Nutrient balancing for enhanced activated sludge reactor performance: UK perspective

J.E. Burgess*, J. Harkness**, P.J. Longhurst* and T. Stephenson*

*School of Water Sciences, Cranfield University, Cranfield, Bedford MK43 0AL UK
**Current address: Urban Systems Ltd, 200-286 St. Paul Street, Kamloops, BC, V2C 6G4, Canada

Abstract Trace metals (K, Fe, