

# Application of water disinfection technologies for agricultural waters

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## ABSTRACT

Irrigation water is a potential source of contamination of leafy vegetables that are grown in the field. There is an urgent need to support technologies that are designed to ensure food safety, including those technologies that can disinfect irrigation water used to cultivate crops. Previous research has yet to evaluate the microbial and economic efficacies of water disinfection technologies to be applied during primary production to combat foodborne pathogens. The literature describes potential water disinfection technologies that could be applied, but studies often focus on plant pathogens and mainly focus on laboratory-scale research. In this study, ozone, UV, and membrane filtration were evaluated at the lab-scale, and UV with and without pre-filtration were examined in a field trial to determine the reduction of *E. coli* in surface water that is used to irrigate leafy vegetables. The cost-effectiveness and applications at the field-scale were also considered. We determined that UV treatment (300–600 J/m<sup>2</sup>) reduced *E. coli* up to 3 log in irrigation water. In the lab, we found that ozone, UF, and combined disinfection technologies reduced *E. coli* up to 4 log. The cost calculation for UV disinfection (0.09 €/m<sup>3</sup>) showed to be less than that of ozone (0.36 €/m<sup>3</sup>) and UF (0.43 €/m<sup>3</sup>). Overall, UV was found to be the most feasible disinfection technology in terms of microbial and cost efficacies to treat surface water used for the agricultural irrigation of crops. The outcomes of this research can provide input into the minimum requirements needed for water disinfection technologies considering the use and reuse of agricultural waters.

## 1. Introduction

Fresh water is a valuable resource that is being challenged, given the need to provide safe and healthy food for the growing population. This growth requires that we efficiently use our freshwater sources amidst a progressively complex and globalized food chain. The circular economy concept, as applied to food systems, is a potential solution to help achieve the challenges associated with climate change as well as population and economic growth (Jurgilevich et al., 2016; Rood et al., 2017). This concept also parallels European Union (EU) efforts to reduce water shortage risks and additional agreements to propose legislation on the requirements for water reuse, e.g., for agricultural irrigation (Council of the European Union, 2019). Food safety plays an essential role in this circular economy concept, especially when it comes to finding technological solutions for mitigating food loss and waste (Vilarino et al., 2017). Equally important is the design and development of technologies for water disinfection that can support food systems. For instance,

climate change can negatively impact the availability of fresh water for irrigation purposes, leading to water scarcity and pressure on food security (Hanjra and Qureshi, 2010). Thus, a need for alternative types of water to be used for irrigation, especially recycled water like treated wastewater, arises. These alternative water sources must still ensure that human and animal health, as well as the environment, are protected. Hence, there is an urgent need for water disinfection technologies that can ensure these requirements. Despite this need, research on the feasibility of recycling freshwater resources that are then applied to food and feed systems is limited (Jurgilevich et al., 2016).

A recent foodborne outbreak resulted in 210 cases of people infected, 96 hospitalizations, and 5 deaths. It was found that water from an irrigation canal was contaminated with *Escherichia coli* O157:H7 and that this strain was the likely contamination source of romaine lettuce during the outbreak (Centers for Disease Control and Prevention (CDC), 2018; Food and Drug Administration (FDA), 2018). The risks attributed to the quality of the irrigation water, namely as a source of pathogenic

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microorganisms like that of pathogenic *E. coli* in fresh produce like leafy greens, has been well-reported (Alegbeleye et al., 2018; Allende and Monaghan, 2015; Jongman and Korsten, 2018; Olaimat and Holley, 2012; Pachepsky et al., 2011; Uyttendaele et al., 2015). For example, leafy greens like lettuce have been reported to be sources of bacterial infections, and endive has been reported to be likely contaminated (Alegbeleye et al., 2018). Therefore, research examining how to prevent contamination of lettuce and endive are of interest to study.

In Europe, a survey on the types of freshwater sources used for irrigation has indicated that groundwater is frequently used. However, other types of water, like surface water, mains tap water, desalinated water, or disinfected urban wastewater, are also used to irrigate horticultural crops (Lechevallier et al., 2018). Research into water disinfection technologies that can be used to disinfect irrigation from riskier water sources, like surface water, is a starting point. Overall, the need to ensure safe irrigation water to satisfy the need for safe food, while also considering the future of a circular economy in food systems is warranted and will be made possible with effective water disinfection technologies.

A variety of water disinfection technologies are available on the market. Many of these have been evaluated for pre- and post-harvest applications (Banach and van der Fels-Klerx, 2020; Van Haute et al., 2015). A recent prioritization of technologies to disinfect bacterial pathogens in irrigation water ranked ultrasound, microfiltration, ultraviolet irradiation (UV), ozone, and ultrafiltration (UF) in the top five disinfection technologies, respectively (Van Asselt et al., unpublished). Given the resource available for this study, the focus was on ozone, UF, and UV. These are conventional technologies when it comes to wastewater and drinking water treatments. Their indicative effectivity, in terms of microbiological ( $\log_{10}$ ) reductions, to remove enteric bacterial pathogens and indicator organisms have been reported to range from 2 to 6 log for ozone, 5–6 log for UF, and 2–4 log for UV (Collivignarelli et al., 2018). Despite the promising efficacy of these technologies, questions regarding large-scale feasibility, mobility, and costs of the technologies were raised when considering their application to disinfect irrigation water (Van Asselt et al., unpublished).

This study evaluated the microbial efficacy of ozone, membrane filtration, and UV at a lab-scale. The cost-effectiveness of ozone, UF, and UV at the field-scale was also considered. Given these results, UV with and without pre-filtration were selected to test in a field trial to determine the reduction of *E. coli* in surface water used to irrigate leafy greens.

## 2. Materials and methods

### 2.1. Surface water

Surface water was collected from the Dijkgraaf canal in Wageningen, which is used to irrigate crops in nearby fields. The water was analyzed for chemical oxygen demand (COD) in accordance with NEN 6633:2006/A1:2007, *E. coli* with the ISO 16649-2 and ISO 9308-1 methods, and coliforms with the NEN-ISO 4832 and ISO 9308-1 methods at Mérieux NutriSciences (Ede, The Netherlands). Analyses were taken before lab experiments ( $n = 3$ ; December 2018–January 2019) and before field trials ( $n = 2$ ; May–June 2019) to evaluate the quality of the surface water.

