT

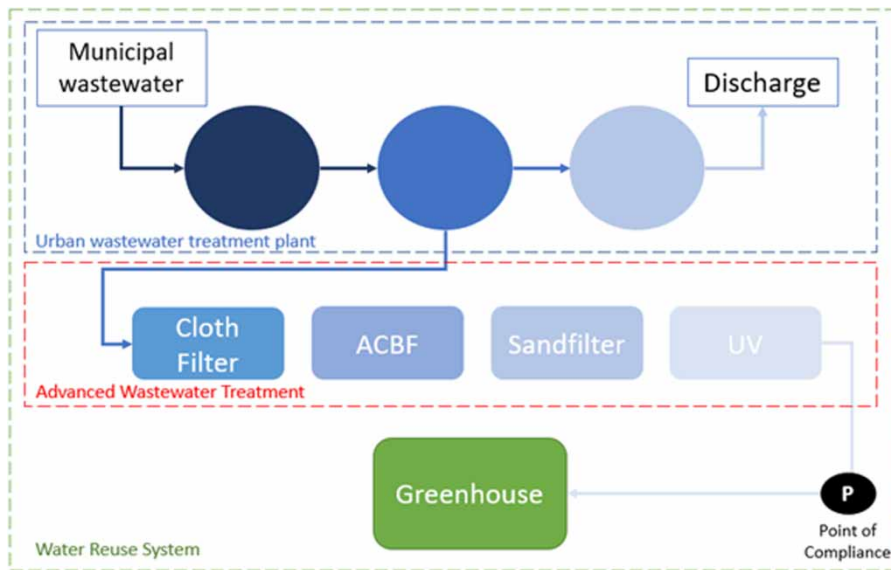
The article focuses on the development of a risk management plan for small-scale water reuse system in Weißenberge, Germany. The reuse system comprises of wastewater treatment ponds, cloth filter, activated carbon biofilter, sandfilter, UV disinfection and a hydroponic tomato cultivation. Multi-stakeholder consultations, pre-validation and preliminary monitoring led to a low-risk perception during the risk assessment. Technical and non-technical barriers before and after the point of compliance resulted in a high level of safety confirmed during the operation. Remaining challenges in implementing EU regulation 2020/741, such as validation monitoring are discussed. Experiences made during the operation of the water reuse system as well as a review of scientific publications indicate that hydroponic cultivation does not have any increased risk compared against other cultivation methods.

Key words: agricultural water reuse, HypoWave, reclaimed water, risk assessment

HIGHLIGHTS

- Regulation 2020/741 was applied to hydroponic water reuse.
- Preliminary monitoring of wastewater treatment ponds and stakeholder consultations supported the risk assessment.
- Operation confirmed the low levels of health and environmental risks.
- Validation monitoring remains among the challenges applying the risk management principles set out by the regulation.
- Current research does not indicate a need to exclude hydroponics from water reuse.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The growing demand for water resources, coupled with the increasing scarcity of clean water, has prompted the European Union (EU) to explore alternative water sources, such as the reuse of appropriately treated wastewater in agriculture (Giakoumis *et al.* 2020). Water reuse can be an essential component of the circular economy, as it promotes the efficient utilization of water and helps overcome pressures on finite natural resources. However, the implementation of water reuse systems in the agricultural sector requires a comprehensive risk management approach to ensure the safety and sustainability of the practice.

The EU has recently taken proactive steps to address this challenge by introducing Regulation 2020/741 on minimum requirements for water reuse (Radini *et al.* 2023). This regulation establishes a standardized framework within the EU for managing the risks associated with agricultural water reuse, underscoring the significance of proactive risk assessment and management. Furthermore, a review of existing reuse schemes and regulations across the world has revealed variations, emphasizing the need for assessing benefits and risks on a case-by-case basis (Voulvoulis 2018).

Before the implementation of Regulation 2020/741, European guidelines for water reuse were less harmonized. While some countries, particularly those facing water stress (like Greece, Malta, Italy, Cyprus, Portugal, and Spain), had established national regulations or guidelines (Garrido-Cardenas *et al.* 2019), there was not a unified EU-wide framework. This lack of harmonization posed challenges, including increased environmental and health risks, and hindered the broader adoption of water reuse practices (Garrido-Cardenas *et al.* 2019). Some countries followed international standards like the Australian guidelines on Water Recycling and WHO recommendations, while others drew inspiration from regulations in places like California (McLennan *et al.* 2024). This fragmented approach underscored the need for a standardized regulation to ensure consistent safety and quality standards for water reuse across the EU with special consideration of a large shared market with frequent trade of agricultural goods between the member states (Partyka & Bond 2022).

A key element of the EU regulation is the requirement for a risk management plan (RMP), which is designed to ensure the safe and reliable operation of water reuse systems.

A robust RMP for agricultural water reuse should encompass several key elements. Initially, a thorough hazard identification process is crucial, pinpointing potential biological, chemical or physical contaminants associated with the reclaimed water (European Commission 2020). Subsequently, a risk assessment should evaluate the likelihood and severity of adverse effects from these hazards on human health, the environment (including freshwater resources and soil) and the irrigated products (Maffettone & Gawlik 2022). Based on this assessment, appropriate control measures should be implemented to mitigate identified risks (Maffettone & Gawlik 2022). These measures include advanced treatment technologies, operational monitoring, and defined procedures for handling and application of the reclaimed water. Regular review and adaptation of the plan are essential to ensure its ongoing effectiveness and address any emerging risks. Finally, effective

communication and cooperation among stakeholders, including water providers, farmers and regulatory bodies, are vital for successful implementation and long-term sustainability (European Commission 2020).

While the issued regulation sets minimum standards for the entire EU, individual member states can develop national standards that might include additional or stricter requirements. Regulation 2020/741 is designed in a way that enables member states and even local authorities to include criteria that account for regional and local circumstances.

Risks associated with water reuse systems refer to the presence of pathogens, chemical contaminants, including heavy metals and micropollutants, as well as the impact of antimicrobial resistance (AMR) genes. Studies highlight that conventional treatment processes may not fully eliminate these hazards, necessitating advanced treatment technologies and robust risk assessment frameworks (Bliedung *et al.* 2020; Helmecke *et al.* 2020; Mohr *et al.* 2020; Mordechay *et al.* 2021; Smalla *et al.* 2023). For example, pathogens such as *Legionella* spp. and norovirus are persistent concerns in irrigation systems, regardless of the water source (Rusiñol *et al.* 2020).

