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# A new method to treat farm dairy effluent to produce clarified water for recycling and to reduce environmental risks from the land application of effluent

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## Abstract

**Purpose** There is increasing public concern about the amount of fresh water used on New Zealand dairy farms and the adverse impacts that farm dairy effluent (FDE) has on the environment. FDE mainly consists of fresh water (99%) with a small amount of solid material (1%). There is an opportunity to treat FDE to remove the colloidal solid material and recycle the water to wash the farm yard.

**Materials and methods** A new method of treating FDE has been developed. The method uses a coagulant to flocculate and settle the colloidal particles in the FDE and thus produce the clarified water for recycling. The research and development programme involved three stages: (i) standard laboratory jar tests to establish the amount of coagulant required to treat the FDE, (ii) large tank tests to confirm the effectiveness of the coagulant at a larger scale and (iii) construction and testing of two pilot plants. A pasture field trial was conducted to test the effect of the clarified water and treated effluent on plant production.

**Results and discussion** The new method of treating FDE was highly successful in removing the colloidal material and producing clarified water that can be recycled to wash the farm yard. The average turbidity of the clarified water from the first pilot plant was 52 nephelometric turbidity units (NTU) (a 97% reduction in NTU compared to the original FDE) and the average *Escherichia coli* concentration was 9 cfu per 100 mL (a 99.99% reduction compared to the original untreated FDE). The average total-phosphorus (P) concentration of the clarified water was 1.8 g m$^{-3}$ (94% reduction), dissolved reactive phosphorus (DRP) was < 0.1 g m$^{-3}$ (99% reduction) and total nitrogen (N) was reduced by > 70% (from 200 to 61 g m$^{-3}$). The average turbidity of the clarified water from the second pilot plant was < 20 NTU (a 99.5% reduction). There was no adverse impact from the land application of the clarified water or the treated FDE on plant growth.

**Conclusions** A new method for treating farm dairy effluent was successfully developed that produced clarified water that could be recycled to wash the farm yard and had a lower potential risk of environmental impacts when applied to land than untreated FDE. Land application of the clarified water or the treated FDE had no adverse impact on plant growth.

**Keywords** Clarified water · Coagulation · Farm dairy effluent · Polyferric sulphate · Water treatment

## 1 Introduction

There is increasing public concern about the amount of water that is used on New Zealand dairy farms. On average, about 70 L of water is used per cow per day to wash the farm

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yard, milking parlour and milking equipment (DairyNZ 2014). Therefore, on average, a NZ dairy farm with c. 400 cows uses about 28,000 L of water per day to wash the yard, milking parlour and milking equipment. Over a typical 270-day milking season, this amounts to more than 7,500,000 L of water for the average farm. Public concern about water use efficiency, and the increasing price paid by some farmers for water, has created an urgent need to find ways to reduce the volume of water used at the farm dairy. In some parts of New Zealand (e.g. Waikato), farmers are required to apply for a resource consent if they use more than 15,000 L of water per day for the farm dairy wash (Waikato Regional Council 2012).

The New Zealand Ministry for Primary Industries (MPI) has recently revised the regulations relating to farm dairy operations in order to encourage recycling of water (Ministry for Primary Industries 2017). 'Green-water' (i.e. farm dairy effluent containing a low content of solids either pumped from the top layer of an effluent pond or from effluent that has been screened) can now be used to wash the farm yard (but not the milking parlour or milking equipment). This regulatory change has created an opportunity to substantially reduce the amount of water used at the farm dairy by about 50% (DairyNZ 2014). Currently, however, the opportunity is limited because of the risk from micro-organisms in the recycled green-water affecting staff health.

Although the composition of the farm dairy effluent (FDE) varies depending on the specific farm infrastructure and farm management system, FDE mostly consists of water, urine, dung, soil, feed, cleaning chemicals and milk. The average solids content of FDE is low (c. 0.9%) (Longhurst et al. 2000) and thus the majority of the FDE is water (c. 99%). Farm dairy effluent contains a large number of pathogenic bacteria which, in addition to posing a risk to staff using 'green-water' recycling, also pose a risk to humans if transferred from soil into water during land application of the FDE (Longhurst et al. 2000; Oliver et al. 2005; Collins et al. 2007). For example, high faecal coliform counts were detected in groundwater below soil that received FDE in Canterbury, New Zealand (Close et al. 2008). Faecal bacteria have also been detected in field drains 750 mm below the soil surface following manure application to land (Culley and Phillips 1982). Fenlon et al. (2000) have emphasised that if heavy rainfall occurs close to the date of manure application then large numbers of bacteria can be flushed through soil into drains. Water-borne micro-organisms are now reported to be responsible for approximately 25% of hospital patients throughout the world (Gerba 1996) and increasing attention is being made to the contribution of agriculture to this health hazard (Oliver et al. 2005).

Farm dairy effluent is irrigated onto land to recycle nutrients and dispose of the large volumes of liquid effluent produced from washing the farm yard and milking parlour (Wang et al. 2004). Although land application of FDE is common practice, there is increasing public concern about the risks of FDE contaminating rivers, lakes and groundwater with phosphorus (P) and nitrogen (N), as well as micro-organisms (Cameron et al. 1997; Houlbrooke et al. 2004a; Monaghan and Smith 2004; Oliver et al. 2005; Monaghan et al. 2008; Laurenson et al. 2017). A review of NZ data by Houlbrooke et al. (2004b) found that between 2 and 20% of both P and N applied in FDE was lost either through leaching or runoff from soil. The risks of leaching and runoff are greatest on soils with a high risk of preferential flow, artificial drainage, coarse soil structure, low infiltration rates (causing ponding), or soils on slopes (Monaghan and Smith 2004; McLeod et al. 2008; Houlbrooke and Monaghan 2009).

Recent research by Laurenson et al. (2017) found that effluent management had no significant effect on annual fluxes of P and *Escherichia coli*. Therefore, a robust and reliable method of removing these contaminants from FDE before applying to the land is required.

The aim of this research programme was to develop and test a new method for treating FDE that would enable clarified water to be recycled to wash the farm yard at the milking parlour, reduce the health risk to staff of using recycled water and reduce the risk of contamination of rivers, lakes and groundwater from FDE applied to land. This paper reports the development and testing of the new treatment technology. The effects of applying the treated effluent and treated effluent mixed with clarified water on nutrient and microbial leaching losses and greenhouse gas emissions are reported in two separate papers (Wang et al. 2018; Chen et al. 2018 both in this issue).

## 2 Materials and methods

The basis of the new method for treating FDE is to use a coagulant to coagulate and flocculate colloidal particles in the FDE into flocs that have sufficient mass for gravity to cause them to settle out of the liquid, thus producing: (i) clarified water and (ii) treated effluent. Coagulation involves the addition of a coagulant to neutralise the negative electrical charges on the surfaces of colloids (e.g. soil, dung, organic matter) that would normally prevent them from coagulating into flocs that have sufficient mass to settle out of the water under gravity. In addition, during mixing of the coagulant into the effluent, the coagulant can create a mechanism called 'sweep floc' which also causes the colloids to stick together producing flocs.

Multiple types of coagulant are used in the treatment of drinking water and wastewater (e.g. aluminium sulphate, aluminium chloride, ferric chloride, ferric sulphate, organic polymers) and each has specific advantages and disadvantages. Our research has found that polyferric sulphate (PFS) (a polymerised form of ferric sulphate) is a very effective coagulant for use in treating FDE and that it does not require the addition of a hydroxide solution or flocculant aids which are often required when other coagulants are used in water treatment plants.