### 2.2. Bacterial strain and inoculum preparations

A commensal *E. coli* strain (12-123.2), originally isolated from surface water, was supplied by the National Institute for Public Health and the Environment (RIVM), Bilthoven, the Netherlands. The strain was kept at  $-80^{\circ}\text{C}$  in Luria Broth (LB; L1704 LB Broth High Salt, Duchefa Biochemie B.V., Haarlem, the Netherlands) supplemented with 25% (v/v) glycerol. Cultures were prepared by transferring a single colony to 20 mL LB and incubated for  $18 (\pm 1)$  h at  $37^{\circ}\text{C}$  (lab study) or  $30^{\circ}\text{C}$  (field

trial) in a 180–200 rpm shaking incubator to obtain stationary phase cells. Afterward, 2.5 mL of the prepared culture was inoculated into 250 mL of freshly prepared LB in triplicate. This culture was incubated for another  $18 (\pm 1)$  h at  $37$  or  $30^{\circ}\text{C}$  in a 180–200 rpm shaking incubator. After incubation, the culture was washed twice at  $1800 \times g$  at  $20^{\circ}\text{C}$  for 10 min with peptone physiological salt solution (PPS; Tritium Microbiologie B.V., Eindhoven, the Netherlands). The pellet was then suspended in 20 mL PPS aliquots to obtain a working solution of about  $10^8$  to  $10^9$  colony forming unit (CFU)/mL.

During lab experiments, 20 mL of the working solution was used to inoculate about 20 L of either tap or surface water collected in a jerry can, thereby with a verified concentration of about  $10^6$  CFU/mL. During field experiments, 300 mL of the working solution was used to inoculate about  $1 \text{ m}^3$  of surface water. A water sample was taken at the moment of inoculation and plated on chromogenic coliform agar (CCA, Tritium Microbiologie B.V., Eindhoven, the Netherlands) to determine the concentration in the water, which showed to be  $10^6$  CFU/mL.

### 2.3. Laboratory study

#### 2.3.1. Experimental design

During the laboratory experiments, three single technologies — ozone, UF, and UV — were tested in tap and surface water. A full factorial design was applied (Appendix A, Table A.1). Four sets of combined technologies were also tested in tap and surface water: (i) UF and ozone, (ii) UV and ozone, (iii) UF and UV, and (iv) UF, UV, and ozone.

#### 2.3.2. Equipment

Laboratory experiments were performed at Nijhuis Industries, Doetinchem, the Netherlands using tap and surface water. A schematic picture of the installation used during the water disinfection experiments is shown in Fig. 1. Measurements during UV experiments were performed with a single low-pressure mercury lamp at 254 nm (Van Remmen UV Technology, W1, 15 W UV-C, and  $0.8\text{--}1.1 \text{ m}^3/\text{h}$  by  $300 \text{ J}/\text{m}^3$ ). Measurements during ozone experiments were recorded with a Jumo Aquis touch S ozone test unit. The  $\text{O}_3$  generator was a NOS Q6, while the  $\text{O}_2$  generator was Airsep AS123-2. During UF experiments, a membrane was installed so that the water was first treated with UF before flowing through the system. The UF membrane was a hollow fiber membrane with a pore size of  $0.03 \mu\text{m}$ . A new membrane was attached before each treatment. Each treatment tested 16–17 L batches of tap or surface water. The hydraulic retention time (i.e., a full-cycle) was 1 min.

During treatments, the ozone dose was set by regulating the ozone

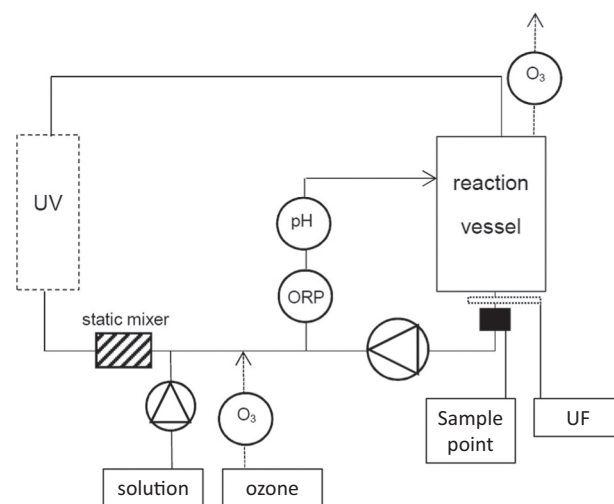


Fig. 1. Schematic diagram of the ozone, ultrafiltration (UF), and ultraviolet irradiation (UV) installation. ORP = oxidation-reduction potential.

concentration in the gas and the oxygen gas flow rate while monitoring the redox value to avoid excess ozone and to monitor safety aspects. The corresponding ozone production (g O<sub>3</sub>/min) was divided by the total volume of the reactor (average 16 L) to determine the ozone dose at each time interval. A UV dose of 5000 J/m<sup>2</sup> was applied during the experiments. The UV dose was calculated at each time interval by using the liquid flow rate of, on average, 16 L/min and the reactor volume (12 L).

### 2.3.3. Microbial analyses in the lab study

The inoculated 20 L jerry cans were sampled to obtain the initial *E. coli* concentration in the water. Subsequently, between 1 and 4 water samples were taken after treatments. Tenfold serial dilutions in PPS were made of the water samples. Then, 100 µL of the diluted and undiluted samples were pipetted onto Petri dishes of CCA for the recovery of *E. coli*. Agar plates were incubated for 24 h at 37 °C with daily inspection of colonies for one additional day to check if potentially damaged cells could grow out.

### 2.3.4. Chemical analyses in the lab study

Surface water samples were periodically sampled during the disinfection experiments, including at the start and end of disinfection, for either total organic carbon (TOC) and/or COD. The TOC of the water was analyzed using a Skalar SAN++ Segmented Flow Analyzer in accordance with NEN-EN 1484 at the Chemical Biological Soil Laboratory (Wageningen, the Netherlands). Water was analyzed for COD with the Hach Lange LCK 314 test kit in accordance with ISO 6060-1989 at Nijhuis Industries (Doetinchem, the Netherlands).

## 2.4. Cost calculation model

The economic feasibility for ozone, UF, and UV was estimated for annual capital expenditure (CAPEX) costs, given factors such as investment costs for the equipment (€), annual investment costs (€/year), leading to total annual costs (€/year). Annual operating expenditure (OPEX) was estimated given factors such as power consumption (kW), maintenance (€/year), and energy costs (€/year). The summation of CAPEX and OPEX represents the total costs per cubic meter of treated water (€/m<sup>3</sup>). The following assumptions were included in the model: 80 m<sup>3</sup>/h of treated water, 50 operational days per year, 5-year linear depreciation time assuming no effects of interests, and 14 h per day operation time, which resulted in an annual amount of water to be treated of 56,000 m<sup>3</sup>/year. An overview of the assumptions specific to each technology and cost is depicted in Table 1. The energy for all installations was assumed to be supplied by a diesel-fueled tractor and generator.

**Table 1**  
Overview of disinfection technology assumptions and associated costs for field-scale application.

Disinfection technology	Assumptions	Annual capital expenditure (CAPEX)	Annual operating expenditure (OPEX)		Annual total costs (k€)
		Annual investment costs (k€) <sup>a</sup>	Annual maintenance costs (k€)	Energy costs (k€)	
Ozone	<ul style="list-style-type: none"> <li>ozone dose: 4 mg/L</li> <li>flow rate: 0.32 kg/h</li> <li>power consumption: 6.4 kW</li> </ul>	14 (ozone generator and connection to tractor)	4.0	2.0	20
Ultrafiltration (UF)	<ul style="list-style-type: none"> <li>energy consumption: 0.2 kW/m<sup>3</sup></li> <li>pressure drop: 0.5 bar</li> <li>power consumption: 16 kW</li> </ul>	18 (incl. membranes)	1.6	4.5	24
Ultraviolet (UV)	<ul style="list-style-type: none"> <li>mobile UV skid installation on the field</li> <li>8 low-pressure UV lamps operating at 254 nm</li> <li>UV transmittance: 65%</li> <li>UV fluence: 600 J/m<sup>2</sup></li> <li>power consumption: 3.2 kW</li> </ul>	3.6	0.3	0.9	4.8

<sup>a</sup> Annual investment costs are assumed over a 5-year linear depreciation time and no effects of interests.

## 2.5. Field trial

### 2.5.1. Experimental design

An experimental field located within a semi-opened high tunnel (Willem Genet Tunnel, Unifarm, Wageningen University & Research, Wageningen, the Netherlands) was used for the cultivation of lettuce (*Lactuca sativa* var. *crispa* 'Lollo Bionda') and endive (*Chicorium endivia* var. *latifolium*) (Fig. 2). Surface water (see Section 2.1) was used to irrigate the experimental field. Each week, new water was collected from the canal and pumped into an agricultural water tank. A coarse filter was used to prevent large particles from entering the tank. The water was immediately transported to the experimental field and transferred into three separate intermediate bulk containers (IBCs) of 1 m<sup>3</sup>. About 24 h later, the IBCs were inoculated with the *E. coli* strain (see Section 2.2). The water was pumped from the IBCs to barrels, during which either no treatment, treatment with UV, or treatment with pre-filtration and UV (F-UV) took place. The water was then pumped from the barrels to the overhead sprinklers for irrigation.

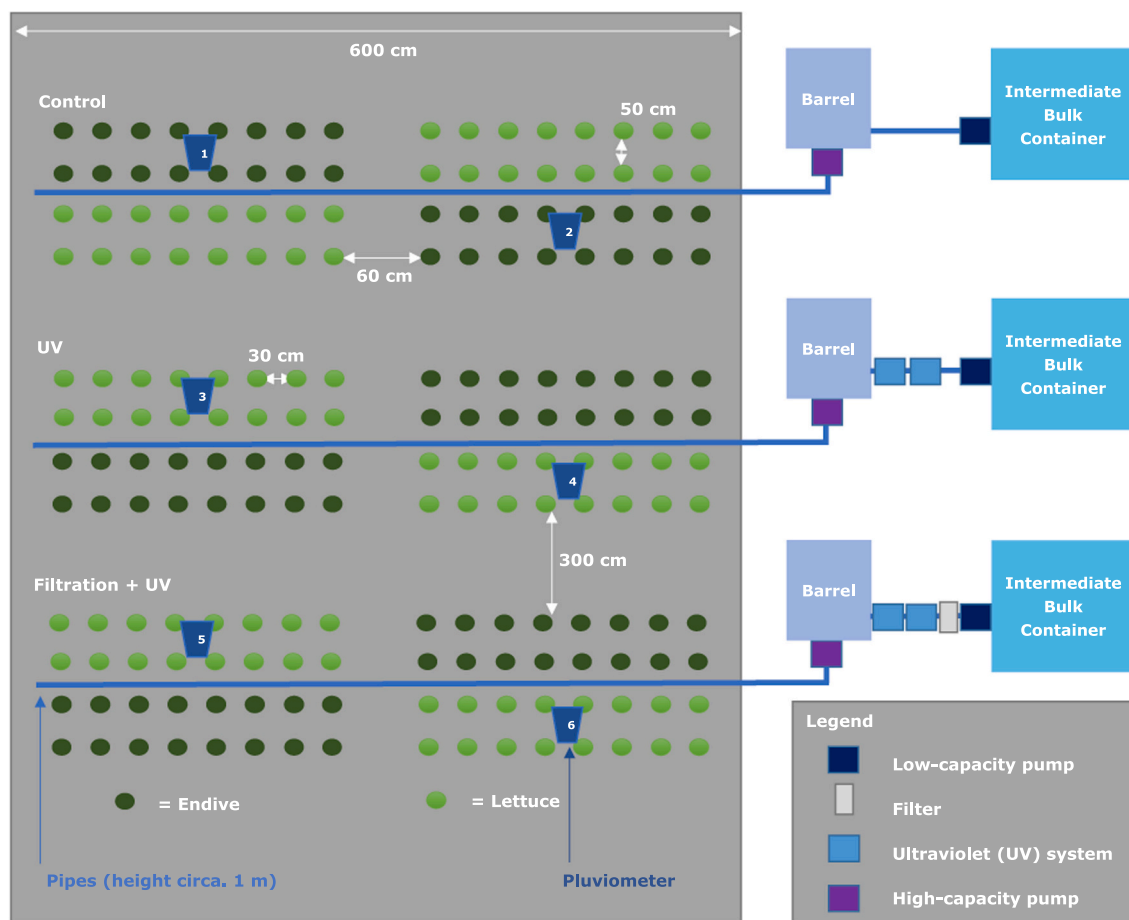
Cultivation occurred over five weeks from June to July 2019. Six plots (two controls and four treated) were used. Each plot (~ 3.75 m<sup>2</sup>) consisted of 4 rows of 8 crops, covered with an anti-rooting mat made of polypropylene. Plots were irrigated 4x per week for about 15–30 min (totaling about 15 mm per time) via irrigation sprinklers (3 per plot, VDL arc sprayer, article no. 780641, Wildkamp B.V., the Netherlands) situated about 1 m from the ground. The amount of irrigation water accumulated was collected by pluviometers and recorded after each irrigation. Control plots (1 and 2) were irrigated with untreated surface water. Plots 3 and 4 were irrigated with surface water treated with UV disinfection, while plots 5 and 6 were irrigated with surface water treated with by F-UV disinfection. During cultivation, the water used for the irrigation of these crops was analyzed for *E. coli*, COD and/or TOC. Crops were grown until the lettuce was visually estimated to be about 200–450 g and the endive 600–700 g.

### 2.5.2. Filter and UV preparation, dosing and monitoring

For the disinfection treatments, irrigation water was treated with UV (GammaLine GS1.10, BestUV B.V., Best, the Netherlands) with and without a pre-filter using a 0.1 mm cylinder sieve (Amiad cylinder sieve for plastic filter – article no. 647345 and Amiad plastic fluid filter – article no. 647180, Wildkamp B.V., the Netherlands). The UV absorbance was set at 254 nm for all treatments. The UV doses were applied with a decreasing dose from 600 to 300 J/m<sup>2</sup>. Each week, after the new water was collected and transferred to the IBCs, the UV transmission of the newly collected water was tested. Measurements to determine the UV lamp settings were carried out with UV T10 meter (BestUV B.V.,



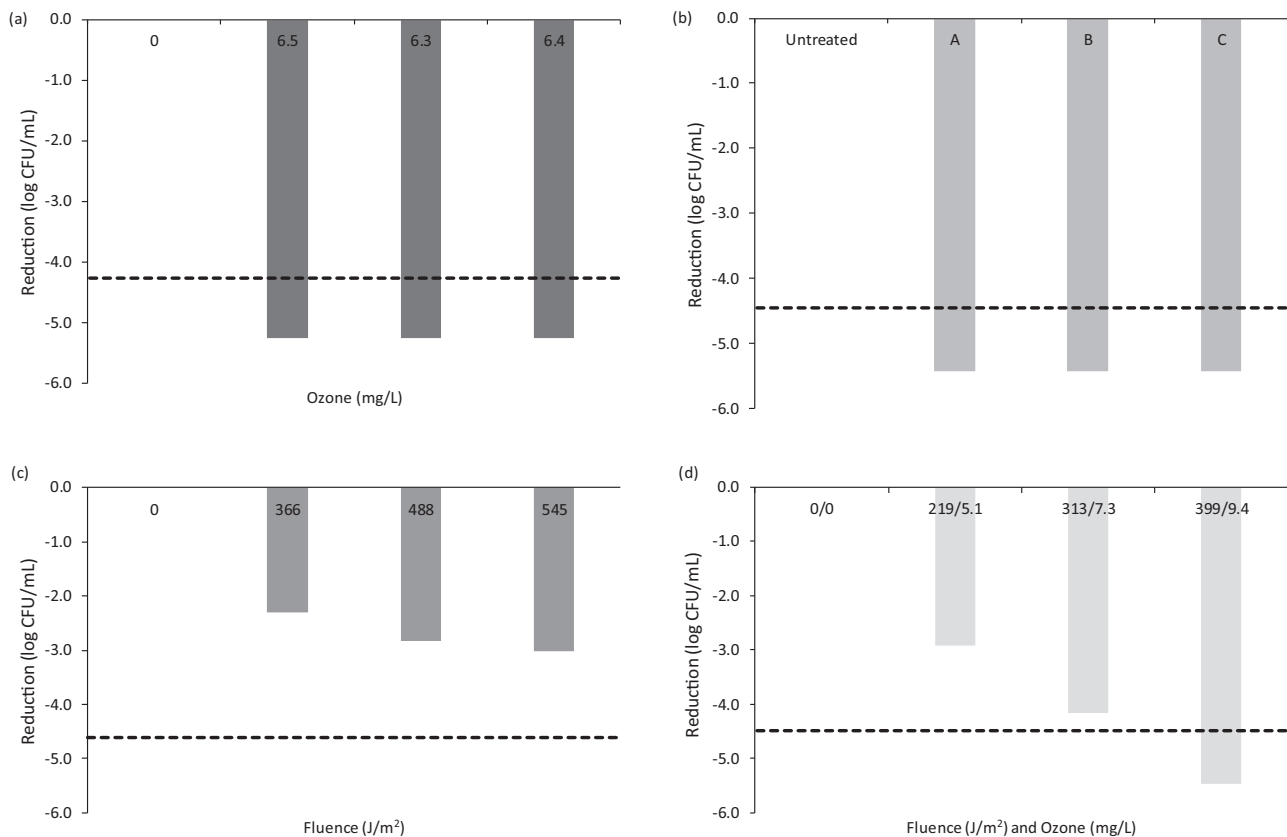
(a)



(b)



Fig. 2. Experimental field (a) schematic design and (b) photo.



**Fig. 3.** Inactivation of *Escherichia coli* in surface water with (a) ozone, (b) ultrafiltration (UF), (c) ultraviolet irradiation (UV), and (d) UV and ozone. Upper case letters indicate samples that were taken after 1 min (A), 2 min (B), and 3 min (C) of UF disinfection. —, the limit of detection.

Best, the Netherlands). Measurements were performed in duplicate, and the average UV transmission was used to calculate the flow required based on the desired UV dose.

A low-capacity pump (AUGA pond pump, article no. 15007726, Wildkamp B.V., the Netherlands) was used to transfer the water from the IBC unit through to the barrel. A flow meter was mounted after the UV lamps to regulate and achieve the desired flow required for the UV dose (Flowmeter type M335, article no. 517.100.215 from Frank GmbH, purchased article no. 10059220 from ERIKS B.V., the Netherlands). After the barrels, a high-capacity pump (LEO self-priming centrifugal pump, type AJm75S, article no. 795612, Wildkamp B.V., the Netherlands) pumped the water through the irrigation pipes and sprayed the irrigation water onto the crops (Fig. 2).

