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Continuous Injection of Hydrogen Peroxide in Drip Irrigation—Application to Field Crops

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Abstract: Drip irrigation offers greater water use efficiency than conventional furrow irrigation practises, though routine maintenance is required for optimal performance. The continuous use of low concentrations (10 ppm) of H_2O_2 stabilized with hydroxyethylidene diphosphonic acid (HEDP) at two concentrations (H_2O_2 $_{Low}$ containing 1 ppb and H_2O_2 $_{High}$ containing 1 ppm of HEDP) in drip irrigation was evaluated in terms of emitter, crop and yield performance across three crop species. Emitter flow rates (EFRs) for subsurface drip in sugarcane were higher by 16% and root intrusion into emitters was almost halved with H_2O_2 $_{Low}$. For above-ground suspended drip lines with table grape, blockage of emitters due to biofouling was reduced by 50% in H_2O_2 $_{Low}$ compared to the control or H_2O_2 $_{High}$ within the second year of use, and the extent of emitters with visible biofouling was reduced even more. Soil microbiology did not differ markedly between treatments in any of the crops, even over four years of use. However, soil microbial carbon and soil carbon were reduced by H_2O_2 $_{Low}$ in the sugarcane trial. Yield increases of 9, 25, and 49% occurred in chilli, table grape, and sugarcane, respectively, for the continuous H_2O_2 $_{Low}$ treatment compared to the control. The yield increases with H_2O_2 $_{Low}$ could be associated with increased uniformity in water supply and/or oxygen supply to plant roots.

Keywords: soil aeration; root intrusion; yield

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1. Introduction

Drip and subsurface drip irrigation (SDI) enhance water use efficiency by minimizing evaporation, leaching and run-off, and suppression of weeds by maintaining a dry soil surface and by accelerated plant growth. However, maintenance issues associated with drip irrigation often result in high variation in emitter performance due to emitter clogging caused by biotic factors such as root intrusion and biofouling, and abiotic factors such as mineral scale formation within the emitters. Drip operators commonly use chemicals such as acids and chlorine to relieve emitter clogging due to chemical and microbial causes, respectively. Intermittent flushing (2–3 times per year) of irrigation lines with 15–50 ppm sodium hypochlorite (12.5% w/v chlorine) for a period of 12–24 h or with strong acids (e.g., hydrochloric, nitric, sulfuric) at a pH of 2–4 for 15–20 min is a common practise to reduce root intrusion and biofouling [1]. However, these products are environmentally unfriendly and are potential risks to human operators.

The type of irrigation system is also relevant to cleaning requirement. Emitters in the surface and subsurface drip lines are installed face up, and thus the cleaning solution is held in the drip line without draining during the treatment period. Emitters in suspended

drip lines (such as are used for grapes) are typically installed either face down or face sideways, allowing these systems to drain during the treatment period.

Hydrogen peroxide is a potential alternative for cleaning irrigation lines. It is relatively stable in the absence of catalysts; however, decomposition to water and oxygen is rapid in the presence of certain metal catalysts or enzymes. In the presence of metal catalysts, such as manganese or iron, the decomposition of hydrogen peroxide occurs via a Fenton-type reaction, releasing not only water and oxygen but also hydroxyl radicals (•OH). Hydroxyl radicals are strong oxidants that are so highly reactive that their typical life is only nanoseconds within the environment. It has been referred to as the 'detergent of the atmosphere', e.g., reacting with methane and volatile organic compounds, and plays a role in soil chemistry through rock weathering and organic matter breakdown. It is used industrially for its disinfection properties. Hydroxyl radicals will react with organic compounds causing emitter blockage but are also toxic to soil micro-organisms [2].

The enzyme peroxidase of hydrogen peroxide catalyzes a rapid decomposition of hydrogen peroxide with oxidation of reduced hydrogen donor organic and inorganic substrates but without the release of oxygen [3]. Organic matter in irrigation lines or soil can act as the hydrogen donor. However, the contribution of these enzymatic pathways to the decomposition of H_2O_2 in the soil is considered to be much less important than the contributions of metal oxides [4].

Hydrogen peroxide (H_2O_2) can be added to drip irrigation water for the control of biofouling and to effectively assist in cleaning scale formed at drip emitters, e.g., as documented by Tachikawa and Yamanaka for the disinfection of biofilm [5] and in a study involving irrigation with treated wastewater [6]. Hydrogen peroxide is in commercial use for maintenance cleaning of emitters, with recommended use through continuous injection of low concentrations (<50 ppm) of H_2O_2 or selective injection (intermittent–daily, weekly, monthly as per need) of medium concentrations (50–100 ppm) during the last hour of each irrigation, or annual maintenance injection of high concentrations (200–500 ppm) at the end of an irrigation cycle [7]. Commercially available H_2O_2 contains chelants and sequestrants (stabilizers) to minimize its decomposition under normal storage, handling and application conditions.

Common commercial stabilizers include colloidal stannate and sodium pyrophosphate [8], organophosphates and phosphoric acid [9,10]. H_2O_2 stabilizers such as those mentioned and acetic acid, 1-hydroxyethylididene-1, 1-diphosphonic acid (HEDP), ethylenediaminetetraacetic acid (EDTA) [11] and tartaric acid [12] retard H_2O_2 decomposition by Fenton and Fenton-like reactions. HEDP is a phosphonate compound formed by a reaction between acetic acid and phosphonic acid (PA). It is used as an inhibitor of scale and corrosion in commercial water treatment systems, with concentrations >1 ppm effective in preventing Ca scale [13].

The release of H_2O_2 from emitters into the soil during irrigation line treatments may have several consequences. It may decompose soil organic matter, impacting soil structure and soil microbiology [14]. The decomposition of HEDP can yield ethylene, a potent plant hormone [15]. In addition, PA and the phosphite salts of PA are effective per se for control of oomycetes *Phytophthora* and *Pythium*, marketed in Australia under names such as 'Yates Anti-rot' [16]) and 'Country Phospot 600′ [17]. Further, the decomposition of H_2O_2 can deliver significant levels of oxygen to plant root systems in soil saturated and purged of air during and after irrigation, resulting in improved crop yields [18–20]. Upon decomposition, each litre of pure H_2O_2 will produce approximately 1000 L of pure oxygen gas at standard temperature and pressure (STP), equivalent to the oxygen content of 4785 L of air.

While the use of H_2O_2 in irrigation water for pipe and dripper cleaning and as an oxygen source is promising, there is a need for further documentation in field conditions, in

the context of both the impact of H_2O_2 on organic materials, potentially preventing biofoul induced clogging of drippers, and the potential for HEDP to reduce scale formation and associated clogging of drippers. Field trials were undertaken for three crops involving irrigation with continuous use of a low concentration (10 ppm) of H_2O_2 with HEDP at either 1 ppm or 1 ppb, resulting from injection of two stock solutions containing 30% *w*/*w* H_2O_2 and either 30 or 30,000 ppm *w*/*v* HEDP. The concentration of H_2O_2 (10 ppm) was recommended in a prior study, which documented higher concentrations to be injurious to root hair development and lower concentrations (c. 2 ppm) to be rapidly broken down by catalysts, such as iron, manganese and hydrogen sulphide present in irrigation water [21].