As a consequence the EU regulation prescribes development of an RMP (European Commission 2020). In addition, water reuse systems that intend to use reclaimed water for the irrigation of food crops that can be consumed raw and might come into contact with the irrigation water (Water Qclass A) are required to demonstrate the treatment performance via a validation monitoring. Validation can be regarded an intense, short-term activity to be performed before commissioning or during the start-up phase of new treatment trains and require the demonstration of a log 6 removal for viruses (or bacteriophages as surrogates), a log 4 removal for protozoa (e.g. *Chlostridium perfringens* spores) and log 5 removal for bacteria (e.g. *Escherichia coli*). Ninety per cent of the samples must comply with the standards and standard deviation (SD) must not exceed 1 log (European Commission 2020).

Integrating reclaimed water with resource-efficient agricultural production methods, such as hydroponic cultivation, poses great potential to reduce water demand for the production of fresh food products. The combination of water reuse and hydroponic cultivation has been subject to various studies (Magwaza *et al.* 2020; Cifuentes-Torres *et al.* 2021). Bliedung *et al.* (2020) investigated the use of primary treated municipal wastewater and different advanced water treatment processes along with their effects on hydroponic lettuce. It could be demonstrated that wastewaters with high and with low nutrient concentrations were suitable, if the mode of operation was accordingly modified (Bliedung *et al.* 2020).

While the potential for nutrient removal and water savings is widely acknowledged, the direct contact of roots with the reclaimed water gives rise to concern regarding the aforementioned risk factors, and micropollutants and pathogens in particular (Bundesinstitut für Risikobewertung 2020; Fernandes *et al.* 2024). Research on the safety of hydroponically grown crops using reclaimed water is needed, especially under consideration of the implications of EU regulation 2020/741 on minimum requirements for water reuse.

HypoWave+ has realized a large-scale implementation of hydroponic water reuse in Weißenberge, district of Gifhorn, Germany. The wastewater of the 479 inhabitants (approximately $26,400 \text{ m}^3 \text{ a}^{-1}$) is currently treated in three serial wastewater treatment ponds consisting of a settling pond, an aerated pond and a polishing pond. The effluent is received by a canal of third order, which later joins a larger surface water. Responsibility for the sewer network and the pond systems lies with the Wastewater Association Gifhorn (Wasserverband Gifhorn). The village is rural in character and is mainly drained via a combined sewer. There are no industrial, commercial or medical facilities connected to the drainage system. In light of efforts to further improve the effluent quality, in particular for nutrients, the Wastewater Association is assessing different scenarios. One is the connection to a larger sewage treatment plant with nutrient removal processes which would require the construction of a pumping station and a pipeline. The water would have to be pumped actively over several kilometers to the nearest treatment facility. The alternative option, if proven feasible and cost-effective, is the local reuse of water and nutrients in agriculture, which would have the additional benefit of increased water availability for local farmers. The region is characterized by high infiltration soils and reliance on groundwater for irrigation has led to increasing restrictions on groundwater abstractions resulting in uncertainty for local farmers in light of climate change.

The HypoWave+ project (2020–2025), funded by the Federal Ministry for Education and Research (BMBF), focuses on sustainable water reuse in agriculture through a hydroponic system ('HypoWave+ – Implementierung eines hydroponischen Systems zur nachhaltigen Wasserwiederverwendung in der Landwirtschaft,' 2023). It involves the hydroponic cultivation of tomatoes with reclaimed water from wastewater treatment ponds. The treatment train consists of a cloth filter, a novel activated carbon biofilter (ACBF), a sand filter and a UV disinfection. The treated water is then used in the greenhouse, which has a cultivation area of approximately $1,800 \text{ m}^2$. Drip irrigation takes place in hydroponic lines consisting of gutters filled with substrate. The water is recirculated to the nutrient mixing tank. At the tank, the system also incorporates a sensor based

nutrient management approach tailored to the plants' needs, utilizing existing nutrients in the water while supplementing deficient nutrients according to the monitored concentrations.

HypoWave+ poses one of the first water reuse projects in Germany that has successfully acquired an allowance under the new EU regulation 2020/741. It also aims to develop a comprehensive integrated quality management system (Winker *et al.* 2025) to support this innovative form of linking wastewater treatment with regional vegetable production.

To our knowledge, no studies have analyzed the implications of EU regulation 2020/741 on the hydroponic cultivation with reclaimed water. The present study aims to demonstrate a potential application of the regulation and guidelines regarding the development of the RMP and discusses the implications in light of the current state of science.

2. METHODS

In order to provide further guidance on the development of the RMP, in particular for the identification of hazards and evaluation of risks, the EU Commission has published additional documents to support the creation of the RMP (European Commission 2022, 2024). However, as the RMP was created prior to the publication of the technical specifications of the key elements of the risk management, the initial process of the RMP development is presented and discussed in this publication.

2.1. Literature study

In preparation of the development of the RMP as prerequisite for the permit for water reuse, a comprehensive literature study was conducted. Besides the requirements set out in the EU regulation 2020/741, additional resources published by the International Organization for Standardization (ISO), Bundesanstalt für Risikobewertung (German Federal Institute for Risk Assessment, BfR), the EU's Joint Research Centre (JRC) and other institutions were studied. Complementary scientific literature was consulted for additional analyses. A pre-validation was conducted to assess the treatment performance of the planned water reuse systems regarding microbiological indicators. The results are compared against the requirements for validation monitoring for Class A applications.

2.2. Stakeholder consultations

Based on the literature review, stakeholder consultations took place in order to capture different views and positions on potential hazards and risks. Stakeholders included the members of the research consortium including the applicants for the water reuse permits and the local authority (Untere Wasserbehörde Gifhorn). The risk assessment conducted took into account the views of various stakeholders consulted in preparation of the RMP. In addition, external experts currently involved in water reuse projects in Germany (e.g. the Abwasserverband Braunschweig, Abwasserverband Wolfsburg) were consulted on their approach to the risk assessment and their view on the risks to be considered in the HypoWave+ project. The risk assessment conducted was presented to and discussed with the experts. Comparisons were made with other risk assessments and RMPs developed by the experts' institutions.

2.3. Preliminary monitoring

Based on the initial treatment concept, literature study, stakeholder consultations and discussions, a preliminary monitoring campaign was conducted for critical water parameters. Since water for the advanced treatment system is drawn from pond 2, the focus of the analyses was on quality in the respective pond. Microbiological analyses for the presence of *Clostridium perfringens* spores, somatic coliphages and *Escherichia coli* were performed. Samples were taken from the wastewater treatment pond 2. In addition, the samples of ponds 1 and 2 were analyzed for chemical oxygen demand (COD), total suspended solids (TSS) and turbidity. Effluent from pond two was also analyzed for heavy metals and micropollutants.