Toxicity studies have shown that drinking water treated with PFS is safe for human consumption (Hendrich et al. 2001). Ferric sulphate is approved by the US Food and Drug Administration (FDA) as a food additive and is affirmed as 'generally recognised as safe' (GRAS) for human consumption (FDA 2017). Iron is an essential dietary element and ferric sulphate is used to increase the iron content of and add flavour to food (FDA 2017).

The research protocol used in this research programme to develop and test the effectiveness of PFS to treat FDE involved three steps: (i) standard laboratory jar tests, (ii) large-scale tank tests and (iii) pilot plant construction and testing; each of these steps will be described below.

## 2.1 Analysis of PFS and preparation of PFS liquid

The polyferric sulphate powder was purchased from New China Chemicals Ltd. (Tianjin, China). Elemental analysis of the polyferric sulphate powder was conducted by microwave assisted nitric acid extraction (MARS Xpress, CEM Corp, USA) followed by inductively coupled plasma optical emission spectrometry (ICP-OES) (Agilent 720ES, Agilent, Australia). As expected, iron (Fe) and sulphur (S) dominate the elemental composition of the material, together accounting for approximately 38% of the total weight (Table 1). There were measurable amounts of magnesium (Mg), sodium (Na) and manganese (Mn) detected and lesser amounts of aluminium (Al) and zinc (Zn). Trace amounts of phosphorus (P), chromium (Cr), nickel (Ni) and lead (Pb) were detected, but no arsenic (As), boron (B), cadmium (Cd), copper (Cu), potassium (K) or molybdenum (Mo). The PFS solution was prepared by dissolving 600 g of PFS powder in 800 mL of water.

## 2.2 Laboratory jar testing

The standard laboratory jar testing procedure was used in this research programme to establish the most effective type of coagulant and the most effective rate of coagulant to use (ASTM 2013). The jar test equipment was comprised of four mixing paddles (80 × 35 mm) centrally mounted in 4-L glass beakers and operated at 200 rpm for 2 min giving a velocity gradient of 742 s$^{-1}$ (ThermoFisher Scientific, New Zealand).

Farm dairy effluent samples were collected from six different farms in Canterbury, New Zealand, throughout the year for use in the jar testing procedure. A total of 75 jar tests were conducted using different rates of PFS coagulant to determine its effectiveness in clarifying the FDE. The turbidity of each

effluent was measured using a hand held turbidity meter (Thermo Scientific Orion Aquafast AQ4500) which provided results in standard NTU values. Each jar test consisted of 800 mL of FDE which was mixed using the standard jar test equipment. The PFS liquid was added by a pipette to different jars of the same effluent to provide a range of rates of treatment (0, 150, 200, 250 mg Fe L$^{-1}$ of effluent) and mixed for 2 min. After settling for 1 h, the turbidity of the clarified water was measured to determine the most effective rate of PFS treatment. The pH of the untreated FDE samples and the clarified water was also measured using a standard pH electrode and meter (Metler Toledo pH meter S220).

### 2.2.1 Large tank trials

Large tank trials were conducted to test the effectiveness of the PFS coagulation process at a larger scale. The trials were conducted using a 300-L acrylic tank which was filled with FDE and stirred using a flat mixing paddle (300 × 100 mm) connected by a shaft to a hand held electrical power drill. A total of eight large tank test trials were conducted using FDE collected from six different farms in Canterbury. The turbidity of each effluent was measured using a hand-held turbidity meter, as described above, and the amount of PFS required to achieve successful clarification of each batch of effluent was calculated from the results of the laboratory jar test experiments. The PFS liquid was poured into the effluent in the large tank and mixed for 2 min. After settling for 1 h, the turbidity of the clarified water was measured, as described above. Samples of the original untreated FDE and samples of the clarified water were taken for further analyses. Each sample was analysed to determine: (i) pH using a standard pH electrode and meter (Metler Toledo pH meter S220), (ii) concentration of *E. coli* using the standard enzyme substrate coliform test APHA 9221 F (APHA 2012), (iii) total-N using the Kjeldahl method APHA 4500-N-org D (modified) (APHA 2012), (iv) ammonium-N using the phenol hypochlorite colorimetry method APHA 4500-NH$_3$ F (modified) (APHA 2012), (v) total-P using acid persulphate digestion and colorimetry method APHA 4500-P B & E (modified) (APHA

**Table 1** Average element analysis of polyferric sulphate material used in the experiments ($n = 4$ samples)

| Element | Al | As | B | Ca | Cd | Cr | Cu | Fe | K |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| | (mg kg$^{-1}$) | (mg kg$^{-1}$) | (mg kg$^{-1}$) | (mg kg$^{-1}$) | (mg kg$^{-1}$) | (mg kg$^{-1}$) | (mg kg$^{-1}$) | (%) | (mg kg$^{-1}$) |
| Mean | 313.9 | nd | nd | nd | nd | 2.8 | nd | 20.1 | nd |
| SEM | 19.4 | | | | | 0.6 | | 0.2 | |
| Element | Mg | Mn | Mo | Na | Ni | P | Pb | S | Zn |
| | (mg kg$^{-1}$) | (mg kg$^{-1}$) | (mg kg$^{-1}$) | (mg kg$^{-1}$) | (mg kg$^{-1}$) | (mg kg$^{-1}$) | (mg kg$^{-1}$) | (%) | (mg kg$^{-1}$) |
| Mean | 3952.7 | 1622.5 | nd | 7355.0 | 4.7 | 6.8 | 8.7 | 17.9 | 186.1 |
| SEM | 146.9 | 10.7 | | 477.6 | 3.3 | 6.8 | 5.1 | 0.1 | 38.1 |

*SEM* standard error of the mean

2012) and (vi) dissolved reactive phosphorus (DRP) using a filtered sample and molybdenum blue colorimetry method APHA 4500-P G (modified) (APHA 2012).
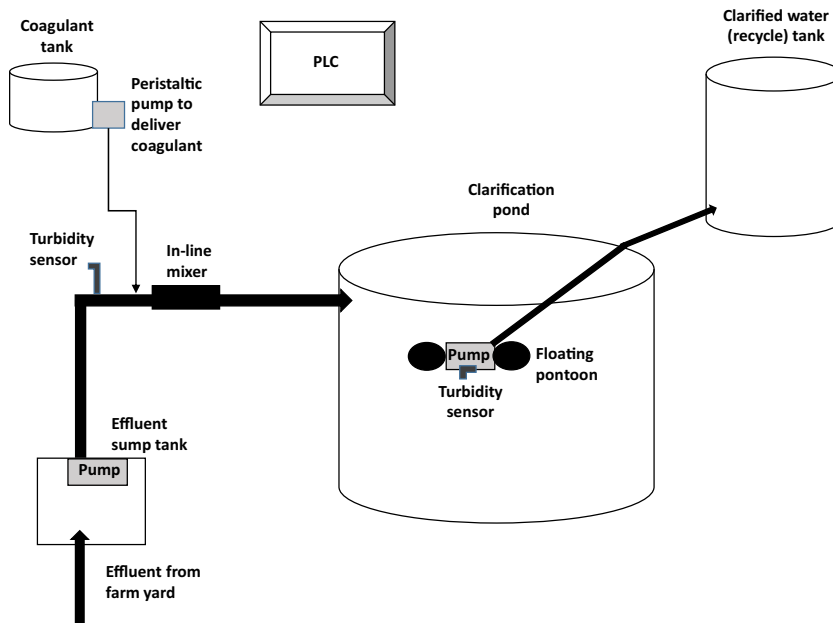
## 2.3 Pilot plant trials

Two pilot plants were constructed to scale up the laboratory and large tank trials and test the effectiveness of the coagulation technology at farm scale.

### 2.3.1 Static in-line mixer pilot plant

The first pilot plant was constructed on the Lincoln University Research Dairy Farm using a 'static in-line mixer' system (Mixtec, Auckland). Effluent washed from the farm yard was collected in an existing concrete sump tank at the end of the yard and pumped through the static in-line mixer into a large 150,000-L clarification pond (Fig. 1). The pump rate was set at 7000 L per hour and the coagulant was delivered into the static in-line mixer unit at a rate that had been pre-determined to adequately treat the FDE based on the FDE flow rate and turbidity. The turbidity was measured continuously using a turbidity probe ('DataStick HR' turbidity sensor; Thermo Fisher Scientific, NZ) mounted inside the pipe before the mixing coil and the data was captured on an 'Aquapro' analyser (Thermo Fisher Scientific, NZ). The turbidity data was transferred to a programmable logic computer (PLC) (Schneider Electric) that controlled the delivery rate of the PFS into the static in-line mixer using a variable speed peristaltic pump (Verder Ltd., UK). The PLC algorithm controlling the rate of delivery was based on the laboratory jar testing results.

The treated effluent coming out of the static in-line mixer was piped into the clarification pond where it was allowed to settle for 5 h. After settling, the clarified water in the upper layer of the pond was pumped into a 20,000 L holding tank. The pump in the clarification pond was mounted on a floating pontoon and a second turbidity probe/analyser (as described above) was mounted 100 mm below the depth of the intake of the Yardmaster® effluent pump (Reid and Harrison, NZ) that was also mounted on the floating pontoon. Data from the turbidity probe was captured by the PLC and the pump was only activated if the turbidity of the clarified water was below a pre-set value of 100 NTU. When the clarified water was removed from the holding pond, the floating pontoon fell downward until the turbidity probe detected the top of the effluent layer (i.e. the turbidity value exceeded 100 NTU) and the pump was turned off automatically by the PLC. The clarified water in the holding tank was used to wash the farm yard. Three replicate samples of untreated FDE entering the static in-line mixer were taken for analysis (as described above) at the start, middle and end of each run of the pilot plant. Three replicate samples were also taken for analysis of the clarified water being used at the start, middle and end of each yard washing.

### 2.3.2 Sequencing batch reactor pilot plant

The second pilot plant was constructed as a sequencing batch reactor (SBR) system where batches of 17,000 L of effluent were treated in a large 20,000-L SBR tank (Fig. 2). The turbidity of the FDE was measured using a turbidity probe ('DataStick HR' turbidity sensor; Thermo Fisher Scientific, NZ) mounted on a floating pontoon inside the SBR tank.



**Fig. 1** Schematic diagram of the first pilot plant using a static in-line mixer to mix the polyferric sulphate (PFS) with the effluent prior to transfer into a clarification pond

**Fig. 2** Schematic diagram of the second pilot plant using a sequencing batch reactor tank including a stirrer to mix the polyferric sulphate (PFS) with the effluent to produce clarified water, which was pumped into a recycle water tank, and treated effluent (slurry), which was pumped into an existing effluent storage pond
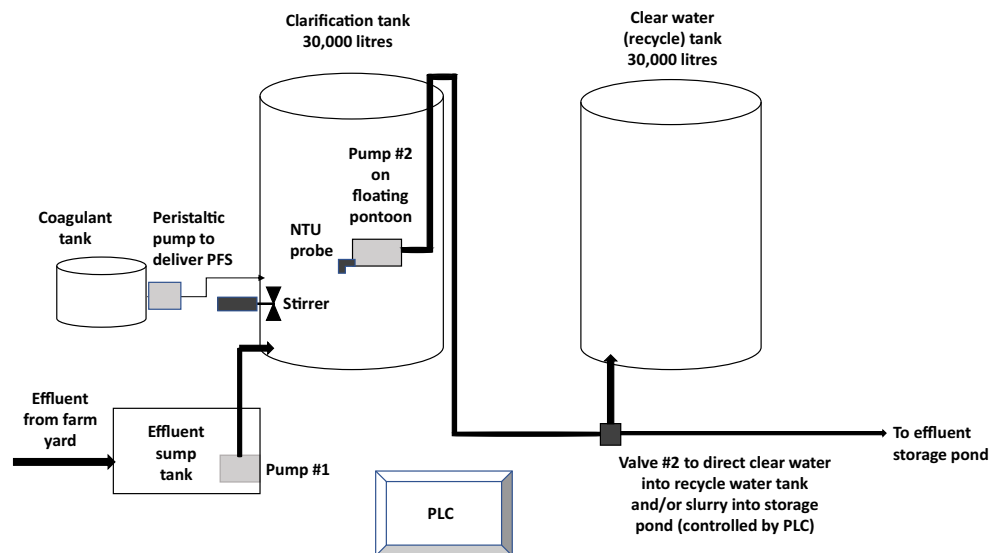


The data from the turbidity probe was captured on an 'Aquapro' analyser (Thermo Fisher Scientific, NZ) and transferred to a PLC (Schneider Electric). The PLC controlled a peristaltic pump (Verder Ltd., UK) to deliver the correct amount of PFS solution to treat the turbidity of the FDE. The PLC algorithm used to control the amount of PFS delivered per batch was derived from the laboratory jar test results. The effluent and PFS solutions were mixed together for 15 min using a Yardmaster® effluent stirrer (Reid and Harrison, NZ) mounted inside the SBR tank (Fig. 2). The effluent and PFS mixture was then allowed to settle for 30 min to allow flocculation and clarification of the surface 200 mm depth to occur. If the turbidity probe detected that the turbidity of the top 200 mm depth had dropped below a pre-set value of 100 NTU in 15 min, then the PLC allowed the liquid to settle for 4 h (which produced c. 10,000 L of clarified liquid). If the turbidity probe did not detect a reading below 100 NTU in 15 min, then the PLC activated both the stirrer and the peristatic pump to mix more PFS into the liquid in the SBR. The effluent and PFS mixture was then allowed to settle for another 30 min to allow flocculation and clarification of the surface 200 mm depth to occur. The same procedure was repeated until clarification occurred.

After the 4 h settling period, the clarified water was automatically transferred to the 30,000-L recycle wash-water tank using the Yardmaster® effluent pump mounted on the floating pontoon inside the SBR. The removal of this liquid caused the pontoon to drop inside the SBR and once the turbidity probe detected an increase in turbidity above 100 NTU (i.e. detected the effluent layer at the bottom of the SBR) the PLC automatically closed the valve to the recycle water tank and opened a valve to transfer the remaining treated effluent to an existing effluent storage pond. The turbidity and pH of the untreated FDE and of the clarified water were measured, as described above.

## 2.4 Pasture field trial

A pasture field trial was conducted to test if there were any differences in plant production or plant chemical composition when clarified water or treated effluent was applied to pasture land, compared to standard untreated effluent. This trial was particularly important to detect any risk of plant uptake of any heavy metals in the PFS.

The trial was established on the Lincoln University Research Dairy Farm, 15 km SW of Christchurch, New Zealand (latitude 43° 38′ S; longitude 172° 28′ E). The soil type was a Templeton fine, sandy loam (USDA: Udic Haplustept, course loamy, mixed mesic (Soil Survey Staff 2014); or New Zealand classification: Immature Pallic soil (Hewitt 2010)). The pasture consisted of perennial ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.) which was established 3 years previously and stock excluded for 1 year, during which time the pasture was cut and removed.

The statistical design of the trial was a randomised block with each block consisting of four treatments: (i) control (water only), (ii) untreated effluent, (iii) clarified water and (iv) treated effluent. There were 17 replicate blocks. Each treatment plot was 0.5 m wide and 2.0 m long with a 0.5-m buffer around each side of each plot.

The treatments were applied by hand using watering cans to ensure there was no runoff of liquid from the plot area. Two treatment applications were made, one on 1 December 2016 and the second on 16 February 2017. Pasture dry matter production was measured by using a rotary mower to cut the pasture at normal grazing height, equivalent to 3200 kg DM ha$^{-1}$, down to a normal pasture residual height equivalent to 1600 kg DM ha$^{-1}$. A sub-sample of pasture was taken from each plot for dry matter measurement and chemical analysis. Chemical analysis was conducted using inductively coupled plasma-mass spectrometry (ICP-MS).
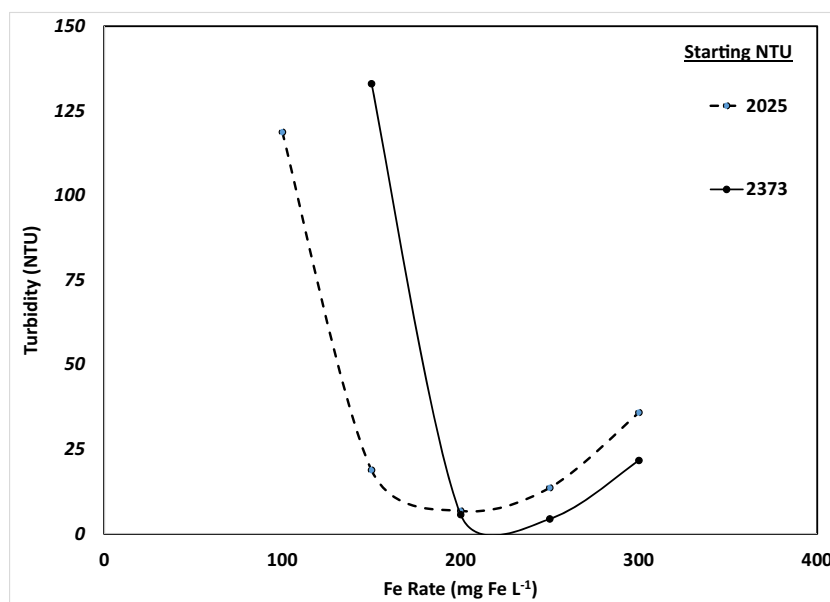
## 2.5 Statistical analysis

Mean values and standard errors of the means (SEM) for each measured parameter were calculated for each experiment using Microsoft Excel (Microsoft Corporation USA). In the effluent treatment trials, the statistical analysis used to test for significant differences between parameter values was conducted using two-tailed Students 't-tests' using Microsoft Excel. In the pasture field trial, the statistical analysis used to test for significant differences between parameter values was conducted by analysis of variance (ANOVA) using Genstat Version 12.2 (VSN International Limited). Where necessary, due to unequal variances, the data were log transformed before statistical analysis was conducted and back transformed into geometric means for reporting.

# 3 Results

## 3.1 Laboratory jar test results

Laboratory jar tests were conducted on 75 different FDE samples to determine the 'optimum' PFS dosage rate required to achieve the lowest turbidity value for each effluent sample. Two examples of the data from the jar tests to determine the effect of PFS dosage rate on turbidity are shown in Fig. 3. When the dose rate was too low, there was insufficient PFS to cause complete coagulation and the residual turbidity of the liquid remained above about 90 NTU. The 'optimum' dose of PFS occurred when there was sufficient PFS to neutralise the negative charges on the surfaces of the colloids and coagulation occurred, producing the greatest reduction in NTU, as shown by the lowest NTU value for each effluent sample

illustrated in Fig. 3. Using an excess of PFS, above the optimum dosage rate, can cause the colloidal surfaces to become positively charged and the colloidal particles repel each other again, causing the NTU value to increase again compared to the optimum dosage rate, as shown by the increase in turbidity of each effluent sample illustrated in Fig. 3.

The average initial turbidity of the 75 FDE samples was 2096 ($\pm$ 101) NTU which, following treatment with the optimum dosage rate of PFS coagulant, was significantly ($p < 0.001$) reduced to 6.3 ($\pm$.5) NTU in the clarified water (Table 2). This represents an average reduction in NTU of greater than 99.5% and provides evidence of the effectiveness of PFS coagulant to clarify FDE. Importantly, these effluent samples were collected throughout the milking season (August to May) and are thus representative of the seasonal range of effluent compositions that are typical of dairy farms in Canterbury (i.e. containing different amounts of solids, milk, detergents, acids and other cleaning fluids).

The average initial pH of the FDE was 7.53 ($\pm$ 0.07) and this was significantly ($p < 0.001$) reduced to 5.45 ($\pm$ 0.07) following treatment and clarification (Table 2). This reduction of approximately two pH units was due to the acidic nature of the PFS solution (pH 0.7) (Table 1).

The average rate of PFS coagulant required to clarify the effluent by 99.5% was equivalent to 214 ($\pm$ 10.2) mg Fe $L^{-1}$ of effluent (Table 2).

## 3.2 Large tank trial results

Treatment of FDE in the large tank trials showed that PFS significantly ($p < 0.001$) reduced the average turbidity from 2214 NTU in the untreated FDE down to 17 in the clarified water (representing a 99% reduction in turbidity) (Table 3).

**Fig. 3** Examples of the effect of different rates of polyferric sulphate (PFS) addition on residual turbidity of clarified water produced after flocculation of farm dairy effluent (FDE)

**Table 2** Summary of 75 jar test results for effluent collected from six farms in Canterbury over a period of 18 months

| | | Turbidity (NTU) | | pH | | Average rate of Fe addition to achieve best clarification result (mg Fe L$^{-1}$) |
|---|---|---|---|---|---|---|
| | | Untreated FDE | Clarified Water | Untreated FDE | Clarified Water | |
| Mean | | 2096 | 6.32 | 7.53 | 5.45 | 214 |
| S.E.M. | | 100.55 | 0.50 | 0.07 | 0.06 | 10.24 |

There was a significant ($p < 0.001$) reduction in *E. coli* concentration from an average of 247,718 cfu/100 mL in the untreated FDE down to 55 cfu per 100 mL in the clarified water (representing a 99.98% reduction) (Table 3). The total N concentration was significantly ($p < 0.001$) reduced from an average of 200 down to 87 g m$^{-3}$ in the clarified water (representing a 57% reduction) (Table 3). Total P concentration was significantly ($p < 0.001$) reduced from an average of 35.3 g m$^{-3}$ down to 0.4 g m$^{-3}$ in the clarified water (representing a 99% reduction) (Table 3). The DRP

concentration was significantly ($p < 0.001$) reduced from an average of 9.7 to 0.02 g m$^{-3}$ in the clarified water (representing a 99% reduction) (Table 3). There were also significant reductions in the concentrations of ammonium-N (NH$_4$-N), K, Al, B, Cu, Zn, as well as reductions in other parameter values (i.e. pH, BOD, and solids content (Table 3).There were no detectable increases in As, Ca, Cd, Cr, Fe, Mg, Na, Ni or Pb (Table 3). There was a significant ($p < 0.001$) increase in the S concentration due to the S content of the polyferric sulphate coagulant.