Work was undertaken to evaluate the use of stabilized H_2O_2 in irrigation water to improve crop yield, through either cleaning of drip lines or increased dissolved oxygen (DO) of irrigation water, with consideration of a negative impact on soil microbiota or soil organic matter levels. Three drip irrigation scenarios involving drip irrigation that are in common use were considered: (i) a surface drip line, used on an annual horticultural crop, chilli; (ii) an above-ground drip line, used on a perennial horticultural crop, table grape; and (iii) a subsurface drip irrigation, used in a high value broadacre crop, sugarcane. The effects of treatments were documented in terms of drip emitter flow rate, blockage and uniformity, and soil and crop parameters.

2. Materials and Methods

2.1. Treatments

Trial amounts of H_2O_2 with two levels of HEDP stabilizer were supplied by the Morrinsville, New Zealand, production plant of Evonik Resource Efficiency GmbH (Essen, Germany).

The following treatments were employed at each of three sites:

T1—no H_2O_2 injection in irrigation—control treatment,

T2—continuous injection of $H_2O_{2\,Low}$ (30% *w*/*w* H_2O_2 with 30 ppm HEDP) into irrigation water to achieve 1 ppb H_2O_2—$H_2O_{2\,Low}$ treatment,

T3—continuous injection of $H_2O_{2\,High}$ (30% *w*/*w* H_2O_2 with 30,000 ppm of HEDP) to achieve 1 ppm H_2O_2—$H_2O_{2\,High}$ treatment.

2.2. Soil Analysis

Soil samples for each site were assessed for moisture (gravimetric method, following oven dry at 105 °C), EC and pH (1:5 soil to distilled water method), soil respiration using EGM-4 (PP Systems, Amesbury, MA, USA) following the methods by Nilahyane et al. [22], soil microbial diversity using the Fluorescein Diacetate Assay (FDA) following the methods by Schnurer and Rosswall [23], soil microbial carbon biomass following the microBIOMETER (USA) protocol which follows the methods by Fitzpatrick et al. [24], and total carbon and nitrogen following using a LECO combustion analyser following the methods by Conyers et al. [25], with the proviso that significant differences in soil organic carbon can arise depending on the sampling approach.

2.3. Surface Drip Tape Irrigation—for Chilli (Capsicum annum L.)

2.3.1. Location, Soil, Crop and Weather Description

The trial was conducted at Austchilli Pty Ltd., Douglas Road, Bundaberg, QLD 4670 (24.931012° S, 152.387825° E) Australia (Supplementary Material S1) during the 2016 winter season on brown ferrosol soil. Weather data were collected from a Bureau of Meteorology weather station within a 10 km line of sight distance. The daily minimum temperature ranged from 6 to 24 °C and maximum from 20 to 37 °C during the cool growing season of June–December (Supplementary Material S2). The weather during the crop trial period

followed the long-term average climate pattern for Bundaberg. Total rainfall during the crop season was 382 mm. The site comprised one paddock, measuring ~600 m × 18 m, with 12 rows, with monitoring of crop and soil confined to nine central rows. Seedlings (30 days old) of the hot chilli variety 'Hong Kong' were transplanted on 23 June 2016, and H_2O_2 injection commenced on 29 July 2016, until the final harvest, for the duration of 102 days.

2.3.2. Irrigation Setup, H_2O_2 Treatment and Sampling Plan

Drip T-tape of 16 mm diameter and emitter spacing of 30 cm (Rivulis 512-30-340, model 101001738; https://www.rivulis.com/product/drip-tapes-drip-lines/t-tape-drip-tape/, (accessed on 18 January 2025) from Toro Ag, Beverley, South Australia) was installed about 5 cm below ground. The tape was operated at pressure of c. 70 kPa with a nominal pressure compensated emitter flow rate of 1.0 L h^{-1}. The crop was irrigated with ~6 ML ha^{-1}. This required 200 L ha^{-1} of each of the two products trialled to achieve 10 ppm H_2O_2 in the irrigation water.

Injection of H_2O_2 into the irrigation line was performed using a DC battery-supported LMI Milroy dosing pump (LMI Pumps, Ivyland, PA, USA), installed in the field powered by a solar panel setup (Supplementary Material S2). Dosing pumps injected H_2O_2 to achieve 10 ppm into irrigation water in the sub-main irrigation lines for each individual treatment. Three Netafim lay-flat sub-mains ran perpendicular to the rows (Supplementary Materials S2) and split the nine rows to 18 equal-sized experimental units, with six replicates for each randomly allocated treatment following a Randomized Complete Block Design (RCBD). Water input measured with an onsite water meter was the same amount for each treatment and set by the controller as determined by the grower. The H_2O_2 injection volume was measured from the supply tank connected to the dosing pump.

Initial soil sampling prior to planting consisted of one composite soil sample (30 cm depth) per row. Final soil sampling carried out at crop harvest comprised samples (20, 70, 120 and 220 m from the sub-main) from each plot, combined from four sampling locations, with a total of 54 soil samples assessed as described in Section 2.2.

Soil samples (n = 18) were also collected from the row ends at the end of the final irrigation event and packed in 100 mL syringes to match the bulk density of soil in the field. An aliquot (20 mL) of 10 ppm $H_2O_{2\,Low}$ or $H_2O_{2\,High}$ solutions, according to the original treatment, was then added to each syringe, and leachate was collected immediately from the needle end of the syringe. The leachate was assessed for residual H_2O_2 concentration with test strips in a calibrated Macherey-Nagel H_2O_2 reader (Macherey-Nagel GmbH & Co., Dueren, Germany). A concentration of H_2O_2 below 0.5 ppm was considered 0.

H_2O_2 stability in the irrigation water was assessed by measuring H_2O_2 concentration in water sampled from the most distal location in the drip lines, using H_2O_2 test strips. Three samples were assessed at the beginning and at the end of the experiment.

2.3.3. Plant and Harvest Data Collection

Crop performance was assessed in terms of plant height, leaf chlorophyll concentration using a SPAD meter (Spectrum Technologies Inc, Aurora, IL, USA), days to flowering and first harvest, duration of harvest, and fruit and harvest yield. Whole-plot harvest data for each plot were collected by the Austchilli harvest crew, and the fruits were separated as green chilli suitable for fresh markets and red chilli for processing markets. Smaller sample plots (3 m^2), two per treatment, at the top, mid and bottom section of the plot, were also harvested for determination of dry matter partitioning of biomass and assessment of *Phytophthora* disease symptoms on roots.

2.3.4. Emitter Performance Data

Drip emitter performance was assessed following crop harvest in terms of emitter flow rate, Christiansen Coefficient of Uniformity (CUC) and % of emitters with no flow (due to clogging). A 2 m length of drip tape was taken at each of four sampling positions (20, 70, 120 and 220 m from the sub-main) for each of the 54 replicate sites. Flow rate was assessed in-field by the "catch-can test" method [26]. These 2 m length samples were then evaluated visually in an indoor setting for percentage blockage and percentage of emitters with some biofoul growth.

2.4. Above-Ground Drip Irrigation—for Table Grapes (Vitis vinifera L.)

2.4.1. Location, Soil, Crop and Weather Description

The field trial was conducted at Glenicy Grapes, Emerald, QLD (23.5867° S, 148.204072° E) Australia (Supplementary Material S1) from February 2016 to January 2020 in a vertisol soil. An existing planting of seven-year-old white table grapes at the start of the trial (variety Menindee Seedless) planted at 2.4 m within and 3.4 m between rows was used for the experiment.