2.4. Development of the RMP

Based on the stakeholder consultations, literature review and preliminary monitoring, the RMP was developed according to the Key Elements of Risk Management (KRM) set out by EU regulation 2020/741. The process required a clear description of all system components (KRM1), a definition of all involved stakeholders and their responsibilities (KRM2), the identification of hazards (KRM 3), exposed groups and exposure routes including the environment (KRM 4), risk assessment (KRM 5), additional measures (KRM 6) and preventive measures (KRM 7) as well as the design of monitoring programs (KRM 8 and 9). The risk assessment was conducted following the semi-quantitative approach as described by International Organization for Standardization (2018) and Maffettone & Gawlik (2022) using the criteria shown in Supplementary material, Tables

S1 and S2. A baseline risk for identified hazards and exposure routes was established and assessed. The remaining risk level was determined after taking into account the mitigating measures within the water reuse system. Risk categories were built in order to reduce the complexity. Thus, the risks assessment was not conducted for individual pathogens or chemicals but rather for the respective category. For example, the likelihood and consequence of a hazardous event involving pathogens was evaluated but not distinguished between e.g. certain types of viruses or bacteria. The risk assessment was then discussed with other water professionals in Germany currently involved in water reuse projects, which served as an additional review of the conducted assessment. Based on the findings, additional barriers and monitoring schemes were designed and implemented.

3. RESULTS

3.1. Conceptual framing of the RMP and compliance requirements

The target water quality class was defined according to the principles described in the guidelines for the application of the EU regulation (European Commission 2022). No direct recommendations for hydroponic cultivation exists. The chosen cultivation approach resembles a drip irrigation system, in contrast to flood or sprinkler irrigation. As tomatoes can be consumed raw and the plants grow close to the ground, as opposed to fruit trees or root crops, water quality class A or B must be selected. Water quality Class B was selected as the edible parts of the plants do not come into contact with the reclaimed water. The choice for Water Quality Class B also corresponds with the criteria set out in the EU regulation, which states that plants that can be consumed raw but where the edible part does not come into contact with the irrigation water, all kinds of irrigation methods, including hydroponics, can be used with water of quality class B (European Commission 2020).

An initial pre-validation of the treatment train was conducted to assess the log-reduction potential for relevant microbial indicators. For this exercise, indicative log reductions for viruses, protozoa and bacteria for each stage of the treatment train were compared against the values described in the Australian Guidelines for Water Recycling (Natural Resource Management Ministerial Council *et al.* 2006). Table 1 summarizes the indicative log-reduction for the individual technologies and processes included in the HypoWave water reuse system. These values represent typical ranges reported in literature.

From Table 1 it can be seen that the described system has a high indicative log-reduction rate for viruses (log 7–14), protozoa (log 7–13.5) and bacteria (log 10–19). The data indicate that the treatment system should be capable of reducing pathogenic risks emerging from reclaimed water and ensuring compliance with the validation monitoring set out by the EU regulation, which are a log 4 removal for protozoa, log 5 removal for bacteria and log 6 removal for viruses. However, as the high variability indicates, actual performance of a process may vary depending on site-specific conditions and system design.

3.2. Preliminary monitoring

Monitoring the quality of the wastewater treatment ponds prior to implementation of the advanced water treatment system was conducted. The analyses gave insights into the variability of the water quality during several months.

Table 1 | Indicative log removal rates of technologies considered in HypoWave +

Process	Indicative log ₁₀ removal rates			References
	Viruses	Bacteria	Protozoa	
Wastewater treatment ponds	1–4	1–5	1–3.5	Natural Resource Management Ministerial Council <i>et al.</i> (2006)
Cloth filter	0.5–1	1–2	0.5–1	WHO (2011)
Activated carbon biofilter	1.5–2	2–3	1.5–2	Maurya <i>et al.</i> (2020)
Slow sand filtration	1–3	3–5	2–4	WHO (2011)
UV disinfection	3–4	3–4	2–3	Hijnen <i>et al.</i> (2006)
Total	7–14	10–19	7–13.5	

3.2.1. Monitoring parameters according to EU regulation 2020/741

The effluents from pond 1 to pond 2 and from pond 2 to pond 3 were analyzed in order to learn more about the treatment performance of the individual ponds and characterize the water quality entering the advanced water treatment system regarding the main parameters relevant to the EU regulation. COD was used as a substitute to BOD₅ as it was easier to measure. Table 2 summarizes the main statistical parameters characterizing the dataset. Minimum, maximum, average, median and SD for all parameters is lower in pond 2 as expected. From the SD it can be seen that the variability in water quality is 2–3 times higher for effluent from pond 1. This underlines the equalizing effect the pond system has on the water quality providing a more reliable feed water to the advanced water treatment system. Average TSS concentration in pond 2 effluent was below the standard of 35 mg L⁻¹ set out by the EU regulation with reference to the Urban Wastewater Treatment Directive.

Figure 1 shows the data across the study period. All three parameters are noticeably lower in effluent from pond 2 than in effluent from pond 1, as expected.

For effluent from pond 2, peaks in turbidity (75.8 NTU) and TSS (79 mg L⁻¹) during a short period in June 2023 can be observed. Overall, the COD in effluent from pond 2 shows only little variability over the year (22.58 mg O₂ L⁻¹) and remains between approximately 50–100 mg O₂ L⁻¹ for most of the time.

3.2.2. Microbiological indicators

Microbiological indicators were analyzed for effluent from pond 2 between May 2023 and March 2024. Figure 2 illustrates the presence of *E. coli*, *Clostridium perfringens* spores and somatic coliphages in the effluent from pond 2. Highest values for *Clostridium perfringens* spores were found in July 2023 (100,000 CFU 100 mL⁻¹). For *E. coli* the highest values were detected in January 2024 (140,000 MPN 100 mL⁻¹). For somatic coliphages, which represent a surrogate parameter for viruses, the highest concentration was found in October 2023 (1,390 PFP 1 mL⁻¹).

3.2.3. Heavy metals

In addition, the effluent of pond 2 was analyzed for heavy metals. In all, 24 samples levels of mercury (Hg), chromium (Cr), cadmium (Cd), lead (Pb) or arsenic (As) were below the detection limit. Nickel (Ni), copper (Cu) and zinc (Zn) could be detected but no sample exceeded the standards for drinking water quality. Iron (Fe), aluminum (Al) and manganese (Mn) were found in water at maximum concentrations of 1.2, 1.5 and 0.13 mg L⁻¹, which is even below the standards for discharge of industrial wastewater in the case of Fe and Al. No specific standards apply to Mn. Variability was <1 mg L⁻¹ for Fe, Al, Mn and B and <1 µg L⁻¹ for Ni. Cu (5.94 mg L⁻¹) and Zn (9.25 mg L⁻¹) showed a higher variability but were generally present in higher concentrations.

3.2.4. Micropollutants

The analyses of micropollutants for effluent from pond 2 consisted of 26 different compounds. Samples were taken May 4, 2023 and February 5, 2024. As expected, the measured concentrations were very low. Figure 3 shows the maximum concentrations for the analyzed compounds. Caffeine (29 µg L⁻¹) and acesulfame (20 µg L⁻¹) showed highest concentrations, followed by iomeprole (12 µg L⁻¹) and ibuprofen (5.2 µg L⁻¹). For 54% of all conducted analyses, the concentrations were below the Limit of Quantification (LOQ). Gabapentin, amoxicillin, mecopop-p, iopamidol and clarithromycin could be

Table 2 | Statistical data of effluents from ponds 1 and 2 for turbidity, TSS and COD (*n* = 24)

	Pond 1			Pond 2		
	Turbidity [NTU]	TSS [mg L ⁻¹]	COD [mg O ₂ L ⁻¹]	Turbidity [NTU]	TSS [mg L ⁻¹]	COD [mg O ₂ L ⁻¹]
Min	6.90	5.80	47.00	5.25	3.80	45.00
Max	135.00	110.00	298.00	75.80	79.00	126.00
Avg.	53.26	49.63	139.96	17.11	18.60	67.37
Median	53.35	56.00	131.50	14.05	14.00	60.75
SD	35.89	33.50	65.51	14.29	17.99	22.58

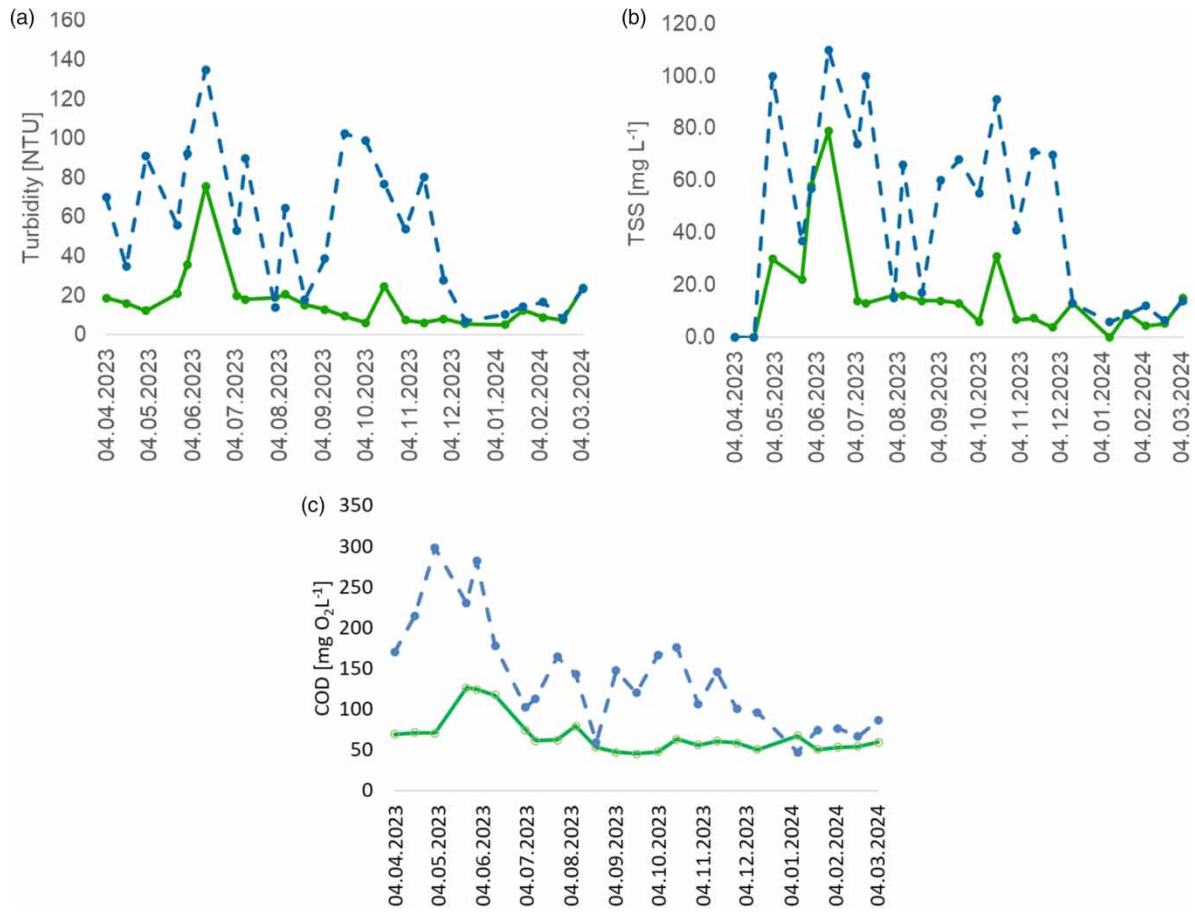


Figure 1 | Turbidity (a), TSS (b) and COD (c) of the effluents of pond 1 (blue dashed line) and pond 2 (green line) ($n = 24$).

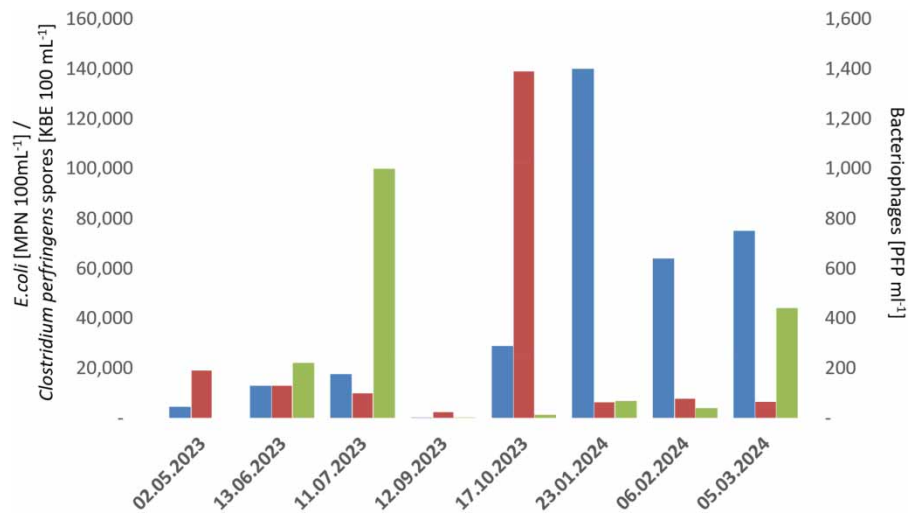


Figure 2 | Microbiological analyses for *Escherichia coli* (blue), *Clostridium perfringens* spores (green) and somatic coliphages (red) monitored in the effluent of pond 2 ($n = 8$).

