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An economic assessment of coagulant recovery from water treatment residuals

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ABSTRACT

Coagulant recovery from waterworks sludge for re-use is a key option towards the reduction of chemical usage in the water industry. Whilst this concept is not novel, process economics and recovered product quality issues have limited its implementation. Ion selective membranes have recently been shown to satisfactorily address the latter, but economic feasibility remains a key issue which has been largely overlooked.

This study used empirical data taken from bench-scale tests of coagulant recovery using Donnan dialysis (DD) with bulk chemical prices to determine the operational expenditure (OPEX) for full-scale recovery. Calculated values were compared with existing coagulant dosing procedures, as well as potential alternative recovery technologies based on electrodialysis (ED) and ultrafiltration (UF), to determine the cost benefit.

It was determined that under current commodity and technology prices, coagulant recovery by DD offers no cost benefit in comparison to conventional practice. Process improvements, such as incorporating acid recovery, identifying alternative waste disposal routes and improving membrane performance, can significantly increase economic viability. UF was shown to provide OPEX reductions of around 40% when compared to conventional practice, and ED was found to be cost neutral. None of the assessed technologies are currently able to offer cost benefit for ferric coagulant.

1. Introduction

Over 70% of water treatment works (WTWs) use coagulant-enhanced solid–liquid separation in their flowsheet for water purification [1] and the process is likely to remain an essential water treatment process for the foreseeable future. It is therefore important that the management of chemical usage and resultant sludge production is continuously improved. Large quantities of coagulants are used in the water industry. For example, >326,000 tonnes of coagulant is used per annum across water and wastewater treatment in the UK [2] and proportionally large quantities of sludge are produced (>182,000 tonnes as dry solids per annum from UK water treatment [3]). On a global scale approximately 10,000 tonnes of waterworks sludge are produced each day [4]. With increasing demand on the quantity and quality of potable water [5], a deterioration in water quality coupled with rising commodity and landfill prices, water utilities are actively seeking alternative coagulant options [6]. A 10% reduction in net coagulant usage across UK water and wastewater treatment would allow annual savings exceeding £2.5 m to be made [2], with additional benefits of improved security of supply and reduced environmental impact.

A number of sludge reduction and re-use strategies have been previously considered, offering varying degrees of success [7]. Re-use in bricks and other construction materials have shown no loss in quality but their economics are dependent on their manufacture being close to the source of sludge [3]. Re-use applications for the improvement of soil structure and immobilisation of excess fertiliser nutrients have also been documented [2]. Re-use of sludge in wastewater treatment for phosphorus adsorption, coagulation, sewage sludge co-conditioning and wetland media, have all been successfully trialled but progression to full-scale implementation remains limited [2]. The majority of water treatment sludge is still disposed to landfill [8] and to sewers, providing incidental benefits to downstream wastewater treatment [9]. More formal re-use in this manner is still under development [10-12].

Whilst sludge re-use strategies and reductions of waste to landfill are undoubtedly of benefit, the applications are often dependant on co-operation of external parties and also fail to realise the total value of the constituents within the sludge. A potentially more rewarding approach is recovery and reuse of the coagulant itself, which reduces both the volume of waste requiring disposal [1] and the virgin coagulant demand by 70% [13]. For re-use in drinking water treatment, this requires adequate purification to comply with potable treatment chemical standards without incurring disproportionate costs.

Re-solubilisation of coagulant metals with acid and re-use of the supernatant saw full-scale use in the 1970's but was withdrawn due to concern surrounding its lack of specificity [13]. Whilst acid is able to solubilise the coagulant metal precipitates in the sludge, many other sludge contaminants are also dissolved at low pHs. Of particular concern is the re-solubilisation of natural organic matter (NOM), which may introduce potential disinfection by-product precursors to the water, heavy metals and non-metallic inorganic material (turbidity).

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This has led to the study of a number of separation technologies applied to the acid eluate in order to remove these contaminants. These processes can be broadly categorised into charge and size exclusion. Ion exchange liquids [14], resins [15] and membranes [13], as well as pressure driven membranes are all theoretically applicable to this role. Of the separation technologies considered, the Donnan dialysis (DD) membrane process [13] has shown the most potential.

Research has shown the DD to be capable of recovering a relatively pure coagulant solution (5500 mg l^{-1} aluminium and 3.5 mg l^{-1} dissolved organic carbon, DOC) from acidified waterworks sludge (2400 mg l^{-1} aluminium and 200 mg l^{-1} DOC), without membrane fouling [12]. Feasibility studies performed for non-selective acid extraction from water and wastewater sludges [16,17] have been positive, and suggest non-selective coagulant recovery to be economically viable for plants of >95 MLD capacity [16], or offering payback periods of less than 2 years for a 90 MLD plant [17]. However, these studies are somewhat out of date, with unrepresentative commodity/energy costs, and have ignored the requirement for recovered coagulant quality improvement.