**Table 3** Average parameter values for untreated farm dairy effluent, clarified water and treated effluent produced by treatment of the FDE with PFS in the large tank studies

| | Untreated farm dairy effluent Mean | Clarified water Mean | Treated effluent Mean | Difference between untreated farm dairy effluent and clarified water Significance | Difference between untreated farm dairy effluent and treated effluent Significance |
|---|---|---|---|---|---|
| Turbidity (NTU) | 2214 | 17 | 6361 | *** | *** |
| *E. coli* (cfu 100 ml$^{-1}$) | 247,718 | 55 | 22,816 | *** | * |
| Total-N (g m$^{-3}$) | 200 | 87 | 447 | *** | *** |
| NH$_4$-N (g m$^{-3}$) | 56 | 43 | 55 | * | NS |
| Total-P (g m$^{-3}$) | 35.27 | 0.44 | 111.80 | *** | *** |
| DRP (g m$^{-3}$) | 9.68 | 0.02 | 0.03 | *** | *** |
| K (g m$^{-3}$) | 198 | 182 | 195 | * | NS |
| S (g m$^{-3}$) | 28.20 | 224.97 | 320.97 | *** | *** |
| Al (g m$^{-3}$) | 13.83 | 0.23 | 34.38 | *** | *** |
| As (g m$^{-3}$) | nd | nd | nd | | |
| B (g m$^{-3}$) | 0.17 | 0.08 | 0.36 | *** | * |
| Ca (g m$^{-3}$) | 134.44 | 139.41 | 193.95 | NS | *** |
| Cd (g m$^{-3}$) | 0 | 0.34 | 0.00 | NS | NS |
| Cr (g m$^{-3}$) | 0.16 | 0.13 | 0.15 | NS | NS |
| Cu (g m$^{-3}$) | 0.16 | 0.01 | 0.42 | *** | *** |
| Fe (g m$^{-3}$) | 15.60 | 13.56 | 966.15 | NS | *** |
| Mg (g m$^{-3}$) | 40.90 | 39.75 | 51.76 | NS | *** |
| Mn (g m$^{-3}$) | 1.28 | 2.43 | 3.71 | *** | *** |
| Na (g m$^{-3}$) | 55.99 | 56.53 | 59.24 | NS | * |
| Ni (g m$^{-3}$) | nd | nd | nd | | |
| Pb (g m$^{-3}$) | 0.48 | 0.18 | 0.14 | NS | NS |
| Zn (g m$^{-3}$) | 1.31 | 0.50 | 2.94 | *** | *** |
| pH | 7.89 | 5.35 | 5.24 | *** | *** |
| BOD (g m$^{-3}$) | 953 | 322 | 1543 | *** | *** |
| Solids (g m$^{-3}$) | 3173 | 24 | 8961 | *** | *** |
| Water (%) | 99.7 | 100.0 | 99.1 | *** | *** |

Statistically significant differences between untreated farm dairy effluent and the clarified water or the treated effluent are shown at $p < 0.001$ as ***; $p < 0.01$ as **; $p < 0.05$ as * and no significant difference as NS

There were significant differences between measured parameters in treated effluent compared with the untreated FDE (Table 3), this included a significant ($p < 0.05$) reduction in *E. coli* concentration from an average of 247,718 cfu/100 mL in the untreated FDE down to 22,816 cfu per100 mL in the treated effluent (representing a 91% reduction). The DRP concentration was significantly ($p < 0.001$) reduced from an average of 9.7 to 0.03 g m$^{-3}$ in the treated effluent (representing a 99% reduction). Significant increases in turbidity, total-N, total-P, BOD and solids content occurred in the treated effluent due to the coagulation process flocculating the FDE material containing these components (Table 3). There were also increases in the concentration of S, Ca, Al, B, Cu, Fe, Mg, Mn, Na and Zn in the treated effluent due to the increase in solids content of the treated effluent. There were no detectable increases in As, Cd, Cr or Pb in the treated effluent compared to the untreated effluent (Table 3).

## 3.3 Pilot plant trials

### 3.3.1 Static in-line mixer pilot plant

The three test runs of the static in-line mixer pilot plant were all successful in clarifying the FDE produced from three separate washes of the farm yard conducted on three different days. The NTU of the clarified water was significantly ($p < 0.001$) reduced each day from an average of 1864 down to 51 NTU (representing a 97% reduction) (Fig. 4) and the *E. coli* concentration was significantly ($p < 0.001$) reduced from an average of 379,647 down to 9 cfu per 100 mL (representing a 99.99% reduction) (Fig. 5).

The total-N concentration in the clarified water was significantly ($p < 0.01$) reduced each day from an average of 200 down to 61 g m$^{-3}$ (representing a 70% reduction) (Fig. 6). The

total-P concentration in the clarified water was significantly ($p < 0.001$) reduced from an average of 31.8 down to 1.8 g m$^{-3}$ (representing a 94% reduction) and the DRP concentration was significantly ($p < 0.001$) reduced from 16.5 down to 0.09 g m$^{-3}$ (representing a 99.5% reduction) over the three test runs of the pilot plant (Figs. 7 and 8).

### 3.3.2 Sequencing batch reactor pilot plant

The second pilot plant consisted of a sequencing batch reactor (SBR) that was run 15 times and successfully produced clarified water that was used to wash the dairy farm yard. The average turbidity of the untreated FDE was significantly ($p < 0.001$) reduced from 2934 down to 16 NTU (representing a reduction of 99.5%) (Table 4). No other measurements were made during this initial development stage of the SBR pilot plant. The average volume of clarified water produced by each run of the pilot plant was 10,600 L (Table 4) which was greater than the average volume of water (c. 9000 L) required per milking to wash the farm yard on the Lincoln University Dairy Farm and was greater than the average volume of water (c. 7000 L) required each milking to wash the farm yard on an average NZ dairy farm milking 400 cows (DairyNZ 2014).

## 3.4 Pasture field trial

### 3.4.1 Dry matter production

There was no significant difference in the amount of pasture dry matter produced by the application of clarified water (16,547 ± 286 kg DM ha$^{-1}$) or treated effluent (16,176 ± 319 kg DM ha$^{-1}$) compared to the untreated effluent (16,271 ± 322 kg DM ha$^{-1}$) over the experimental period (1 year). As would be expected, there was a significant



Fig. 4 Effect of polyferric sulphate (PFS) treatment of farm dairy effluent (FDE) on turbidity (NTU) in the clarified water used to wash the dairy farm yard
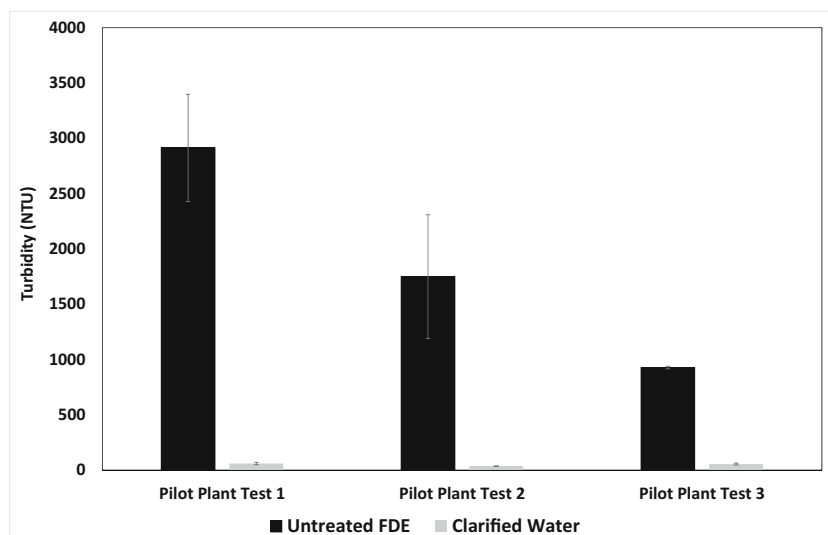
**Fig. 5** Effect of polyferric sulphate (PFS) treatment of farm dairy effluent (FDE) on the *E. coli* concentration in the clarified water used to wash the dairy farm yard (note the $\log_{10}$ scale on the *y*-axis)