Weather data were collected from a BOM weather station located within a 5 km line of sight. The daily minimum temperature ranged from 8.3 to 25.9 °C and maximum from 32.7 to 42.5 °C from bud burst in September until harvesting in November–December across four years. The weather during the trial period followed the long-term average climate pattern for this site. Total rainfall during the crop growing years from February 2016 to January 2020 was 2036 mm, with eight heavy rainfall events (>100 mm) recorded (Supplementary Material S3).

2.4.2. Irrigation Setup, H_2O_2 Treatment and Sampling Plan

Rows were individually irrigated using a 7-year-old above-ground UniRam^{TM} CNL 16,012 drip tube (Netafim, Australia). The system contained pressure-compensated emitters at 50 cm centres and was operated at a 2.3 L h^{-1} flow rate per emitter. Input water was filtered with an inline sand filter and volume measured using an onsite water meter. H_2O_2 injection volumes were measured from the supply tank connected to a dosing pump. Separate dosing pumps (EMEC-VCO-VACO, Apopka, FL, USA) with flow triggered switches were installed for inline injections of the two H_2O_2 products (Supplementary Material S3). Irrigation input was based on soil moisture deficit and crop water demand in the control treatment and set by the grower. Total irrigation inputs from 2016 to 2020 were between 8 and 12 ML ha^{-1} year^{-1} and averaged 10 ML ha^{-1} year^{-1}.

The three irrigation treatments were applied to the three irrigation blocks, respectively, with 14, 25 and 25 rows in each, with three randomly selected (but non-edge) rows in each irrigation block selected as three pseudo-replicates for each treatment. Each row contained c. 111 vines and was ~222 m in length. Treatments were maintained for four years.

Soil samples were collected within the wetting front at 20 cm from the emitters at the beginning of year 1 and end of experiment in year 4. At each sampling time, a core was collected from each of six randomly selected rows per treatment, resulting in eighteen samples across the three treatments. Cores were analyzed for soil moisture, pH, EC, respiration, carbon and nitrogen. Soil biological properties (FDA for microbial diversity, microbial biomass carbon) were assessed for the samples collected at the end of the trial. The methods used were the same as for the chilli trial.

2.4.3. Plant and Harvest Data Collection

The crop growth and reproductive traits of date of bud burst, flowering, berry setting, maturity and days to harvest were recorded from 12 randomly selected grape vines per

treatment. Leaf chlorophyll concentration was assessed using a SPAD unit, every 6 months, over the trial period. Marketable grapes for each row were hand-harvested by a skilled labourer, and weight was recorded in the field using a weighing scale mounted on a trolley.

2.4.4. Emitter Performance Data

The drip performance parameters were evaluated, as for the chilli crop, at c. 6-month intervals. The stability of H_2O_2 in the irrigation water and H_2O_2 decomposition in the soil (as for the chilli trial) were assessed c. 6-month intervals by sampling water from the drip line automatic flush valves at the end of individual rows (https://duralirrigation.com.au/products/dripline-automatic-flush-valves (accessed on 18 January 2025)) and from soil within the wetting fronts (three samples for each treatment, taken from the middle of the row during irrigation events).

Drip emitter performance was assessed using the "catch-can test" [23] twice a year over the crop period of four years. Emitter flow rate was measured at 10 sampling positions along the length of the drip tube in a given row, with assessment of tape in three rows per irrigation treatment. The operating pressure of irrigation was c. 55 kPa. Flow for each emitter was collected over a period of about 30 min. The CUC, blockage and biofoul were assessed as for the chilli crop.

2.5. Subsurface Drip Irrigation—for Sugarcane (Saccharum officinarum L.)

2.5.1. Location, Soil, Crop and Weather Description

A field trial was established in June 2016 in a sugarcane farm, at 275 Gropper Greek Road, Home Hill, Burdekin QLD 4806, North QLD 4806 (19.675261° S, 147.453212° E) Australia (Supplementary Material S1), one of the largest sugarcane production regions of Australia (Supplementary Material S4). The sugarcane crop (variety KKQ228) is often ratooned for 3–4 years (ratoon cane) after the planting of a new crop (plant cane). The experimental crop was planted in double rows in beds at 1.8 m centres on a deep black cracking clay soil (vertisol), a common soil type in the sugarcane growing area of the Burdekin.

Weather data were collected from a Bureau of Meteorology weather station located in Home Hill, QLD, within a 10 km line of sight distance. The mean daily minimum temperature ranged from 11.8 to 24.6 °C and maximum ranged from 25.3 to 35.3 °C during the trial period. The cooler weather occurred from drier May to August and hotter weather occurred in the wetter November–February months. Total rainfall for the 36 months trial was 2224 mm, with 10 rainfall events exceeding 100 mm, and 14 exceeding 50 mm. Summer precipitation dominated the distribution, as winter rainfall events were infrequent and small (Supplementary Material S4).

2.5.2. Irrigation Setup, H_2O_2 Treatment and Sampling Plan

Three separate irrigation blocks, each with an area of 2–3 ha ($H_2O_{2\,Low}$—2.84 ha, $H_2O_{2\,High}$—3.24 ha and control—3.24 ha) were used, with random assignment to the three irrigation treatments. UniRam^{TM} HCNL drip lines (inside diameter 14.2 mm, wall thickness 1 mm), containing pressure-compensated TurboNet emitters manufactured by Netafim (Laverton North, VIC, Australia), were laid 40 cm below ground for subsurface drip irrigation prior to planting (uniram-hcnl-technical-product-sheet.pdf (accessed on 18 January 2025)). The emitters were spaced at 50 cm and the emitter flow rate was 1.25 L h^{-1} per emitter. Irrigation occurred on average every three days during the dry season.

Irrigation input was based on soil moisture deficit and crop water demand in the control treatment as determined by the grower. Water inputs to each irrigation treatment were from an underground well and were measured by an on-site water meter. Annual irrigation input for the sugarcane crop was 6–8 ML ha^{-1} year^{-1}. H_2O_2 injection volumes were measured using a dosing pump. Two dosing pumps, similar to those in the above-

ground drip for the table grape site, were used for injection of $H_2O_{2\ Low}$ and $H_2O_{2\ High}$ into the water (Supplementary Material S4).

Soil cores were taken to the emitter depth of 40 cm at a point 15 m upstream from the end of the row at the end of the experiment in year 3. Cores were collected from six random rows per treatment, giving a total of 18 samples. Soil was analyzed as described in Section 2.2.

2.5.3. Plant and Harvest Data Collection

The crop growth parameters of stem number, plant height, leaf chlorophyll and biomass were assessed during each year. Measurements were performed within three random sampling areas of 15 × 0.9 m^2 per block. Leaf chlorophyll concentration was measured with 10 leaves per sampling location using a SPAD chlorophyll meter. Sugarcane yield (machine harvested) and sugar concentration (commercial cane sugar—CCS) data were collected from the mill receiving the product.

2.5.4. Emitter Performance Data

The operating pressure of the drip irrigation system was maintained between 55 and 70 kPa. Emitter performance was assessed once a year, from the drip line 15 m upstream in the row where soil samples were collected. A 2 m length of pipe was exposed, and emitter flow rate assessment was undertaken using the "catch-can method" over a period of about 30 min. Total flow rate for the block (a proxy for emitter blockage by root intrusion and biofoul) was determined using calibrated water meter readings over a one-hour period. The stability of H_2O_2 in the irrigation water and H_2O_2 decomposition in the soil was monitored as for the table grape trial. Emitter clogging by root intrusion was also assessed on 12 emitters per treatment at the end of the trial by inserting an endoscope camera equipped with a light source (REMS, Waiblingen, Germany) into the drip line, capturing images of root penetration into emitters.

2.6. Data Analysis

Water, crop, soil and components of yield and yield data from all three trials were analyzed using a one-way generalized ANOVA in Genstat 23 (VNSI, Hemel Hempstead, UK). A factorial ANOVA was also carried out for assessing the drip emitter performance (at three different sample locations along the length of the drip rows) in the chilli trial.

3. Results

3.1. Chilli with Surface Drip Tape Irrigation

3.1.1. Drip Emitter Performance

There were no visibly blocked emitters or root intrusions in the drip tape within the first six months of drip irrigation. In-season assessments of emitter flow rate (EFR) ranged from 1.003 to 1.198 L h^{-1} across treatments, with no significant differences between treatments (Table 1) and little different to the manufacturer's specification (1.1 L h^{-1}) for this operating pressure. The CUC of the emitter flow rate ranged from 83 to 86%, with that of both H_2O_2 treatments being marginally, but significantly, greater than the control. At harvest, the soil moisture content in the wetting front zone was significantly higher for the control compared to $H_2O_{2\ Low}$ and $H_2O_{2\ High}$ treatments (Table 1).

The EFR along the length of drip tape after the crop season ranged from 0.870 to 1.214 L h^{-1} (Table 2) with lower EFR, as expected with pressure drop, in the distant positions from the sub-main irrespective of treatment. The emitter flow rate averaged across the tape length did not differ between treatments.

Table 1. In situ emitter flow rate (EFR) and Christiansen Coefficient of Uniformity (CUC) of tape installed in a chilli crop for six months, assessed at 70 kPa immediately before harvest. Soil moisture content assessed at the same time.

Treatment *	EFR Field (L h^{-1})	CUC Field (%)	Soil Moisture (%)
Control	1.198	83.0	14.0
H_2O_2 Low	1.111	86.0	11.7
H_2O_2 High	1.003	85.0	10.8
LSD 5%	0.346	1.76	1.64

* Control = irrigation with water; $H_2O_{2\,Low}$ = irrigation with water plus 10 ppm H_2O_2 plus 1 ppb HEDP; $H_2O_{2\,High}$ = irrigation with water plus 10 ppm H_2O_2 plus 1 ppm HEDP.

Table 2. In situ emitter flow rate (L h^{-1}) at positions along the length of drip tape, with or without H_2O_2 treatment, assessed following six months of use and after harvest of the chilli crop. Positive values for row position refer to positions downstream from the sub-mains (see Supplementary Material S2), while negative values are upstream.

Row Position	Control	H_2O_2 Low	H_2O_2 High	Mean
+120 m	1.195	1.131	1.148	1.161
+70 m	1.146	1.098	1.106	1.119
+20 m	1.214	1.025	0.929	1.060
−20 m	1.076	0.995	1.060	1.050
−120 m	0.972	0.908	0.882	0.923
−220 m	0.979	0.870	0.895	0.920
Mean	1.097	1.005	1.003	1.039
p value	Treatment = 0.003 ***, Position $\leq$ 0.001 ***, Trt × Position = 0.124 ^{ns}			
LSD (28 df)	Treatment = 0.086, Position = 0.122, Trt × Position = 0.211			

Treatments as defined in Table 1. *** significant at 0.1%, ** significant at 1%, * significant at 5%, ^{ns} non-significant.

3.1.2. Peroxide Levels

The irrigation water was dosed to contain 10 ppm H_2O_2. This concentration was maintained in the $H_2O_{2\,High}$ treatment at all sampling locations (average = 11 ppm), whereas in the $H_2O_{2\,Low}$ treatment, a decline in H_2O_2 concentration with distance to sampling point was observed, with the concentration average across the sampling locations being <2 ppm (Table 3).

Table 3. Concentration of H_2O_2 (ppm) in water from drip lines in a chilli crop at distances of 120, 70 and 20 m downstream and 20, 120 and 220 m upstream of the sub-mains.

Replicate	Treatment	Position						
		+120 m	+70 m	+20 m	−20 m	−120 m	−220 m	Average
1	Control	Nil	Nil	Nil	Nil	Nil	Nil	Nil
2	Control	Nil	Nil	Nil	Nil	Nil	Nil	Nil
3	Control	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1	$H_2O_{2\,Low}$	2.3	0.5	3	1.5	1.4	0.6	1.5
2	$H_2O_{2\,Low}$	0.5	0.5	5.4	5.8	1.9	0.5	2.4
3	$H_2O_{2\,Low}$	NA	NA	NA	NA	NA	NA	NA
1	$H_2O_{2\,High}$	13.8	8.4	15.1	9.6	11.4	9	11.2
2	$H_2O_{2\,High}$	11.2	7	14	12.1	11.7	12.1	11.4
3	$H_2O_{2\,High}$	11.2	8.7	12.6	10.5	11.6	12.1	11.1

Treatments as defined in Table 1.

3.1.3. Yield

The total green chilli yield and gross chilli fruit yield was significantly higher for both $H_2O_{2\ Low}$ and $H_2O_{2\ High}$ compared to the control (Table 4). Similarly, the manual-pick marketable yield of green chilli fruit increased by 14% and 5.6% for the $H_2O_{2\ Low}$ and $H_2O_{2\ High}$ treatments, respectively, compared to the control (Table 4). Red chilli fruit yield was not significantly different between treatments (Table 4). Above-ground plant biomass (fruits removed) and root weights also did not differ between treatments (Table 4).

Table 4. Green fruit yield, red fruit yield, above-ground biomass yield (fruits removed) and root weight per plant after the chilli harvest for different H2O2 treatments of chilli crop.

Treatment	Green Total (t ha^{-1})	Green Marketable (t ha^{-1})	Red Total (t ha^{-1})	Gross Yield (t ha^{-1})	Red Marketable (t ha^{-1})	Biomass Yield (g Plant^{-1})	Root Weight (g Plant^{-1})
Control	24.34	23.77	26.25	50.59	24.84	95.6	25.2
$H_2O_{2\ Low}$	28.29	27.16	28.26	56.55	25.72	105.8	25.2
$H_2O_{2\ High}$	28.03	25.12	26.78	54.81	24.08	88.2	23.4
p value	0.011 ***	0.001 ***	0.129 ^{ns}	0.007 ***	0.241 ^{ns}	0.21 ^{ns}	0.983 ^{ns}
LSD (16 df)	2.803	1.516	2.033	3.69	1.946	20.24	7.11

Treatments as defined in Table 1. *** significant at 0.1%, ^{ns} non-significant.

3.1.4. Soil Processes

Soil pH, electrical conductivity (EC) and FDA did not significantly differ between the treatments after six months of treatment (Table 5). Soil respiration was significantly different between treatments, in the ascending order of control, $H_2O_{2\ High}$ and $H_2O_{2\ Low}$ (Table 5).

Table 5. Soil pH, EC, Fluorescein, soil carbon, microbial biomass carbon, total soil N, total soil C and soil respiration from chilli soil irrigated with hydrogen peroxide-treated irrigation water.

Treatments	Soil pH (1:5)	EC (µS m^{-1})	Fluorescein Diacetate (µg Fluorescein/g Soil^{-1}/h^{-1})	Microbial Biomass Carbon (mg C kg Dry Soil^{-1})	Total Soil N (%)	Total Soil C (%)	Respiration (g CO_2 m^{-2} h^{-1})
Control	7.32	90.20	476.43	47.99	0.035	0.88	0.032
$H_2O_{2\ Low}$	7.21	87.91	442.59	51.33	0.031	0.88	0.057
$H_2O_{2\ High}$	7.36	79.61	427.58	47.18	0.033	0.84	0.036
p value	0.148	0.323	0.337	0.607	0.667	0.236	0.032
LSD	0.157	15.160	69.500	9.190	0.008	0.052	0.015

Treatments as defined in Table 1.

3.2. Grape with Above-Ground Drip Irrigation

3.2.1. Drip Emitter Performance

Emitter flow rate (EFR), measured in the field in each of four years, averaged 2.32 L h^{-1} (Table 6). A significantly higher EFR was recorded for the $H_2O_{2\ Low}$ treatment compared to the control and $H_2O_{2\ High}$ treatments.

Both blockage and biofouling were significantly reduced by H_2O_2 treatments (Table 6).

Table 6. Average emitter flow rate for six occasions (EFR, L h^{-1}), percentage of emitters with complete blockage, percentage with some biofoul, Christian Uniformity Coefficient (CUC) and H_2O_2 (ppm) at the end of the irrigation tape for different H_2O_2 treatments in the table grape crop, Emerald, QLD.

Treatments	Average EFR	Blockage	Biofoul	CUC	H_2O_2 Discharge
Control	2.37	13.7	20.0	95	0
H_2O_2 Low	2.39	5.7	3.4	95	6.3
H_2O_2 High	2.22	6.2	3.5	93	8.3
LSD 5%	0.052	5.2	9.0	2.3	4.1

Treatments as defined in Table 1.

3.2.2. Peroxide Levels

The concentration of H_2O_2 in the emitted irrigation water at the end of the plot, averaged across six sampling occasions, was 43 and 83% of the target concentration for the H_2O_2 Low and H_2O_2 High products, respectively (Table 6). H_2O_2 was not detectable in soil samples collected from surface soil cores (1–5 cm depth) within one hour of irrigation in any treatment.

3.2.3. Yield

No differences in the dates of bud burst, flowering, berry setting, maturity and days to harvest (earliness) were evident between treatments (data not presented). However, yield (Figure 1) was significantly impacted by treatment, year, and their interaction, with a CV of 25% yield across treatments and years. In the first year, H_2O_2 High outyielded H_2O_2 Low and the control. In the second year, there was no significant yield difference between the treatments, while in the third and fourth years, H_2O_2 Low outyielded the control and H_2O_2 High treatments (Figure 1). Across all years, a yield improvement of 25% above that of the control was associated with the H_2O_2 Low treatment.

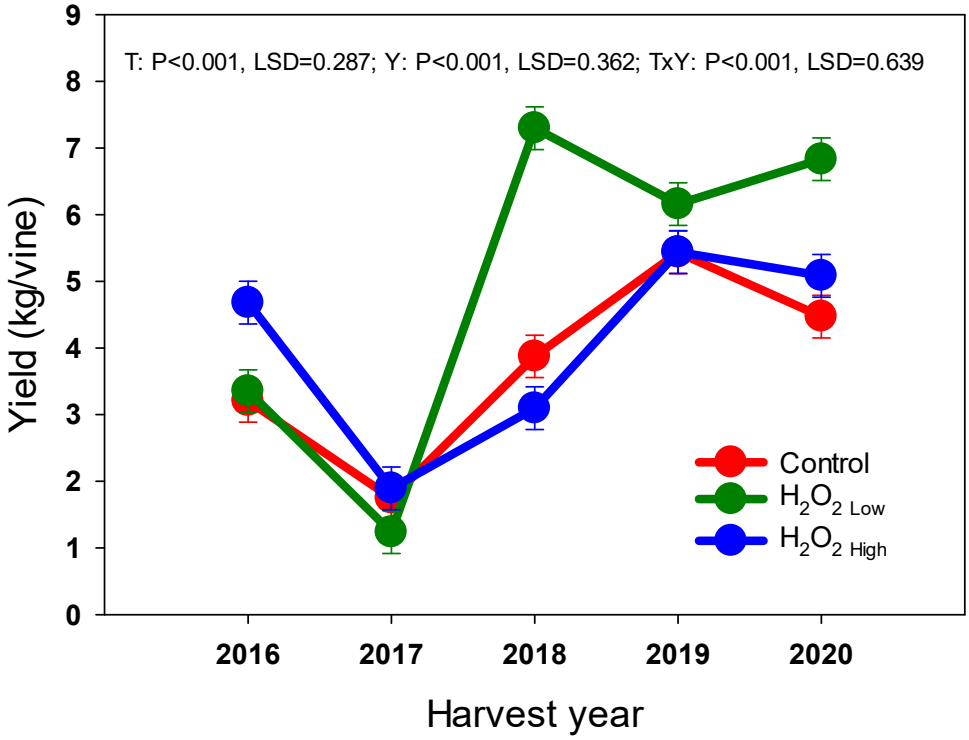

Figure 1. Table grape yield (kg $vine^{-1}$) in response to hydrogen peroxide irrigation treatments over five years (2016 to 2020) at Emerald, QLD. Treatment means are separated by LSD bar. Treatments as defined in Table 1.

3.2.4. Soil Processes

There were no visible differences evident between the irrigation treatments in terms of root diseases.

At the final harvest in the final year, the soil moisture content in the wetting front zone (20 cm radius from the point where emitter drops water to the ground) was significantly higher for $H_2O_{2\ Low}$ compared to the control and $H_2O_{2\ High}$ treatments (Table 7). Soil pH did not differ between treatments (Table 7); however, the soil solution EC was lowered by the H_2O_2 treatments, more so for $H_2O_{2\ Low}$. Soil respiration post irrigation was consistently but not significantly higher in $H_2O_{2\ Low}$ irrigation compared to $H_2O_{2\ High}$ and control irrigation treatments (average of four dates throughout the trial, control—0.857; $H_2O_{2\ Low}$—1.132; and $H_2O_{2\ High}$—0.807 g CO_2 m^{-2} h^{-1}). FDA and microbial biomass carbon did not differ significantly between the treatments. Both total soil carbon and soil nitrogen were significantly higher for $H_2O_{2\ Low}$, followed by control and lowest in the $H_2O_{2\ High}$ treatment (Table 7).

Table 7. Soil moisture, pH, EC, respiration, fluorescein release (FDA), microbial biomass carbon, total soil carbon and nitrogen measured at the end of the grape crop, Emerald, 2019.