### 2.5.3. Water sampling and analyses

For *E. coli* analyses, irrigation water (10 mL) samples were taken once per week about 18 h after the IBCs were inoculated. Duplicate samples were collected from the sprinklers above each plot ( $n = 6$ ) and the IBC tanks ( $n = 3$ ). Tenfold serial dilutions in PPS were made of the water samples. Then, 100  $\mu$ L of the diluted and undiluted samples were pipetted onto Petri dishes of CCA for the recovery of *E. coli*. Agar plates were incubated for 48 h at 37 °C before the enumeration of the individual CFU of *E. coli*. Furthermore, during experiments, the filter was rinsed each week with fresh water to remove any organic matter that may have clogged the sieve.

For analyses of COD and TOC, samples of the irrigation water were collected during the first, third, and fifth weeks of the experiments. Duplicate samples were collected from the IBCs (150 mL) and transported under refrigerated conditions to the lab before analyses. Water was analyzed for COD in accordance with NEN 6633:2006/A1:2007 at Mérieux NutriSciences (Ede, the Netherlands) and for TOC in accordance with NEN-EN 1484 (AL-West, B.V. Deventer, the Netherlands).

### 2.5.4. Crop sampling and analyses

Two days before harvest, the sensory quality of the crop in the inner rows of each plot was analyzed by an expert according to the Karlsruher Evaluation Scheme for the sensory analyses of foodstuffs to get an indication of the sensory quality of the crops (Appendix A, Table A.2). At the end of the cultivation period (week 5), lettuce and endive were harvested. The crops were manually sampled using a clean knife and immediately packed in numbered polyethylene liners. The harvested crops were weighed and stored under refrigerated conditions, about 4 °C. In total, three samples of lettuce and endive were randomly selected from the inner rows of each plot. These samples were stored cool, about 4 °C, for approximately 3–4 h before being transported under refrigerated conditions to the lab for further analyses. Crops were analyzed for aerobic mesophilic bacteria at 30 °C with the ISO 4833-1 method, coliforms with the NEN-ISO 4832 method, and *E. coli* with the ISO 16649-2 method at Mérieux NutriSciences (Ede, the Netherlands).

## 3. Results and discussion

During the laboratory study, tap and surface water were tested. The results of those experiments (Section 3.1) combined with cost estimates (Section 3.2) were used to select an optimal technology for treating the surface water during the field trial (Section 3.3).

### 3.1. Laboratory study

Results from the pre-analyses of the surface water showed that background *E. coli* levels ranged from < 1 to 1 CFU/g, while presumptive coliforms ranged from < 1 to 100 CFU/g. Results from the pre-analyses of COD of the surface water showed that it ranged from < 10 to 29 mg/L. In most cases, the efficacy of the technologies was

comparable for tap and surface water, with the reduction of viable *E. coli* being below the limit of detection (LOD). The results per technology are given below.

### 3.1.1. Ozone

Results in surface water treated with ozone doses of 6.3–6.5 mg/L showed a reduction of *E. coli* to below the LOD, resulting in  $> 4.2$  log reduction (Fig. 3a). In tap water, *E. coli* levels of ozone disinfected water with doses of 2.8–8.7 mg/L were also below the LOD, resulting in  $> 4.4$  log reduction (data not shown). The COD and TOC of the surface water before ozone disinfection were, respectively, 40.2 mg/L and 15.1 mg/L and afterward was, respectively, 17.3 mg/L and 14.3 mg/L. The decrease in COD was expected as ozone can oxidize organic and inorganic compounds. Similarly, the TOC was reduced since ozone functions as an oxidant and can decrease TOC.

Our results concur with previous research, which reported the disinfection efficacy of ozone to range from 2 to 6 log for *E. coli* and bacterial pathogens (Collivignarelli et al., 2018). Ali et al. (2018) reviewed the use of ozonated water to extend the shelf-life of fresh-cut vegetables as well as reduce bacterial loads. For instance, ozonated water (4 mg/L for 2 min) significantly reduced mesophilic, psychrotrophic, and *Enterobacteriaceae* bacteria, respectively, by 1.7, 1.5, and 1.6 log CFU/g in fresh-cut lettuce (Akbas and Ölmöz, 2007). In another study, Papachristodoulou et al. (2018) reported that ozonated water (0.8 mg/L for 30 s) prevented yellowing and maintained the quality of fresh-cut spinach. Also, it helped decrease *Enterobacteriaceae* spp. and Gram-negative bacteria about 1.8 and 2.8 log CFU/g, respectively, during the first 5 d of storage compared to experiments with non-treated water. Our study evaluated higher doses of ozone compared to some literature, which can explain the higher log reductions ( $> 4$  log for *E. coli*) reported for both ozone disinfected tap and surface water.

### 3.1.2. Ultrafiltration

Results in surface water treated with UF showed a reduction of *E. coli* to below the LOD, resulting in  $> 4.5$  log reduction (Fig. 3c). This observation was also found in tap water (data not shown). Our results

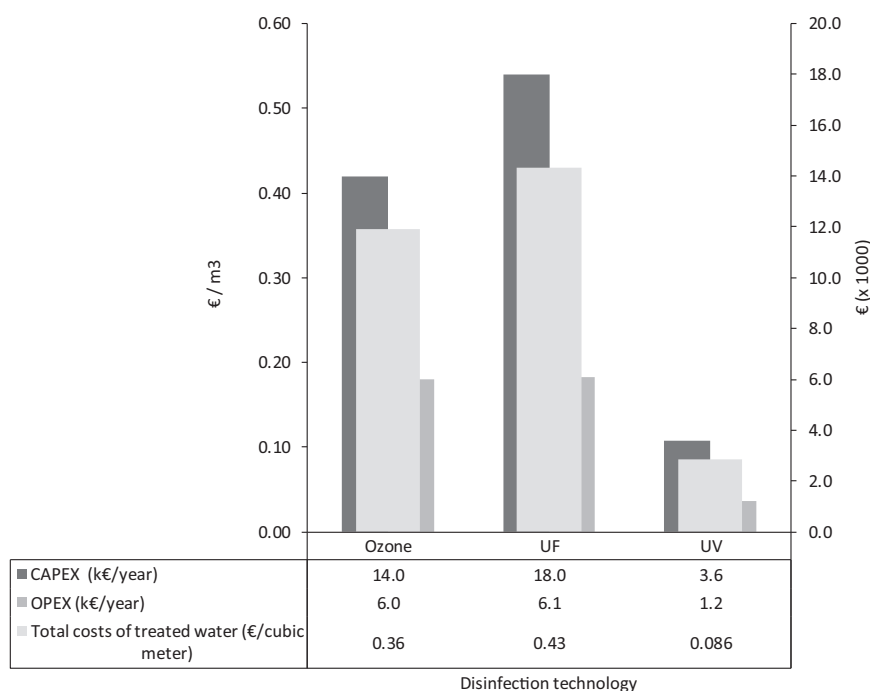
concur with previous research, which reported the disinfection efficacy of UF to range from 5.5 to 6 log for *E. coli* and fecal coliforms (Collivignarelli et al., 2018).