### 3.4.2 Plant chemical composition
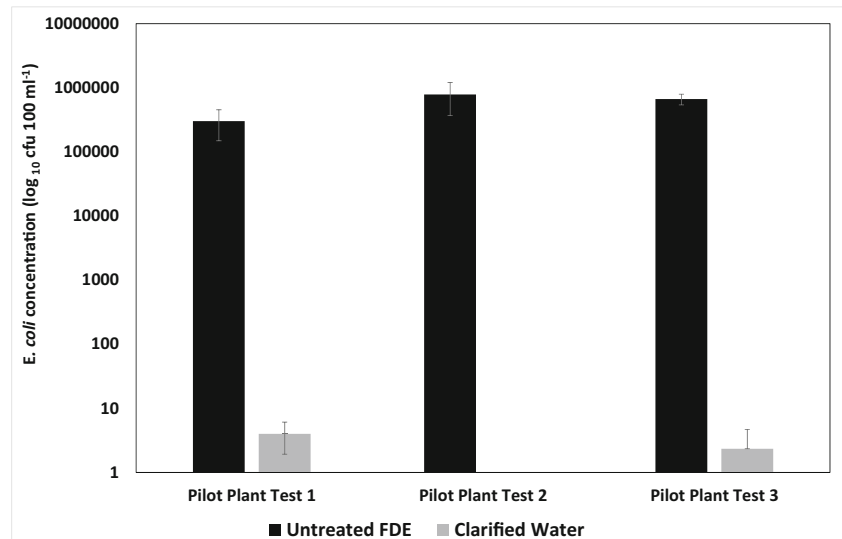
($p < 0.001$) difference between the control treatment ($13,608 \pm 265$ kg DM $ha^{-1}$) and all the effluent treatments due to the higher nutrient contents of the effluent treatments.

### 3.4.2 Plant chemical composition

There was no significant difference between the annual average plant concentrations of N, P, K, Ca, Mg or Na between the untreated FDE and the clarified water or treated effluent plots (Table 5). The concentrations of these macronutrients are within the range of typical concentrations found in New Zealand pastures (McLaren and Cameron 1996). There was also no significant difference between the treatments in the amount of these macronutrients taken up by the pasture (Table 5).

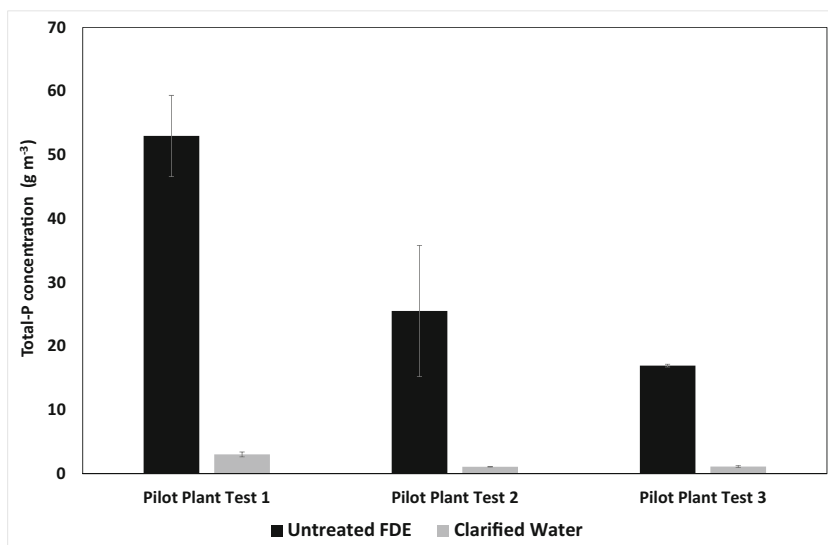The concentration of S was significantly ($p < 0.001$) higher in the plants grown on the clarified water and the treated effluent plots compared to the plants grown on the untreated FDE plots (Table 5a). This resulted in a greater uptake of S in the plants grown on these plots compared to the untreated FDE plots (Table 5b). The higher concentration of S can be attributed to the addition of S in the polyferric sulphate coagulant.

There was a significantly ($p < 0.001$) higher concentration of Fe in the plant material grown on the treated effluent pasture plots compared to the untreated FDE plots and this can be attributed to the Fe present in the PFS coagulant used to treat the effluent. There was no difference in the concentration of Fe in the plants grown on the clarified water plots compared with those grown on the untreated FDE plots (Table 5a). There was no difference between pasture plant concentrations of As, Al, B, Cd, Co, Cu, Cr, Mn, Mo, Ni, Se, Zn or Pb between the untreated FDE plots and the plants grown on the clarified water or treated effluent plots (Table 5a). There was also no

**Fig. 6** Effect of polyferric sulphate (PFS) treatment of farm dairy effluent (FDE) on the total-N concentration in the clarified water used to wash the dairy farm yard
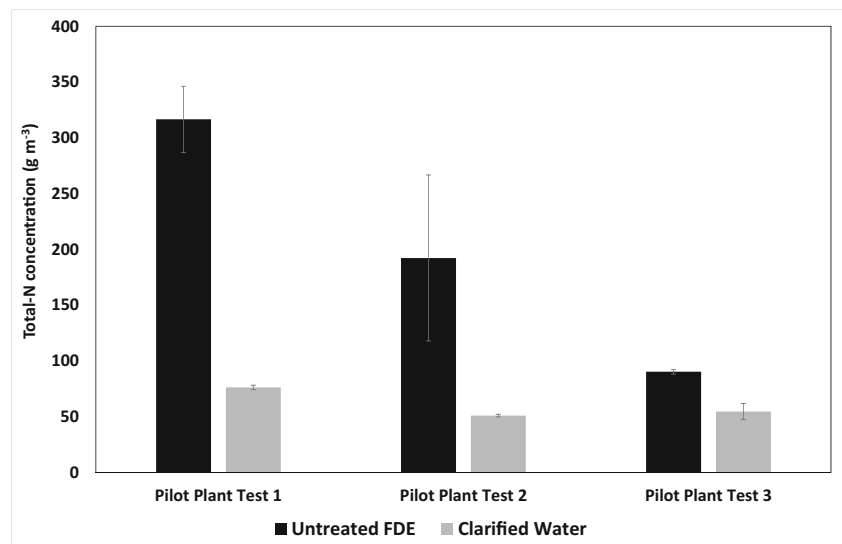
**Fig. 7** Effect of polyferric sulphate (PFS) treatment of farm dairy effluent (FDE) on the total-P concentration in clarified water used to wash the dairy farm yard



## 4 Discussion

The *E. coli* concentrations measured in the clarified water (CW) produced in these trials (< 55 cfu per 100 mL) were about 90% below the critical value (540 cfu per 100 mL) for water that can be used for recreational purposes in New Zealand (New Zealand Ministry for the Environment 2017). These low *E. coli* concentrations therefore represent a lower health risk to farm staff when clarified water is recycled to wash the farm yard compared to 'green water', which has *E. coli.* concentrations that are many times the critical value. In addition, because most of the *E. coli.* have been killed, land

difference in the amount of these trace elements taken up by the plants grown on the clarified water or treated effluent plots compared to the untreated FDE plots (Table 5b).

application of the clarified water would be less likely to cause adverse impacts due to *E. coli* pollution of water than the current practice of land application of untreated FDE (e.g. Wang et al. 2018). Land application of untreated FDE has been reported to cause leaching of bacteria, such as *E. coli*, through soil and thus represent a significant risk to groundwater quality (Culley and Phillips 1982; Aislabie et al. 2001; Oliver et al. 2005); this risk could now be reduced by using this new system to treat FDE.