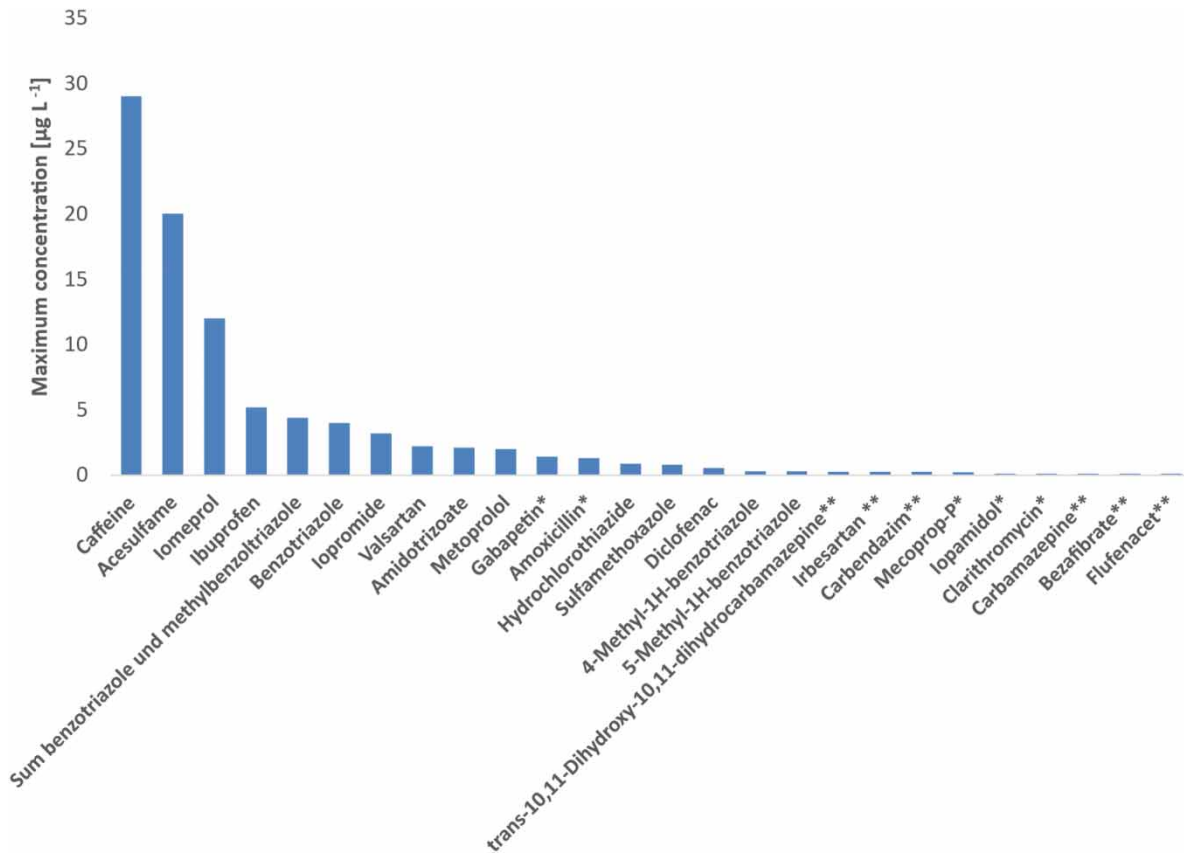


Figure 3 | Maximum concentrations of analyzed micropollutants from effluent of pond 2 ($n = 8$). For samples which showed values below the limit of quantification (LOQ), the value was divided by 2; * indicates >50% of samples were below the LOQ; ** indicates all samples were below the LOQ.

quantified in only half of the samples. Irbesartan, arbandazim, carbamazepine, bezafibrate and flufenacet could not be quantified in any sample.

3.3. Identified hazards and risk assessment

The assessment of risks for human health and the environment took into account the views of various internal and external stakeholders consulted in preparation of the RMP.

Table 3 shows an excerpt of the conducted risk assessment. The full assessment can be found in the Supplementary material (Table S4). As can be seen from Table 3, all base risks regarding health implications for human from micropollutants or pathogens were evaluated as low. While the consequences were evaluated as minor to moderate, the likelihood of occurrence was mostly seen as rare or unlikely. For the uptake of micropollutants by consumers, the likelihood was higher (Table 3).

Under consideration of the implemented barriers and preventive measures, the remaining risk for the health of humans was assessed as low to very low (Table 3; Supplementary material, Table S4). In fact, the only difference between base and remaining risk in the evaluation of consequence and likelihood, refers to the reduced likelihood ('Rare') of direct exposure of farm workers and pedestrians to micropollutants (Supplementary material, Table S4).

The base risks for soil, ground- and surface water were assessed to be low. After consideration of the preventive measures, the remaining risks from micropollutants for soil and groundwater were considered very low (Supplementary material, Table S4). Risks from nutrients entering water bodies and soil have been estimated as low (Table 3).

3.4. Preventive measures and additional barriers

The wastewater system itself has barriers that increase the safety of the water reuse system. For example, the catchment area is purely municipal. No commercial, industrial or medical wastewater is discharged to the wastewater treatment ponds.

Table 3 | Extract from the semi-quantitative risk assessment

Health	Hazard	Subject at risk	Hazardous event	Base risk			Preventive measures	Remaining risk		
				Conseq.	Likelh.	Risk		Conseq.	Likelh.	Risk
Micropollutants	Consumers	Uptake via products	Minor	Possible	Low	Reduction of micropollutants via biological wastewater treatment and activated carbon Hydroponic irrigation; no direct contact of irrigation water with food product Concentrations of micropollutants in wastewater very low (μg or ng) thus limited accumulation	Minor	Possible	Low	
Pathogens	Consumers	Uptake via products	Moderate	Unlikely	Low	UV disinfection within advanced wastewater treatment Spatial separation between wastewater treatment and plant cultivation Hydroponic irrigation; no direct contact of irrigation water with food product	Moderate	Unlikely	Low	
Environment	Micropollutants	Surface water	Discharge to water body	Insignificant	Possible	Low	Indirect discharge and sewage regulations Reduction of micropollutants via biological wastewater treatment and activated carbon Online monitoring of water quality parameters (e.g. turbidity), treatment plant components (e.g. energy intensity of UV disinfection); alarm system with notifications on mobile phone; hence short reaction times Regular monitoring of effluent for operational adaptation	Insignificant	Possible	Low
	Nutrients	Surface Water	Eutrophication	Moderate	Unlikely	Low	Nutrient conversion and nitrification via activated carbon biofilter Reduced nutrient load via controlled application in greenhouse and nutrient uptake by plants Recirculation of greenhouse effluent to wastewater treatment pond 3	Moderate	Unlikely	Low

The assessment was conducted by several stakeholders. The remaining risk considers the base risk and preventive measures.

Discharge is governed by the indirect discharge regulation and sewage regulation (Niedersächsisches Wassergesetz (NWG)). Only municipal and stormwater enter the wastewater treatment ponds. The retention time in the ponds is about 90 days during dry weather conditions.