The COD and TOC of the surface water before disinfection treatments were 26 mg/L and 10 mg/L, respectively. After disinfection, the COD of the surface water was above the upper limit of quantification (150 mg/L), while the TOC was determined to be 351 mg/L. These results showed that the COD and TOC increased after the installation of a new filter, which was not expected and was probably caused by the release of glycerin (c.a. 20%) from the newly installed filter. This increase may be avoided if the filter is flushed before use. The possibility of an increased TOC and COD due to the installation of a new filter is relevant to realize for on-site field applications. Moreover, with UF, it is important to prevent the possibility of membrane fouling, as this may then result in increased operating costs to either clean or replace the membrane or can negatively affect the quality of the water to be treated.

### 3.1.3. Ultraviolet irradiation

Results for surface water treated with UV applied in a dose ranging from 363 to 545 J/m<sup>2</sup> showed that the reduction varied between about 2 and 3 log (Fig. 3c). In the tap water, a 2–3 log reduction of *E. coli* was also observed given UV doses of 313–500 J/m<sup>2</sup> (data not shown). The COD of the surface water before and after UV disinfection was, respectively, 40.8 mg/L and 40.6 mg/L. Stable COD values were expected, as UV photolysis can only reduce some organic compounds. TOC was not analyzed.

Our results concur with previous research, which reported the disinfection efficacy of UV to range from 2 to 4 log for *E. coli* and bacterial pathogens (Collivignarelli et al., 2018). Even though higher UV doses were applied to treat the surface water, there were minimal differences observed in the *E. coli* log reductions compared to that in tap water. This result can be expected since the COD and TOC levels in surface water were higher than in tap water. Suspended soils and organic matter in the water are known to reduce UV transmittance (Van Haute et al., 2015). The results of our study showed that with the doses tested, UV alone (up to 545 J/m<sup>2</sup>) was the least effective singly applied



**Fig. 4.** Cost estimation for annual capital expenditure (CAPEX), annual operating expenditure (OPEX), and total costs of treated water per cubic meter for ozone, ultrafiltration (UF), and ultraviolet (UV) disinfection technologies. The total amount of water treated is estimated at 56,000 m<sup>3</sup>/year for all technologies. For annual investment costs, under CAPEX, a 5-year linear depreciation time and no effects of interests are assumed.

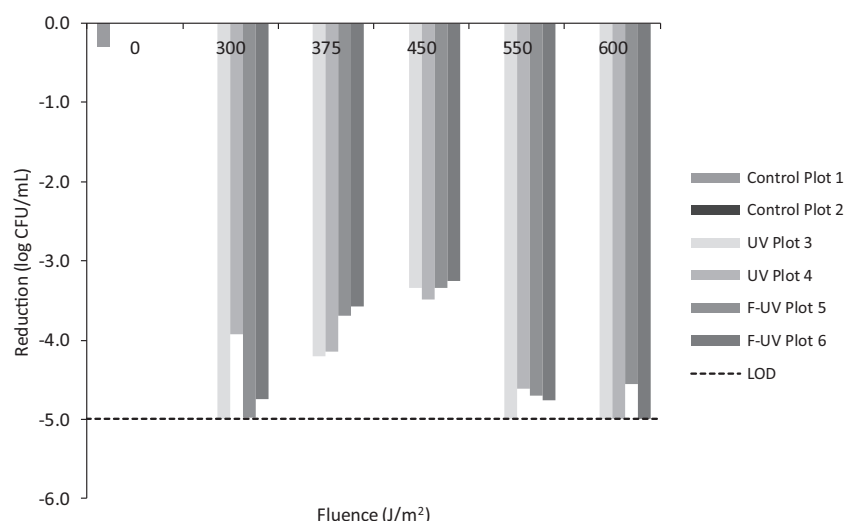


Fig. 5. Inactivation of *Escherichia coli* in irrigation water during the field trial given varying fluence of ultraviolet (UV) and pre-filtration and UV (F-UV). —, the limit of detection (LOD).

technology in reducing *E. coli* in the tap and surface water.

### 3.1.4. Combined technologies

Results for (i) UF and ozone (doses 2.0–10.6 mg/l) in tap water showed a reduction of *E. coli* to below the LOD ( $> 4.8$  log), while in surface water (with doses 4.1–16.9 mg/L) the reduction was also to below the LOD ( $> 4.5$  log). Results with (ii) UV and ozone in tap water showed a reduction of *E. coli* to below the LOD ( $> 4.7$  log) given UV doses of 119–476 J/m<sup>2</sup> and ozone doses of 2.8–11.4 mg/L. In surface water, *E. coli* reduction ranged between about 3 log and to below the LOD ( $> 4.5$  log) depending on the dose applied (Fig. 3d). Results for (iii) UF and UV disinfection in tap water with UV doses of 299–478 J/m<sup>2</sup> showed a reduction of *E. coli* to below the LOD ( $> 4.6$  log), while in surface water (with UV doses of 367 J/m<sup>2</sup> and 489 J/m<sup>2</sup>) the reduction of *E. coli* was also to below the LOD ( $> 4.4$  log). Finally, for (iv) UF, UV, and ozone disinfection, there was a reduction of *E. coli* to below the LOD of 4.7 and 4.5 log, respectively, for tap and surface water. The doses in the tap water of UV were 122–365 J/m<sup>2</sup> and of ozone were 2.8–8.6 mg/L. The doses in surface water of UV were 235–470 J/m<sup>2</sup> and of ozone were 5.1–10.5 mg/L.