Treatment	Soil Moisture (%)	pH	EC (µS cm^{-1})	Respiration (g CO_2 m^{-2} h^{-1})	FDA (µg g dw $soil^{-1}$ h^{-1})	Microbial Biomass Carbon (mg C kg dry $soil^{-1}$)	Total Carbon (%)	Total Nitrogen (%)
Control	23.2	6.83	142.2	0.770	167.9	122.0	1.74	0.19
$H_2O_{2\ Low}$	33.5	6.47	84.9	1.205	188.8	99.0	1.84	0.21
$H_2O_{2\ High}$	22.5	6.63	104.6	1.130	159.1	124.1	1.53	0.13
p value	0.006	0.294	0.001	0.301	0.375	0.405	0.054	<0.001
LSD (16 df)	6.73	0.47	25.34	0.530	45.30	43.18	0.254	0.030

Treatments as defined in Table 1.

3.3. Sugarcane with Subsurface Drip Irrigation

3.3.1. Drip Emitter Performance

Emitter flow rate averaged over twelve samplings was significantly higher for $H_2O_{2\ Low}$, followed by $H_2O_{2\ High}$ and the control treatments (Table 8). Flow rate associated with $H_2O_{2\ Low}$ was 16% higher than in the control treatment. In consequence, the volume of irrigation water applied was significantly higher for $H_2O_{2\ Low}$ followed by $H_2O_{2\ High}$ and least for the control treatment (7.76, 7.02 and 6.69 ML ha^{-1} yr^{-1} respectively, LSD = 0.28), although the additional water applied was above that required based on the soil moisture deficit and crop water demand in the control. The soil moisture contents of the samples collected from the wetting fronts on the day following full irrigation (Table 8) and the moisture content of the soil from the wetting front zone at the end of the trial (Table 9) were significantly lower for $H_2O_{2\ Low}$ compared to the control treatment.

Root intrusion was reduced significantly by $H_2O_{2\ Low}$ and $H_2O_{2\ High}$ treatments compared to the control treatment (Table 8).

Table 8. Average emitter flow rate, irrigation flow rate, percentage of emitters with root intrusion, soil moisture, residual H_2O_2 in irrigation water and soil respiration (post irrigation) for different irrigation treatments (three measurements/year, over four years) in the sugarcane trial, Home Hill, Qld. Root intrusion (%) refers to the percentage of drippers observed to have root intrusion.

Treatments	Emitter Flow Rate (L h^{-1})	Irrigation Flow Rate (mm h^{-1})	Root Intrusion (%)	Soil Moisture (%)	H_2O_2 Discharge (ppm)	Soil Respiration (g CO_2 m^{-2} h^{-1})
Control	1.39 ^{b*}	6.4 ^{c}	19.8 ^{a}	33.4 ^{a}	0	1.54 ^{b}
H_2O_2 Low	1.61 ^{a}	7.5 ^{a}	11.2 ^{b}	32.2 ^{b}	6.6 ^{b}	2.13 ^{a}
H_2O_2 High	1.54 ^{ab}	6.7 ^{b}	14.7 ^{b}	31.6 ^{b}	8.8 ^{a}	1.92 ^{ab}
p value	0.050	0.059	0.037	0.048	0.030	0.002
LSD 5%	0.23	0.13	3.4	0.853	1.331	0.499

Treatments as defined in Table 1. * Mean values with the same letter do not differ significantly at $p = 0.05$.

Table 9. Soil moisture, pH, EC, respiration, fluorescein release, microbial biomass carbon, total soil carbon and nitrogen measured at the end of sugarcane crop trial at Home Hill, North QLD, Australia.

Treatment	Soil Moisture (%)	pH	EC (µS cm^{-1})	Respiration (g CO_2 m^{-2} h^{-1})	FDA (µg g dw Soil h^{-1})	Microbial Biomass Carbon (mg C kg Dry $Soil^{-1}$)	Total Carbon (% *w*/*w*)	Total Nitrogen (% *w*/*w*)
Control	25.1	6.24	79.7	0.367	476	63.6	1.69	0.118
H_2O_2 Low	22.7	6.41	93.4	0.430	465	37.0	1.25	0.104
H_2O_2 High	24.5	6.31	85.8	0.462	431	58.9	1.68	0.123
Mean	24.1	6.32	86.3	0.419	457	115.0	1.54	0.114
p value	0.008	0.687	0.521	0.825	0.668	0.008	0.001	0.001
LSD 5%	1.42	0.47	25.99	0.344	115.1	15.83	0.102	0.008

Treatments as defined in Table 1.

3.3.2. Peroxide Levels

The H_2O_2 High treatment maintained higher H_2O_2 concentrations in irrigation water at the distal emitter discharge point compared to the H_2O_2 Low treatment (Table 8). Soil samples collected one hour post irrigation from soil cores within the wetting fronts did not show detectable levels of H_2O_2.

3.3.3. Yield

Leaf SPAD measurements prior to harvest ranged from 36.1 to 39.0 SPAD units and did not differ significantly between the treatments. However, stem counts taken just prior to harvest for 15 m linear row lengths were significantly greater for H_2O_2 Low (213 stems) followed by H_2O_2 High (208 stems) and control (196 stems, LSD = 11.02). Machine-harvested sugarcane yields (Figure 2) averaged over four years were consistently and significantly greater for H_2O_2 Low, followed by H_2O_2 High, compared to the control treatment.

However, the commercial cane sugar (CCS) measured by the mill at the point of cane arrival was, on average, significantly lower for the H_2O_2 Low (13.5%) and H_2O_2 High treatments (13.7%) compared to the control (14.3%, LSD = 0.95).

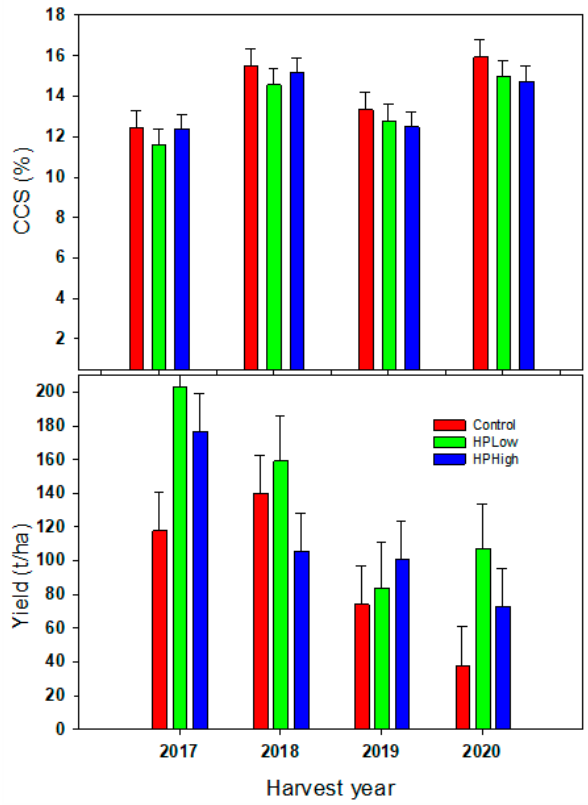

Figure 2. Cane yield (t ha^{-1}) and commercial cane sugar content (%) over four years for three irrigation treatments in sugarcane at Home Hill, North QLD, Australia. ±, standard error of the mean.

3.3.4. Soil Processes

No visible effect of the three irrigation treatments was noted on the root diseases of the sampled sugarcane plants.