The preventive measures considered for the RMP and the risk assessment are stated in Table 3. Technical barriers refer to the processes deployed for the advanced water treatment consisting of multiple filtration steps, an ACBF and a UV disinfection. In addition, validation monitoring of the treatment train was proposed. The hydroponic cultivation, realized via drip irrigation in substrate-filled gutters, further reduces the likelihood of workers getting into contact with the reclaimed water. This measure also increases the chemical and biological safety of the irrigation water as the substrate in the gutters represent an additional barrier that has to be passed before the water comes into contact with the plant. Aspects of the overall design of the water reuse systems have also been taken into account. In the event of system failure the irrigation water supply of the greenhouse can be interrupted quickly and can be switched to other water sources like harvested rainwater or drinking water. The comprehensive online and offline monitoring scheme supports the early identification of any faults or deterioration of the water quality. The spatial separation of wastewater treatment, advanced water treatment and agricultural irrigation also reduces the exposure of people to any hazards. While spatially separated, the distances between the individual stages of the water reuse system are relatively small. Hence, only short pipe and hose lengths, respectively, are required, minimizing potential of leakages. Water is retained in the treatment plants and nutrient dosing tank only for a short period of time, which further reduces related risks. Exposure of farm workers with the reclaimed water is further minimized by the use of personal safety equipment and complementing capacity development measures, such as trainings.

Additional measures have been implemented during the commissioning and implementation of the hydroponic greenhouse. In addition, the farmer has acquired a quality assurance certification for Good Agricultural Practice (QS-GAP), an industry standard certification commonly requested by food retailers. QS-GAP looks at production and management aspects beyond the water quality used for irrigation and presents a more production-oriented approach.

3.5. Design of monitoring programs

The EU regulation on minimum standards for water reuse states clear monitoring requirements for reclaimed water quality class A. For water quality class B and lower, the regulation only prescribes routine monitoring for *E. coli* (<100 CFU 100 mL^{-1} ; measured once a week for water quality class B). While turbidity monitoring is not required, for BOD₅ and TSS the regulation refers to Section D, Annex I of the Urban Wastewater Treatment Directive 91/271/EEC. The wastewater treatment ponds in Weißenberge have a lower population equivalent (PE) than the urban wastewater treatment directive regulates. Thus, the requirements for treatment plants between 2,000 and 9,999 PE were considered (European Union 1991). This resulted in standards for TSS of 35 mg L^{-1} or 90% reduction and $25\text{ mg O}_2\text{ L}^{-1}$ or 90% reduction for BOD₅. This implies the collection and analysis of 12 samples for the first year and four samples in subsequent years as long as all samples comply with the directive.

Comprehensive monitoring schemes for water quality parameters were developed during the creation of the RMP in order to complement the requirements set out by the EU regulation and built on the official discharge monitoring carried out by the wastewater association (Wasserverband Gifhorn). Additional analyses for heavy metals, nutrients, microbiological indicators and micropollutants were defined for the first year of operation of the water reuse system.

Multiple elements of the advanced wastewater treatment system are equipped with sensors to monitor operational parameters (e.g. flow, pump runtimes) and water quality parameters (e.g. UV light intensity, turbidity, SAK₂₅₄). Any faults and failures in the treatment train would trigger an alarm that notifies the operator. Hence, the sensors in the water reuse system function as an early warning system. In addition, the nutrient solution in the hydroponic mixing tank to which the reclaimed water is fed is equipped with sensors to monitor pH, electric conductivity, ammonium, nitrate and chloride. This provides a sound water quality control system to the farmer that needs to adjust the nutrient dosing accordingly, but also serves as an additional quality control element for the produced water. Any significant changes in water quality would be detected quickly, adding an extra level of security to the plants and hence the consumers.

As a measure of additional safety regarding the treatment performance of the treatment train, validation monitoring was proposed. Due to the lack of validation criteria for water quality classes other than class A, it was proposed to use those criteria as set out by regulation 2020/741.

The comprehensive initial monitoring should provide a solid basis for the future operation. It was suggested that during the first 4 weeks of irrigation, *E. coli* was monitored on a weekly basis. After this period and in case that all samples comply with

the standards, the interval would be adapted to 14 days. The monitoring frequency could be further extended to monthly intervals if after 8 weeks all samples comply with the standards. The monitoring frequency would be set back to a weekly interval when a sample exceeds the standards.

The relationship between COD and BOD₅ was also investigated. At the end of aerobic treatment, as realized in pond 2 and the ACBF, the readily biodegradable compounds should be largely eliminated. In this respect, COD should be the more representative and sensitive parameter when it comes to the residual organic load. It could potentially replace BOD₅ as a monitoring requirement if the relationship is stable and strong. The correlation between the two parameters during the study period was 0.88 ($n = 31$) and thus below the threshold of certainty of 0.9 commonly used for compliance measures (European Commission 2022; Seis *et al.* 2025). These results do not allow for a substitution. Further data and discussions on the practical implications are needed.

Monitoring of *Legionella* spp. was omitted since the risk of aerosol formation is at a minimum due to the drip irrigation system. According to EU regulation 2020/741 nematodes need to be monitored when pastures and forage are irrigated with reclaimed water. Thus, nematodes were not considered in the monitoring.

The guidelines to support the application of regulation 2020/741 contain a list of chemicals and priority pollutants potentially present in urban wastewater that could be used to screen for any potential hazards, the characterization of the wastewater sources, for example, the presence of industrial plants in the area (Maffettone & Gawlik 2022). Examples include anthracene, benzol, chloroalkanes, naphthalene or perfluoro octane sulfonic acid (PFOS). Due to the absence of industrial effluent in the catchment area, the chemicals have not been considered as hazards for the water reuse systems and thus have been omitted from further monitoring and risk assessment.

4. DISCUSSION

4.1. Multi-method risk assessment confirmed during operation

In the absence of sufficient data to perform quantitative risk assessments, the semi-quantitative approach was performed under consultation of researchers, the end user, the wastewater treatment operators and the Lower Water Authority Gifhorn. The risk assessment conducted was presented to and discussed with external experts currently involved in water reuse projects in Germany (Table 3). Comparisons were made with other risk assessments and RMPs developed by the experts' institutions. As suggested by Partyka & Bond (2022), the perception of risk is personal and should be considered carefully. The interdisciplinary evaluation of hazards and risks, combined with the preliminary monitoring of the wastewater treatment ponds, was followed in order to capture as many aspects as possible and minimize any bias in the risk assessment. The majority of risks evaluated were assessed as low. Described barriers and preventive measures resulted in even lower remaining risks. The preliminary monitoring (Figures 1–3) and pre-validation of the water reuse system (Table 1) further supported the assessment of risks. For example, the preliminary monitoring campaign revealed very low concentrations of heavy metals (Table 4) and micropollutants (Figure 3). Thus, the detailed evaluation of the risk emerging from heavy metals was omitted. The high treatment performance regarding microbiological and chemical hazards was later confirmed during the operation of the water reuse system (Gebhardt *et al.* 2025), although the pre-validation anticipated higher log removals.

Gebhardt *et al.* (2025) concluded that for BOD, TSS, *E. coli* and turbidity no samples exceeded the standards for water quality class A. In addition, the HypoWave+ project conducted a validation process according to the EU regulation. The *E. coli* removal of log 5 could be demonstrated in all cases. However, the respective log removal rates could not be demonstrated for *Clostridium perfringens* spores (log 4) and somatic bacteriophages (log 6) due to insufficient and inconsistent

Table 4 | Metal concentrations found in effluent from pond 2 ($n = 24$)

	Fe [mg L ⁻¹]	Al [mg L ⁻¹]	Mn [mg L ⁻¹]	B [mg L ⁻¹]	Cu [µg L ⁻¹]	Ni [µg L ⁻¹]	Zn [µg L ⁻¹]
Min	0.23	0.09	0.03	0.05	6.00	2.00	9.00
Max	1.20	1.50	0.13	0.07	28.80	4.10	53.90
Avg.	0.47	0.56	0.05	0.06	11.74	2.94	25.53
Median	0.40	0.49	0.05	0.06	10.10	3.00	24.35
SD	0.24	0.33	0.02	0.01	5.94	0.67	9.25

concentrations in the influent to the wastewater treatment ponds. In five samples (11%) at least one bacteriophage could be detected (Gebhardt *et al.* 2025). While according to the requirements set by EU regulation 2020/741, the validation was not successful, the low presence of pathogens supported the initial risk assessment. Barriers implemented after the point of compliance, including the use of drip irrigation and hydrogen peroxide, further reduce the risk of pathogens but are not accounted for in the validation. Challenges with the validation procedure have also been reported by Ho *et al.* (2024) and Seis *et al.* (2025).

Besides the presence of pathogens, the impact of micropollutants in water reuse systems is often discussed. In the HypoWave+ project, Gebhardt *et al.* (2025) could demonstrate that the respective concentrations of micropollutants were so low that, according to the Threshold of Toxicological Concern (TTC), the consumption of fruit produced with treated water is not expected to have any negative impacts on health. In a worst-case scenario, assuming a 40-fold concentration of micropollutants through tomato uptake and accumulation exclusively in the fruits, the TTC would remain below the target concentration even when consuming 7.7 kg of tomatoes per day grown with water from the HypoWave+ system. Adding to that, He *et al.* (2017) found that only a small fraction (4–37%) of micropollutants in water is actually taken up by plants, depending on the species, with the majority accumulating in the roots. The accumulation in tomatoes is expected to be lower than in other crops, such as leafy greens or root crops (Mordechay *et al.* 2021). These findings complement the low-risk perception based on the preliminary monitoring of micropollutants (Figure 3).

These findings also enable an estimate on the risk of AMR formation in the hydroponic reuse scheme. In a study on hydroponic lettuce, Smalla *et al.* (2023) concluded that it is yet to be clarified whether hydroponic cultivation with reclaimed water has an impact on the transferability of AMR genes. For Weißenberge, the low concentrations of antibiotics in the wastewater treatment ponds as well as at the point of compliance, combined with the low concentration of bacteria in the irrigation water (*E. coli*: 1 MPN 100 mL⁻¹ in three samples) indicate that the risk of AMR formation and AMR gene transfer into the plant and tomatoes can be regarded as low. This estimate is supported by findings of Gatica & Cytryn (2013) who concluded that irrigation with treated wastewater does not affect AMR levels in soil microbiota.

The described multi-method approach to the development of a RMP in Weißenberge could provide further guidance on the development of risk management and water reuse systems. However, McLennan *et al.* (2024) believe that more details on the development of RMPs need to be provided by the EU Member States. While not necessarily more regulation is needed, further specifications of elements of the existing regulation could pose beneficial. This is particularly relevant for smaller systems that could be overwhelmed with the regulatory processes and associated monitoring requirements (Reynaert *et al.* 2021). The presented case study from the HypoWave+ research project resembles such a small wastewater reuse system with around 500 PE of municipal wastewater. Future regulatory developments need to focus on the applicability of the regulation in order to enable safe water reuse adoption in the EU. Technical, operational (e.g. monitoring) and administrative efforts need to be balanced against risk considerations regarding health and environment (Dingemans *et al.* 2020). Setting unobtainable requirements for water reuse does not favor the development of this practice urgently needed as a tool to address water shortages and increased climate resilience (Partyka & Bond 2022).

4.2. Remaining challenges with EU regulation – accounting of barriers and validation

The guiding principle of safe water reuse and adequate risk management is the multi-barrier approach. The EU regulation 2020/741 defines barriers as ‘any means including physical or process-related steps or conditions of use, that reduces or prevents a risk of human infection [...]’. However, various elements of the EU regulation remain unclear.

For example, the regulation text itself does not state requirements for a certain number of barriers or assigns log reductions to individual measures and barriers. The supporting documents to the regulation suggest the consideration of a certain number of barriers depending on the type of irrigation and crop cultivated (International Organization for Standardization 2018, 2020; European Commission 2022). Proposed measures include sun protection covers or weak disinfection. According to ISO16075:2020, a weak disinfection corresponds to <1 mg L⁻¹ total chlorine after 30 minutes of chlorination and accounts for a log 2 reduction of pathogens. A strong disinfection of 1 mg L⁻¹ total chlorine after 30 minutes of chlorination would correspond to a log 4 reduction.

In horticulture, and in particular in hydroponic cultivation, the regular use of low dosages of hydrogen peroxide to prevent biofilm formation and proliferation is a standard application (Kriem *et al.* 2023). It is not clear which equivalent could be attributed to the regular use of peroxide and its varying contact time as used in hydroponic water reuse systems. Chlorine based disinfectants typically have higher disinfection rates (Tao *et al.* 2024). However, they bear higher risks of disinfection

by-product formation and might not be suitable in all water reclamation systems. For example, [Bonetta et al. \(2022\)](#) report that the application of 1.2 mg L^{-1} of chlorine dioxide (ClO_2) resulted in a mean reduction of microbial indicators between 0.63 and 1.44 with values $>1 \text{ Log}$ for *E. coli* and Enterococci. Hence, the barrier recommendations described in ISO16075:2020 seem disputable.

A similar situation can be observed for the drip irrigation system as approximation for the substrate-based hydroponic cultivation. ISO16075:2020 states that drip irrigation systems could account for a log 2 reduction of pathogens. In both cases, no distinction is made between different microbial indicators. The water reuse system needs to comply with the standards at the point of compliance and both the hydrogen peroxide dosing and drip irrigation occur after the point of compliance. In general, these measures are additional barriers contributing to the overall safety of the described water reuse system in Weißenberge. On the other hand, as suggested by ISO 16075: 2020 it would be favorable to account for these additional safety measures. While this is currently not the case in the regulation, potential implications of such risk reduction measures could be the extension of monitoring intervals, consideration in validation processes for Class A applications or allowance of using the water for applications of higher water quality classes in general.

The validation monitoring is a powerful risk management tool. While intended as a public health instrument to ensure adequate treatment performance of water reuse systems, the procedure described in its current form in the regulation can be regarded as a barrier to water reuse ([Dingemans et al. 2020](#)). As seen in [Gebhardt et al. \(2025\)](#), the validation in Weißenberge was not successful mainly due to insufficient quantities of indicator microorganisms in the untreated wastewater and strong influence of individual spores or phages detected in samples at the point of compliance. Alternative approaches include spiking of sewage in order to increase the inlet concentration of organisms and could result in regulatory, environmental or even health problems. Enrichment methods might be suitable, but require a validation of the recovery rate themselves ([Seis et al. 2025](#)). [Ho et al. \(2024\)](#) proposed that validation as well as routine monitoring take into account the operational procedures and online measurements of disinfection steps, possibly alleviating challenges associated with validation and compliance monitoring.

4.3. Implications of EU regulation 2020/741 for water reuse in hydroponics

Hydroponic systems pose great potential for a resource-efficient cultivation of fresh food products. The provision of optimal ratios of plant nutrients and protective environment in greenhouses makes hydroponic cultivation very productive and independent from environmental factors, such as climate and water availability. In combination with reclaimed water the approach has significant potential for a sustainable food production system.

In a public statement the German Federal Institute for Risk Assessment (BfR) took the position of excluding hydroponic cultivation of raw edible crops from irrigation with reclaimed water since pathogenic bacteria could easily colonize plant roots in hydroponic systems and could be taken up by the respective plants ([Bundesinstitut für Risikobewertung 2020](#)). The BfR proposes that no pathogens should be detectable in irrigation water and hydroponic systems should be used only in combination with water that meets drinking water standards. In contrast, in a quantitative microbial risk assessment (QMRA) on hydroponically grown lettuce with reclaimed water, [Mohr et al. \(2020\)](#) concluded that the risk of infection to the consumer is within limits tolerated by the World Health Organization ([WHO 2016](#)).

BfR has renewed its position in a review study on the risk from viruses in water reuse systems ([Bundesinstitut für Risikobewertung 2022](#)). The conclusion comes from an analysis of available scientific literature. However, a closer look at the studies considered reveals that most experiments were conducted in laboratory environments under viral loads that resemble concentrations more common in untreated sewage ([Carducci et al. 2015](#); [Wang & Kniel 2016](#); [McCall et al. 2020](#); [Fuzawa et al. 2021](#)). Also, the analyses of viral material in edible parts of the plants were mostly conducted by molecular methods, such as Polymerase Chain Reaction (PCR). While PCR is a relatively simple and cheap screening tool for pathogens in wastewater, it does not distinguish between vital, and thus infectious, viral material, and RNA or DNA fragments that pose no risk to consumers, and thus could result in false positives ([Dingemans et al. 2020](#)). In its statement the BfR acknowledges the lack of data on the reduction of infectivity by the plants themselves ([Bundesinstitut für Risikobewertung 2022](#)). However, the institute takes a position of extreme precaution stating that ‘it cannot be ruled out that infectious human pathogenic viruses may enter plant parts growing above ground via the roots. In contrast, several studies indicate a reduction of viral load by plants exposed to high viral titers. Hydroponic experiments on leafy greens inoculated with human norovirus ($1 \times 10^6 \text{ PFU mL}^{-1}$), animal caliciviruses ($2 \times 10^6 \text{ PFU mL}^{-1}$) ([Dicaprio et al. 2012](#)), Tulane virus and Rotavirus ($1 \times 10^6 \text{ PFU mL}^{-1}$) ([Fuzawa et al. 2021](#)) and Murine norovirus ($1 \times 10^{3.5} \text{ PFU mL}^{-1}$) ([Wang & Kniel 2016](#)) confirmed the

uptake of viral material into edible parts of the plants. However, plaque assays in all studies showed the level of infectious particles decreased over time while RNA detected by PCR methods remained consistently high and stable. For water reuse systems that adhere to the EU regulation, these high virus titers are unlikely. In Weißenberge, Gebhardt *et al.* (2025) experienced that only five (11%) reclaimed water samples contained somatic phages at the point of compliance, with the maximum concentration being 7 PFU mL⁻¹, and the drip irrigation system after the sampling point has not even been accounted for. This significant difference makes a general assumption about the internalization of viral material to edible parts of crops difficult. Also, the implications of different hydroponic methods (e.g. substrate-based systems) and cultivated crops need to be taken into account. Thus, a general exclusion of hydroponic cultivation methods from water reuse seems disputable.

5. CONCLUSIONS

The present study presents experiences and a critical assessment of guidelines for the development of an RMP for hydroponic water reuse under EU Regulation 2020/741 on minimum requirements for water reuse. A multi-method approach including literature studies, stakeholder consultations and preliminary monitoring formed the basis of a risk assessment that focused on risks from pathogens, micropollutants and nutrients. The assessment identified low-to-very-low risk levels for human health and the environment. The estimate was later confirmed during the operation of the water reuse system (Gebhardt *et al.* 2025). A comprehensive scheme of technical and non-technical preventive measures following the multi-barrier approach justified the assessment of the remaining risks. To avoid the introduction of bias into the risk assessment, it is crucial to capture the perception of various stakeholders and involve the regulatory body during the preparation of the risk assessment and the overall RMP. During the preparation of the RMP some uncertainties and challenges in the application of the EU regulation and its supporting documents were identified. These include the procedure for accounting of barriers and respective log reductions, as well as the applicability of the validation process for Class A water.

Comprehensive monitoring requirements have been identified as a bottleneck for further adoption of water reuse, in particular for small-scale systems, such as described in the HypoWave+ project. Thus, a comprehensive monitoring scheme for an initial period followed by more flexible and larger monitoring intervals is proposed. Synergistic potential between wastewater treatment and agriculture, such as the removal of nutrients via plants, could be explored further especially for smaller systems. Regulatory development on water reuse in Germany along with the implications of the updated Urban Wastewater Treatment Directive are expected to provide more guidance on risk management in water reuse systems in the future. However, the opinion to exclude hydroponic systems from water reuse applications is not shared under the current state of research.

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DATA AVAILABILITY STATEMENT

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

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