The COD and/or TOC were also analyzed for four combinations of water disinfection treatments. After treatments, the COD ranged from 37.4 to 49.3 mg/L, while the TOC ranged from 14.3 to 19.2 mg/L. The TOC was not analyzed for treatment (iii) UF and UV.

Overall, when the four sets of combined technologies were tested in tap and surface water — (i) UF and ozone, (ii) UV and ozone, (iii) UF and UV, and (iv) UF, UV, and ozone — *E. coli* was reduced to below the LOD in all cases ( $> 4$  log). Our lab study investigated UV disinfection given a one lamp application. However, other studies have shown the increased

effectivity in microbial reductions given higher doses, e.g., from the use of additional lamps, longer treatment times, and/or in the case of combined technologies. When UV was combined with ozone (ii), this also increased the microbial efficiency. Research on the use of UV and ozone disinfection technologies, singly and in combination, in ultrapure and tap water has shown that co-exposure to these disinfection technologies enhanced *E. coli* inactivation (Fang et al., 2014). The longer the treatment dose and contact time, the higher the *E. coli* reduction. This result concurs with our study, which found that with (ii) UV and ozone treatment, a  $> 4$  log reduction of *E. coli*, given the applied doses, was found in tap and surface water. Besides this, the type of water to be treated can influence the efficacy of some technologies. This influence was observed during the combination of (ii) UV and ozone in surface water.

The other water disinfection technology combinations that were tested all included the use of UF. UF alone was observed to inactivate *E. coli* in the tested waters. Thus, the additional effect of UF in combination with other technologies, could not be differentiated. However, previous research has reported a 7.5 log reduction of *E. coli* given ozonation-membrane (ultra-) filtration using iron oxide-coated membranes (Karnik et al., 2007). Besides this inactivation, using filtration and ozone has been reported to offer advantages such as a low level of membrane fouling given minimal ozone concentrations (Schlichter et al., 2004). From the literature, other disinfection combinations, namely coagulation before low-dose ozone and UF treatments of contaminated surface water, were performed to mitigate membrane fouling (Yu et al., 2016). Therefore, besides microbial activation, the use of combined technologies can provide other advantages such as preventing membrane fouling or the possibility to use lower doses of ozone. Overall, research that evaluated the disinfection efficacy of multiple combinations of disinfection technologies on irrigation water is limited, and therefore, our results help remedy this data gap.

### 3.2. Cost calculation model

The cost calculation model provided a cost estimate for each of the singly applied technologies — ozone, UF, and UV — when used to treat irrigation water at the field scale. Results showed that for this application, UV had the lowest costs per m<sup>3</sup> of water treated at 0.09 €/m<sup>3</sup>, followed by ozone at 0.36 €/m<sup>3</sup> and UF at 0.43 €/m<sup>3</sup> (Fig. 4).

Previous research has shown that cost is a relevant managerial criterion when considering water disinfection technologies to be implemented for water disinfection during irrigation (Dandie et al., 2019; Van

**Table 2**  
APCs, TCCs, and ECCs for lettuce and endive harvested after field trials with control, UV, and F-UV water disinfection treatments<sup>a</sup>.

Crop	Treatment	Mean $\pm$ SD (log CFU/g) (n = 3)		
		APC	TCC	ECC
Lettuce	Control	4.75 $\pm$ 0.73	3.72 $\pm$ 0.97	$< 1$
	UV	6.11 $\pm$ 0.26	4.29 $\pm$ 1.34	$\leq 1$
	F-UV	5.69 $\pm$ 0.81	4.10 $\pm$ 0.86	$< 1$
Endive	Control	6.52 $\pm$ 1.47	4.73 $\pm$ 2.17	$< 1$
	UV	5.57 $\pm$ 0.73	3.97 $\pm$ 0.68	$< 1$
	F-UV	5.84 $\pm$ 0.32	3.55 $\pm$ 0.78	$\leq 1.65$

<sup>a</sup> APC, aerobic plate count; TCC, total coliform count; ECC, *E. coli* count; UV, Ultraviolet irradiation; F-UV, pre-filtration and UV.



Haute et al., 2015). Since using water disinfection technologies for open-field irrigation is currently not yet state of the art, and the costs of water disinfection technologies are limited, an evaluation can be made to other, comparable applications. An example of this is the disinfection of irrigation water for horticultural greenhouse applications. A recent report evaluated the costs for UV disinfection, which ranged from 0.1 to 0.47 €/m<sup>3</sup> for comparable volumes (11,100–110,000 m<sup>3</sup>/ha/year). For disinfection using microfiltration or ultrafiltration technologies, the average operating costs were estimated to be 0.1–0.15 €/m<sup>3</sup> of produced permeate (Thompson et al., 2018).

Our study is novel in that it evaluates the costs for three water disinfection technologies for use in agricultural water, also showing the differences in CAPEX and OPEX. Also, the scale and mobility of the technologies are considered for a field application. It is essential to realize that there may be further effects on like the economic depreciation in comparison to the technical life span of the equipment, which had not been implemented in this model and hence is a limitation of the model. Moreover, it is important to realize that the effects of total costs were partly due to energy costs (as calculated in the OPEX). In the agricultural sector, the use of renewable energy sources has a large potential (Chel and Kaushik, 2011) and is more often being implemented. Given an increased use of renewable energy, the final costs calculated could then change. Nonetheless, the current model allows for a comparison of costs when assessing and selecting the most feasible technologies to be applied at the field scale.

### 3.3. Field trial

A combination of the microbial efficacy observed with UV treated surface water (> 3 log reduction of *E. coli*) along with the low costs for UV, prompted further research in a field trial. During the field trial, UV was evaluated with and without pre-filtration. A post-calculation based on the executed field trial and given the model assumptions demonstrated that the total expected costs for water treatment by UV for an 80 m<sup>3</sup>/h situation with 300 J/m<sup>2</sup> UV dose are about 0.052 €/m<sup>3</sup> water, with costs ranging from € 0.039 to € 0.065 given a 45–65% UV transmittance.

Testing UV in the field trial showed that UV treatment of the irrigation water was capable of inactivating > 3 log CFU/mL of *E. coli* in the water irrespective of pre-filtration (Fig. 5). There was no clear UV dose-effect detected in the field trial, given the UV doses tested. The COD and TOC of the irrigation water before inoculum and treatments were also analyzed during weeks 1, 3, and 5. During week 1, COD was 26–28 mg/L, and TOC was 9.8–10 mg/L, while during week 3, COD was about 32 mg/L, and TOC was 10–51 mg/L. Finally, during week 5, COD was 31–35 mg/L, and TOC was 11–78 mg/L. Overall, COD appeared stable during cultivation, while TOC had a wider variation. During cultivation, there is a slight dip in the log reduction observed at 450 J/m<sup>2</sup> (week 3). A reason for the variation in microbial efficacy may be because before the water was collected and transported to the field site for week 3, sandbags lining the canal had been removed, resulting in water with higher turbidity and increased suspended solids. Suspended solids and organic matter affect UV transmittance (Van Haute et al., 2015), and the microbial effectivity of the technology is limited by turbid water (Dandie et al., 2019). In the field trial, we corrected for the transmission of the water; however, particulate can influence UV, the amount of which can vary depending on the water source, and if too high, then extra costs would be needed to be able to pre-treat before UV disinfection. Crops were analyzed for sensory aspects before harvest. According to the Karlsruher Evaluation Scheme, lettuce for the aspect “color” scored satisfactory (6) regardless of the treatment. For lettuce that was treated with irrigation water disinfected by F-UV, the aspect “shape” scored excellent (9), while the lettuce from the control and UV treated irrigation water scored very good (8). All lettuce, regardless of the treatment, scored excellent (9) for the aspect “odor” and very good (8) for the aspect “texture/consistency.” The quality classification of the endive

was lower than that for lettuce concerning the aspect “appearance” (color and shape). Endive irrigated with water treated with UV scored mediocre (5) for the aspect “color,” while control (untreated) endive and endive with water treated with F-UV scored poor (3). Concerning the aspect “shape,” the endive irrigated with water treated with by F-UV scored borderline (4), while control (untreated) endive and endive with water treated with UV scored bad (2). Nevertheless, the scores for the aspects “odor” and “texture” for all the endive samples scored excellent (9). In addition to the sensory aspects, the weights of the crops were measured after harvest and ranged from 146 to 507 g for lettuce and 185 to 843 g for endive. Overall, the expert reported that disinfection technologies did not negatively affect the sensory quality of the crops.

Lettuce and endive were analyzed (n = 3) for microbiological loads after harvest. The mean (± standard deviation) of the aerobic plate counts (APCs), total coliform counts (TCCs), and *E. coli* counts (ECC) for control (untreated surface water), UV, and F-UV treatments were examined (Table 2). APCs for leafy greens in this study ranged from 4.8 to 6.5 log CFU/g, which is similar to that found in leafy greens reported by Johnston et al. (2005) of 4.5–6.2 log CFU/g. APCs are used as a quality indicator. Our results for TCCs ranged from 3.6 to 4.3 log CFU/g. The TCCs in crops irrigated with treated water were comparable to the TCCs in the control treatment. Coliforms are often used as a hygiene indicator. Our values are slightly higher than other studies reporting coliforms on leafy greens and lettuce of 2.0–4.0 log MPN/g (Mukherjee et al., 2004) and on several types of leafy greens of 1.0–3.4 log CFU/g (Johnston et al., 2005). Results for ECC showed ≤ 1 log CFU/g for both crops, except for endive when irrigation water had been treated with F-UV, which had ≤ 1.65 log CFU/g (Table 2). For *E. coli*, there are EU legal limits available for pre-cut vegetables (ready-to-eat) taken during the manufacturing process. Given a sampling plan of n = 5 (where n is the “number of units comprising the sample”) and c = 2 (where c is the “number of sample units between m and M”), the limits, which refer to each sample unit tested, are m = 100 CFU/g and M = 1000 CFU/g (European Commission, 2005). Results are considered unsatisfactory “if one or more of the values observed are > M or more than c/n values are between m and M” (European Commission, 2005). For irrigation water, EU guidelines for *E. coli* in irrigation water indicate levels between 1000 and 10,000 CFU/100 mL. For vegetables that are likely to be eaten uncooked and where the irrigation water comes into direct contact with the edible portions of the vegetable, then the guideline for *E. coli* in irrigation water is 100 CFU/100 mL (European Commission, 2017).

The results in the field trial showed that the application of UV or F-UV are promising technologies to disinfect irrigation water for agriculture. However, once the water has been disinfected with physical methods, such as UV or F-UV, it is susceptible to re-contamination if not used directly since a residual effect from the disinfection technology is not available. The use of filters may also cause additional stress on the technology if proper maintenance is not followed and biofilms form. Therefore, the set-up and application of UV disinfection should be designed to avoid potential re-contamination.

Overall, UV disinfection of the irrigation water is a promising technology to disinfect alternative irrigation water sources like surface water. The use of this technology to treat recycled irrigation water and support the circular economy concept in food systems should be carefully evaluated. The outcomes of this research are also of relevance to upcoming EU regulations on the minimum requirements for the quality of (reused) water for agricultural irrigation. It is expected that a water disinfection technology would be needed to ensure the minimum requirements for microbiological safety.

## 4. Conclusions

The laboratory study performed showed that the tested doses of UV disinfection (313–545 J/m<sup>2</sup>) resulted in a 2–3 log reduction of *E. coli* in both tap and surface water, while other disinfection technologies showed *E. coli* reductions from 3 to > 4 log. The study also considered



the differences in CAPEX and OPEX for ozone, UF, and UV. UV resulted in the lowest costs per m<sup>3</sup> of water. Even though ozone and UF reduced *E. coli* in surface water, they were calculated to be less cost-effective than UV, which motivated the evaluation of UV in the field trial. Furthermore, the study showed that the application of UV in the field is feasible, and UV water disinfection is an effective technology against bacterial foodborne microorganisms like *E. coli* to treat surface water used for irrigating leafy greens. Overall, the study describes, for the first time, the efficacy of using several combinations of water disinfection technologies to treat irrigation water as well as the economics of water disinfection technologies ozone, UF, and UV. The results showed that the most suitable technology for the disinfection of surface water used to irrigate leafy greens was UV.

UV can be used to treat surface water intended to irrigate leafy greens if care is taken to prevent any re-contamination of already treated water and if the doses are adjusted to the type of the irrigation water to be treated. Further research into the technical feasibility of the water disinfection technologies implemented on-site at the full scale, including for promising cases like UV water disinfection, needs to be further piloted and substantiated with business cases.

### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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### Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.agwat.2020.106527](https://doi.org/10.1016/j.agwat.2020.106527).

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