Soil respiration post irrigation was generally higher in $H_2O_{2\ Low}$ compared to the $H_2O_{2\ High}$ and the control treatments (Table 8), although at final sampling there was no significant difference between treatments (Table 9). Likewise, at final sampling (Table 9), soil pH, EC and FDA did not differ significantly between treatments. Soil microbial biomass carbon, total soil carbon and total soil nitrogen were significantly lower in $H_2O_{2\ Low}$ compared to the $H_2O_{2\ High}$ and the control treatments (Table 9).

4. Discussion

4.1. Overview

The greatest yield gains were generally associated with the $H_2O_{2\ Low}$ treatment, ranging from 12% in chilli, 25% in grapes to 49% in sugarcane when compared to the untreated controls, with the effects of the use of 10 ppm H_2O_2 impacted by crop/site/drip irrigation type and stabilizer concentration. This greatest yield increase in sugarcane could be associated with in-ground use of drip tape, with direct delivery/contact of H_2O_2 and its breakdown products to the root mass.

The positive yield response associated with $H_2O_{2\ Low}$ may be associated with four different effects:

(i) An improvement in emitter flow rate due to reduced biofilm and/or scale clogging of emitters, and thus increased supply of water to the plant root zone, as shown by Japhet et al. (2022) [5].

(ii) Increased oxygen in the root zone associated with H_2O_2 breakdown. Aerated rhizospheres of drip irrigated crops in the tropics have been reported to produce favourable

crop growth response in a number of trials, e.g., Bhattarai et al. [27] for zucchini, vegetables soybean and cotton; Gil et al. [28] for avocado; Abd Elhady et al. [29] for potato; and Sariyev et al. [30] for corn.

(iii) Disinfection of the rhizosphere due to production of the hydroxy radical (•OH). The breakdown products of H_2O_2 have been linked to improved tolerance to root diseases [31].

(iv) Plant-priming effects of H_2O_2 (Zhang et al. [32] and references therein).

There is a balance required in the stabilization of H_2O_2—ideally protecting H_2O_2 from breakdown while in irrigation pipes and during entry to soil but allowing for eventual breakdown with an effect in soil primarily of suppling O_2 to plant roots (to offset what is purged from the soil during irrigation).

4.2. Four Possible Effects of H_2O_2

4.2.1. Reduced Emitter Clogging and Improved Emitter Flow Rates

Biofoul and scale build up in a drip line is dependent on water quality and exposure time [33]. In consequence, greater responses were seen in the multiple year grape and sugarcane trials relative to the six-month chilli trial. The proportion of totally blocked emitters was reduced by 50% in both H_2O_2 treatments compared to the control in the grape crop and root intrusion to a lesser, but still significant, extent in the sugarcane crop. Biofoul was also reduced considerably in the grape trial. Emitter flow rates were increased in the $H_2O_{2\,Low}$ treatment, particularly in the longer-term sugarcane trial. The CUC did not markedly differ between treatments in either crop, indicating that the restriction in water flow caused by biofoul or scale was consistent across drippers in a given treatment. Of interest, the $H_2O_{2\,High}$ treatment improved yield in the first season of the table grape trial (Figure 2), in line with this treatment being expected to have the greatest impact on the removal of scale due to the effect per se of HEDP.

These findings are consistent with observations and claims made by drip irrigation providers recommending H_2O_2 as an alternative to the commonly used chlorine or acid-based products for cleaning and maintenance of drip irrigation lines [7]. A reduced blocked emitter count with $H_2O_{2\,Low}$ means less emitter cleaning, and this should result in grower preference for this treatment.

Stabilized peroxide ensures longevity from breakdown in irrigation and to a lesser extent in soil. $H_2O_{2\,High}$ dosed at low levels (in the 10–100 ppm range) is generally considered ineffective as a disinfectant but acts as a source of oxygen for water, soil and plant roots [34]. Breakdown of H_2O_2 in the irrigation water for the two products under trial supplied at 10 ppm was significant, and, on average, across the three crops, 52% and 7% of the peroxide in $H_2O_{2\,Low}$ and $H_2O_{2\,High}$, respectively, was already decomposed at the exit of the emitters, in line with expectations given the concentrations of stabilizer. The difference in breakdown between the sites (more of $H_2O_{2\,Low}$ remained in the irrigation flow of grape and sugarcane, 6.3–6.6 ppm of the delivered 10 ppm of H_2O_2, than in chilli, where 2.8 ppm of the delivered H_2O_2 remained) is possibly associated with the quality of irrigation water in terms of total suspended solids and the presence of catalysts in the irrigation water in the chilli trial, which contained a high concentration (0.77 mg L^{-1}) of iron. Therefore, H_2O_2 injection plans should take into consideration irrigation water quality and other farm chemicals that are applied through the irrigation water so that the catalysis of H_2O_2 decomposition can be effectively minimized in irrigation water. In addition, greater H_2O_2 degradation was observed in the surface compared to the subsurface drip irrigation; the latter, where the emitters are located 30–40 cm below the ground surface, may be ascribed to the exposure of water to lower temperatures in the subsurface irrigation system. The use of greater stabilization of H_2O_2 could provide an extra buffer by delaying

breakdown of H_2O_2 into oxygen and water within the irrigation streams, until delivered through emitters, but at the same time precluding the desired oxidative effects of hydroxyl radicals on emitter biofoul.

4.2.2. Increased Soil Oxygen from Decomposition of H_2O_2

Once H_2O_2 exits the emitters, the soil conditions determine the H_2O_2 breakdown to oxygen, •OH and OH^-. The supply of oxygen to the roots from H_2O_2 is greatest when the soil is less acidic and lower in transition metals such as Fe, conditions that favour H_2O_2 breakdown to O_2 rather than to •OH and OH^- through the Haber–Weiss mechanism, for these are the two principal routes through which H_2O_2 breakdown occurs in the soil.

The observations made in chilli and grapes with surface and above-surface drip irrigation, respectively, where H_2O_2 application occurs at ground surface level, showed an increase in total soil carbon and nitrogen as well as greater soil respiration associated with $H_2O_{2\,Low}$ treatment compared to the respective control and $H_2O_{2\,High}$ treatment. Indeed, Ma et al. [35] report an increase in soil organic carbon, dissolved organic carbon and total nitrogen with a 10 cm depth in aerated irrigation. These results contrast to those for the subsurface drip irrigation where $H_2O_{2\,Low}$ injection in particular reduced the total C and N, presumably because of the greater Fenton-like decomposition of H_2O_2 in the subsurface zone due to reduced photolytic decomposition of H_2O_2 in the subsurface than the soil surface [36] and less easy diffusion of free radicals released in Fenton-like reactions of $H_2O_{2\,Low}$. The proximity of irrigation to the root zone for the injection of H_2O_2 allowed for greater access to H_2O_2 breakdown products, e.g., oxygen, for the benefit of root respiration and •OH for disease and pest control, contributing to greater yield benefits with H_2O_2 in SDI. This hypothesis is substantiated by the results of Petigara et al. [37]. They suggested that in surface soils with higher organic matter or manganese content, H_2O_2 usually decayed rapidly, with disproportion to water and oxygen dominating the decomposition, with the formation of the hydroxyl radical (•OH) representing <10% of the total H_2O_2 decomposed. In contrast, for soils with lower organic matter content, which is common for the subsoil, H_2O_2 usually decayed much more slowly, and •OH was a major product of the decomposed H_2O_2, therefore sustaining disinfection of the root zone and decomposition of organic matter. This is of interest because, in contrast with our results, where apparently more hydroxyl radicals were produced with the lower concentration of stabilizer, Watts et al. [2] reported greater hydroxyl radical production in monobasic sodium phosphate-stabilized versus -un-stabilized H_2O_2 formulations. Nevertheless, the lower soil temperature slowing H_2O_2 decomposition at depth in the soil may have been responsible for the slower disproportionation of H_2O_2 and therefore possibly a greater decomposition of soil C and N with $H_2O_{2\,Low}$.