This assessment aims to combine the costs associated with the predicted performance of three prospective coagulant recovery processes with current commodity prices alongside sludge management and disposal costs to provide a cost benefit appraisal for coagulant recovery. The three membrane-based processes considered are DD, ultrafiltration (UF) and electrodialysis (ED) processes.

ED provides an alternative means of extracting coagulant from the organic-rich acidified sludge solution. The technical capability of the technology has been demonstrated in a similar role for recovery of metals from electroplating liquors [18,19], and is widely used to desalt organic-rich solutions [20]. The NOM contaminants have a lower charge to mass ratio than the metal coagulants, such that they would be expected to be retained while the trivalent metal cations would be extracted under the action of the electromotive force [20]. NOM fouling would be expected to be minimal since, as with DD, bulk transport is ostensibly diffusive rather than convective as in a pressure-driven process. Also, the chemical requirements are lower than for DD. Against this, metal hydroxide scaling near the cathode demands control and, most significantly, the process OPEX is constrained by Faradaic principles: the electrical power requirement is proportional to the amount and valency of ions transported.

UF operates by exclusion of the larger NOM contaminant particles whilst selectively permeating the smaller coagulant metal and acid ions. However, lower molecular weight NOM molecules will permeate with the coagulant. As a classical pressure driven process, membrane fouling by the organic material is likely to be significant [21]. However, membrane bioreactors (MBRs) routinely treat waters of 10 g l^{-1} concentration of flocculant particle concentration using coarse ultrafiltration (UF) membranes [22]. In contrast to the DD and ED processes, UF costs are more closely linked to permeate volume than ion concentration [23]. For the relatively highly concentrated ionic solutions involved in coagulant recovery, this would be expected to prove highly advantageous.

Many studies have shown the benefit of diffusion dialysis for acid recovery from electroplating waste liquors [24,25], including >70% yields from nickel electroplating waste [26]. Such a technology is directly relevant to coagulant recovery since it can be used to offset net acid usage and waste generation (two principal drivers of implementing such a process). The economics of combining upstream acid elution of the coagulant with its recovery using each of the three different membrane separation technologies is considered and compared with costs associated with conventional reagent procurement and waste disposal to sewer.

2. Materials and methods

2.1. Operating costs model

The economic analysis was based on data for a large WTWs, treating 200 million litres per day (MLD) and generating approximately 100,000 wet tonnes per year of sludge. Published membrane performance data on DD of metal coagulants [13] was used to determine costs. In the case of UF and ED, no empirically-derived performance data is available for coagulant recovery; conservative performance estimates from published data on relevant applications were used, coupled with standard design calculations. Costs for chemical

Table 1
OPEX model components, the key inputs and boundaries.

Model OPEX components	Economic model inputs	Potential limitations
Fresh coagulant cost as pure metal	Coagulant bulk cost	Market fluctuations
	Coagulant bulk concentration	Different performance at full-scale to lab-scale data
	Metal recovery percentages	
Solubilisation acid	Empirical acid: M^{3+} extraction molar ratio	Variable sludge buffering capacity; mass transfer issues
	Sulfuric acid bulk concentration	
	Sulfuric acid bulk cost	Market fluctuations
DD recovery acid	Empirical acid: M^{3+} DD molar ratio	Variable membrane selectivity
	Sulfuric acid bulk concentration	
	Sulfuric acid bulk cost	Market fluctuations
UF electricity	UF specific energy demand per flow	Fouling decreasing energy efficiency
	Metal content per volume flow	
	Electricity unit cost	Market fluctuations
ED electricity	Current efficiency	Fouling induced resistance
	Stack resistivity	Non-coagulant ion transport
	Faradaic current requirement	
	Electricity unit cost	Market fluctuations
Polishing adsorbent	Empirical DOC : M^{3+} membrane leakage ratio	Higher DOC carryover at full-scale
	GAC K value for DOC adsorption	Poor adsorption at low pHs
	GAC cost per weight	Market fluctuations
Metal recovery membranes	Specific membrane M^{3+} flux	Different performance at full-scale to lab-scale data
	M^{3+} flow rate in sludge	
	Membrane cost per unit area	Market fluctuations
Acid recovery membranes	Specific membrane acid flux	Reduced performance due to high DOC content
	Acid production rate in acidic residuals	Different performance at full-scale to lab-scale data
	Membrane cost per unit area	Market fluctuations
Neutralisation and disposal	Acid amount in unrecovered residuals	Market fluctuations
	Molar ratio of lime : acid for neutralisation	Ease of thickening
	Cost of lime	Changes due to legislation
	Mass of neutralised sludge (at 25% dry solids)	
	Cost of landfill per mass of inert waste	