The reductions in total-N, total-P and DRP indicate that land application of the clarified water would be less likely to cause adverse environmental impacts on water quality (e.g. less risk of eutrophication) than the current practice of land application of untreated FDE. The treatment of FDE with PFS results in the formation of ferric-phosphate chemical bonds that decrease the solubility and thus mobility of phosphorus. Indeed it has been proposed that coagulants, such as

**Fig. 8** Effect of polyferric sulphate (PFS) treatment of farm dairy effluent (FDE) on the dissolved reactive phosphate concentration in the clarified water used to wash the dairy farm yard
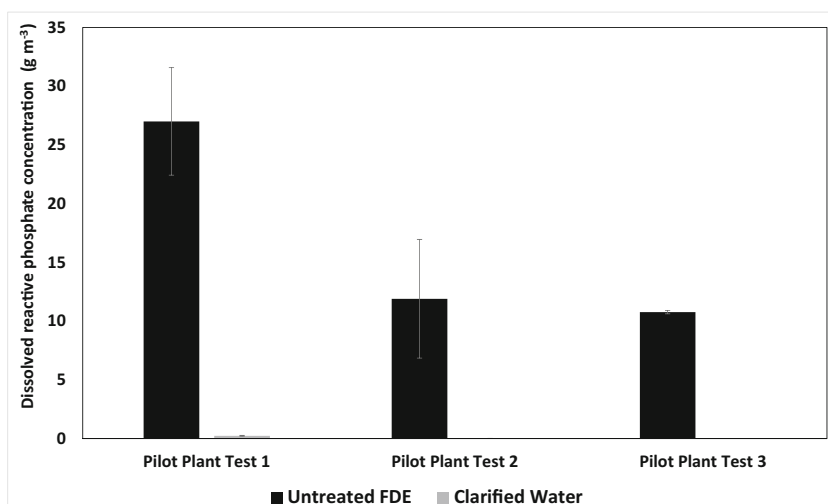
**Table 4** Sequencing batch reactor pilot plant trial results

| SBR pilot plant batch number | Date | Turbidity of untreated FDE (NTU) | Turbidity of clarified water (NTU) | Volume of clarified water produced (L) |
|---|---|---|---|---|
| 1 | 22.03.2018 | 1560 | 16 | 7.000 |
| 2 | 26.03.2018 | 2500 | 17 | 14.000 |
| 3 | 27.03.2018 | 2200 | 14 | 11.500 |
| 4 | 04.04.2018 | 3000 | 45 | 8.500 |
| 5 | 06.04.2018 | 3500 | 45 | 7.000 |
| 6 | 09.04.2018 | 3100 | 8 | 7.000 |
| 7 | 10.04.2018 | 3983 | 5,3 | 8.300 |
| 8 | 11.04.2018 | 3345 | 17 | 11.500 |
| 9 | 24.04.2018 | 3447 | 6,6 | 12.700 |
| 10 | 27.04.2018 | 3600 | 9,7 | 14.000 |
| 11 | 01.05.2018 | 3190 | 15 | 14.000 |
| 12 | 08.05.2018 | 2864 | 12 | 13.000 |
| 13 | 11.05.2018 | 1887 | 14,5 | 13.500 |
| 14 | 15.05.2018 | 2554 | 2,3 | 10.500 |
| 15 | 23.05.2018 | 3281 | 18 | 10.500 |
| | Average | *2934* | *16* | *10.867* |

Average values are shown in italics

aluminium sulphate, be applied directly to land to reduce the mobility of P and thus reduce the risk of P transfer to water via runoff and/or drainage (McDowell and Nash 2012). In the UK, drinking water reservoirs have been treated with ferric sulphate to precipitate the available phosphate in the water column and transfer it into the sediment on the lake bed (Randall et al. 1999).

There was no significant difference between pasture dry matter yield following land application of clarified water or treated effluent (TE) compared to the untreated FDE, and the amount of pasture produced (16,000 kg DM ha$^{-1}$) is a typical amount of dry matter production for an irrigated dairy pasture in Canterbury, New Zealand. This finding indicates that land application of CW or TE will not reduce the amount of plant production compared to the current practice of applying untreated FDE onto land.

The finding that there was no significant difference in plant P concentration or P uptake by pasture plants grown on the CW or TE plots compared to the untreated FDE plots (Table 5) indicates that using polyferric sulphate to treat FDE did not cause a reduction in the amount of P available to plants. This is important because PFS treatment of FDE reduces the DRP concentration in CW and TE, compared to untreated DFE (Table 3), which will reduce the risk of P transfer from soil into water, and that this can be done without reducing P availability to plants, P uptake by plants or plant dry matter production.

The higher concentration of Fe in the plant material can be attributed to the Fe in the PFS coagulant and the fact that most of this Fe accumulates in the treated effluent material (as described above). The average Fe concentration in the treated effluent plant material of c. 250 mg Fe kg$^{-1}$ DM is within the range of concentrations of Fe reported in NZ pastures (which range from 41 to 3850 mg Fe kg$^{-1}$ DM; Campbell et al. 1974; Grey and McLaren 2005). It is therefore unlikely that the slightly elevated Fe concentration in the treated effluent pasture plants compared to the untreated FDE plants would be of concern in relation to an induced stock copper deficiency (Campbell et al. 1974). The average concentration of copper (Cu) in the treated effluent pasture plants (c. 5.56 mg Cu kg$^{-1}$ DM) was not significantly different to the concentration of Cu in the pasture grown on the untreated effluent plots (5.68; Table 5a) and above the critical concentration of 4 mg Cu kg$^{-1}$ DM for pasture eaten by grazing animals (McLaren and Cameron 1996). It should also be noted that cattle can ingest approximately 1 kg of soil per day which is a significant source of Fe, as is drinking water sourced from Fe rich groundwater (often with Fe concentrations of over 100 mg Fe L$^{-1}$; Campbell et al. 1974). In addition, Fe concentrations in plants can be high (often > 1000 mg Fe kg$^{-1}$ DM) when soils become flooded, due to the low redox potential in anaerobic soil causing insoluble ferric ions to be reduced to soluble ferrous ions that can then be taken up by plants (Campbell et al. 1974; McLaren and Cameron 1996). As noted above, ferric sulphate is approved by the FDA as a food additive for human consumption, so a slightly elevated Fe concentration in food products derived from pastures receiving treated effluent should not pose a health concern.

The finding that there was no significant difference in pasture plant concentrations of As, Al, B, Cd, Co, Cu, Cr, Mn, Mo, Ni, Se, Zn or Pb between the untreated FDE plots and the clarified water or treated effluent plots is important because it confirms that there is little or no risk of heavy metal contaminants being introduced into plant material when using polyferric sulphate as a coagulant to treat FDE. For example, the average concentration of Cd in the pasture plants of c. 0.02 mg Cd kg$^{-1}$ DM (Table 5) is at the lower than the typical concentration of Cd (0.06–0.6 mg Cd kg$^{-1}$ DM) reported in New Zealand pastures (Roberts et al. 1994; Grey and McLaren 2005).

This new method of treating farm dairy effluent has been successful in producing clarified water that can be recycled to wash the farm yard and save over 14,000 L per day on a typical NZ dairy farm. If adopted by all 10,500 dairy farms in NZ, this new treatment system could save approximately 41 billion litres of water per year. In addition, land application of clarified water and/or treated effluent would reduce the current risks of water pollution posed by land application of untreated FDE and that this can be achieved without compromising plant growth.

**Table 5** Effect of polyferric sulphate (PFS)-treated clarified water and treated effluent compared with untreated farm dairy effluent (FDE) and control (water only) on (a) plant chemical composition and (b) plant uptake in the pasture field trial

(a)

| Element | Concentration in plant material Control | Untreated FDE | | Clarified water | | Treated effluent | | LSD (0.1%) |
|---|---|---|---|---|---|---|---|---|
| N (%) | 2.609 | 2.696 | a | 2.773 | a | 2.716 | a | 0.181 |
| P (%) | 0.363 | 0.348 | a | 0.350 | a | 0.351 | a | 0.022 |
| K (%) | 2.190 | 2.388 | a | 2.627 | a | 2.483 | a | 0.268 |
| S (%) | 0.288 | 0.275 | a | 0.327 | b | 0.317 | b | 0.025 |
| Ca (%) | 0.636 | 0.614 | a | 0.603 | a | 0.619 | a | 0.058 |
| Mg (%) | 0.175 | 0.167 | a | 0.177 | a | 0.172 | a | 0.014 |
| Na (%) | 0.428 | 0.433 | a | 0.411 | a | 0.408 | a | 0.077 |
| Fe (mg kg$^{-1}$) | 190.284 | 176.220 | a | 193.690 | a | 249.480 | b | 22.803 |
| Al (mg kg$^{-1}$) | 216.834 | 188.791 | a | 201.923 | a | 199.696 | a | 33.786 |
| B (mg kg$^{-1}$) | 8.555 | 8.194 | a | 7.911 | a | 8.346 | a | 1.136 |
| Co (mg kg$^{-1}$) | 0.133 | 0.119 | a | 0.133 | a | 0.125 | a | 0.019 |
| Cu (mg kg$^{-1}$) | 5.433 | 5.686 | a | 5.623 | a | 5.562 | a | 0.673 |
| Mn (mg kg$^{-1}$) | 105.572 | 96.036 | a | 104.131 | a | 96.215 | a | 16.784 |
| Mo (mg kg$^{-1}$) | 0.650 | 0.568 | a | 0.524 | a | 0.547 | a | 0.072 |
| Se (mg kg$^{-1}$) | 0.008 | 0.007 | a | 0.005 | a | 0.006 | a | 0.003 |
| Zn (mg kg$^{-1}$) | 17.729 | 18.016 | a | 18.640 | a | 18.208 | a | 1.268 |
| As (mg kg$^{-1}$) | 0.054 | 0.050 | a | 0.052 | a | 0.053 | a | 0.006 |
| Cd (mg kg$^{-1}$) | 0.020 | 0.020 | a | 0.026 | a | 0.020 | a | 0.006 |
| Cr (mg kg$^{-1}$) | 3.331 | 3.094 | a | 3.242 | a | 3.204 | a | 0.369 |
| Ni (mg kg$^{-1}$) | 1.651 | 1.612 | a | 1.597 | a | 1.581 | a | 0.186 |
| Pb (mg kg$^{-1}$) | 0.129 | 0.111 | a | 0.115 | a | 0.115 | a | 0.010 |

(b)

| Element | Plant uptake Control | Untreated FDE | Clarified water | | Treated effluent | LSD (0.1%) | | |
|---|---|---|---|---|---|---|---|---|
| N (kg ha$^{-1}$) | 356.091 | 439.485 | a | 459.452 | a | 440.300 | a | 48.207 |
| P (kg ha$^{-1}$) | 49.605 | 56.928 | a | 58.086 | a | 57.050 | a | 6.196 |
| K (kg ha$^{-1}$) | 299.711 | 389.816 | a | 436.308 | a | 402.716 | a | 56.538 |
| S (kg ha$^{-1}$) | 39.2455 | 44.910 | a | 54.075 | b | 51.462 | b | 6.197 |
| Ca (kg ha$^{-1}$) | 86.636 | 99.969 | a | 99.604 | a | 100.201 | a | 11.499 |
| Mg (kg ha$^{-1}$) | 23.879 | 27.233 | a | 29.299 | a | 27.793 | a | 3.186 |
| Na (kg ha$^{-1}$) | 58.101 | 70.526 | a | 67.699 | a | 66.043 | a | 14.272 |
| Fe (g ha$^{-1}$) | 2577.030 | 2865.367 | a | 3200.823 | a | 4051.271 | b | 480.702 |
| Al (g ha$^{-1}$) | 2937.415 | 3067.512 | a | 3321.766 | a | 3233.928 | a | 561.550 |
| B (g ha$^{-1}$) | 116.537 | 132.971 | a | 130.771 | a | 134.993 | a | 19.296 |
| Co (g ha$^{-1}$) | 1.8044 | 1.941 | a | 2.194 | a | 2.027 | a | 0.347 |
| Cu (g ha$^{-1}$) | 74.208 | 92.852 | a | 93.114 | a | 90.179 | a | 13.703 |
| Mn (g ha$^{-1}$) | 1438.391 | 1567.570 | a | 1722.939 | a | 1556.006 | a | 292.661 |
| Mo (g ha$^{-1}$) | 8.848 | 9.284 | a | 8.668 | a | 8.857 | a | 1.297 |
| Se (g ha$^{-1}$) | 0.110 | 0.110 | a | 0.085 | a | 0.101 | a | 0.048 |
| Zn (g ha$^{-1}$) | 241.927 | 293.992 | a | 308.645 | a | 295.647 | a | 34.024 |
| As (g ha$^{-1}$) | 0.736 | 0.807 | a | 0.865 | a | 0.860 | a | 0.117 |
| Cd (g ha$^{-1}$) | 0.272 | 0.332 | a | 0.393 | a | 0.320 | a | 0.094 |
| Cr (g ha$^{-1}$) | 45.038 | 50.364 | a | 53.443 | a | 51.942 | a | 7.195 |
| Ni (g ha$^{-1}$) | 22.298 | 26.145 | a | 26.357 | a | 25.590 | a | 3.198 |
| Pb (g ha$^{-1}$) | 1.741 | 1.800 | a | 1.891 | a | 1.863 | a | 0.291 |

Different letters after individual element values indicate significant ($p < 0.001$) differences between untreated FDE compared with clarified water or treated effluent

*LSD* least significant difference at $p < 0.001$

# 5 Conclusions

A new method for treating farm dairy effluent was successfully developed that produced clarified water with significantly reduced *E. coli*, total P, DRP and total N concentrations that could be recycled to wash the farm yard and had a lower potential risk of environmental impact when applied to land compared with untreated FDE. Land application of the clarified water or the treated FDE had no adverse impact on plant growth or plant chemical composition. Impacts of applying the treated and untreated effluents on soil N cycling processes, nutrient leaching and greenhouse gas emissions are reported in two separate papers (in this issue).

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