Schumb et al. [8] suggested that stabilized H_2O_2, containing phosphate, is stable at low pH. Phosphate appears to inhibit H_2O_2, decomposition reactions that are catalyzed by mineral surfaces, possibly by affecting the surface charge or redox potential at the mineral surface. Therefore, both low pH and the presence of phosphate promote H_2O_2 stability and slow its decomposition [2]. The water pH of the trial sites was, however, near neutral, ranging from 6.24 to 7.32; therefore, the effect of pH on stabilizing H_2O_2 is unlikely. Such neutral pH is also less conducive to the destruction of soil organic matter by H_2O_2, as reported by Bissey et al. [38].

The chilli crop trial was conducted for a single season only, with a duration of 6 months. The emitter flow rate did not differ between treatments presumably because there had been insufficient time for significant scale and biofoul to develop. The positive effect of H_2O_2 on the crop could have been largely due to availability of oxygen and its effect on the crop and soil. The drier soil in the $H_2O_{2\,Low}$ treatment might also indicate that the roots were more

active in extracting water from the soil. As the chilli crop used the equivalent of c. 60 L of pure H_2O_2 per hectare (equivalent to that in 96,857 L or 9.7 mm of air into the soil), this is a significant amount, particularly when some parts of the chilli roots are concentrated around the emitter and the plot is covered by plastic mulch, which slows the natural diffusion of oxygen into the rhizosphere. The positive benefits of the H_2O_2 treatment were greater for the low stabilizer concentration than the high stabilizer concentration, and the former formulation was designed for a quicker breakdown and release of O_2.

In the grape trial, soil respiration was much greater, but not significantly so, in the $H_2O_{2\,Low}$ treatment, suggesting a quicker and greater supply of oxygen to the soil, enhancing root activity, which may have also contributed to the greater berry yield. In contrast to the chilli crop and the sugarcane crop, in the table grape crop, we suggest that the higher soil moisture at the end of the crop may be due to the benefits of reduced emitter blockage and therefore greater supply of irrigation water to the $H_2O_{2\,Low}$ treatment that overcompensated for the additional transpiration effected by the enhanced oxygen to the root system.

In the sugarcane trial, soil respiration was significantly enhanced by H_2O_2 treatments, more so by $H_2O_{2\,Low}$, and again, there was a suggestion of greater supply of oxygen to the soil and to the crop roots, resulting in greater cane yield. The lower soil moisture in the $H_2O_{2\,Low}$ treatment might also indicate a greater rate of transpiration in that treatment. The effect of the $H_2O_{2\,Low}$ treatment was greatest in three of the four years of the trial; the year when there was no effect was one with a very wet summer and less use of irrigation. Although the cane yield averaged over four years was increased by 49% compared to the control, the increase in sugar yield was less (41%) due to an offsetting effect of cane yield on CCS (Figure 2).

4.2.3. Rhizosphere Disinfection

Low H_2O_2 dose rates are considered safe for soil micro-organisms; in fact, natural decomposition of low levels of peroxide is beneficial to aerobic soil microbial activity (Zappi et al., 2000 [39]) and for access to oxygen by the plant root system.

4.2.4. Priming Effects

Plants treated at different developmental stages with exogenous H_2O_2 (for example at 1.5 mM) show enhanced systemic acquired tolerance to various abiotic stresses, and exposure to such abiotic stresses has less impact on their physiology and growth than on non-treated plants (Zhang et al. [32] and references therein). The mode of action of H_2O_2 as a priming agent is not fully understood; however, the evidence of common tolerance activation sites and signalling pathways that appear related to enhanced tolerance against different abiotic stresses strongly supports their potential for enhanced multi-stress tolerance [40]. Thus, priming with H_2O_2 enables seeds or seedlings to activate their antioxidant mechanisms and acclimatize prior to abiotic stress exposures. Therefore, H_2O_2 priming hardens the plants to better cope with abiotic stress conditions [41].

5. Conclusions

H_2O_2 injection into irrigation water results in a multitude of effects that influence crop yield response. These include the following: (i) direct effects by improving the performance of drip emitters, (ii) indirect effects through increased access to oxygen, (iii) •OH radical disinfection and (iv) possible priming effects for improved tolerance to abiotic stress.

Low-dose $H_2O_{2\,Low}$ (10 ppm, with 1 ppb HEDP stabilizer, i.e., $H_2O_{2\,Low}$) injection continuously in irrigation with three distinct drip irrigation placements (surface, above surface and subsurface) showed positive and consistent effects for emitter and crop per-

formance compared to the same concentration of H_2O_2 with 1 ppm HEDP (i.e., $H_2O_{2\,High}$) and the control. For the annual horticultural chilli crop irrigation with single-use drip tape, emitter blockage was less of an issue compared to longer-term permanent drip tape, which is common in perennial cropping. In the perennial crops, table grape and sugarcane, $H_2O_{2\,Low}$ improved emitter flow rate compared to the untreated control and to $H_2O_{2\,High}$.

Yield was favoured by injection of $H_2O_{2\,Low}$. Yield increased by 49, 25 and 12% in sugarcane (subsurface), grape (above surface), and chilli (surface), respectively, due to the $H_2O_{2\,Low}$ treatment when compared to the untreated control; the greatest treatment effect was evident where irrigation delivery was proximal to root mass. We show that the application of $H_2O_{2\,Low}$ is effective in improving crop yields at the field scale when applied as either suspended, surface or subsurface drip irrigation systems, a result of practical importance to commercial growers and supporting conclusions reported in earlier studies. Economic analyses of the benefit of the treatments are still required, but, given the magnitude of the yield benefits, they are likely to be favourable.

The effects of long-term H_2O_2 irrigation on microbial biodiversity did not indicate any direct negative effects of H_2O_2 treatments, but microbial biomass was reduced by $H_2O_{2\,Low}$, significantly so in the sugarcane trial, and this requires further study. H_2O_2 breakdown in irrigation and soil was slower for $H_2O_{2\,High}$ compared to $H_2O_{2\,Low}$; however, the H_2O_2 breakdown process in soil in the presence of catalysts was rapid, even with a high concentration of stabilizer; hence, any residual H_2O_2 in the soil with low-dose (10 ppm) continuous injection irrigation is highly unlikely soon after irrigation.

Nevertheless, we still recommend specific further work, for example on the effective H_2O_2 half-life in the soil, determining how far from the irrigation dripper H_2O_2 exists, and the long-term effects of H_2O_2 on soil organic matter and microbiota.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy15020385/s1, Supplementary Material S1: Location of trials in Australia; Supplementary Material S2: Trial setup in Bundaberg, and weather data during trial; Supplementary Material S3: Trial setup in Emerald, and soil analyses and weather data during trial; Supplementary Material S4: Trial setup in Homehill, and weather data during trial.

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Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

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Conflicts of Interest: The authors declare no conflicts of interest.

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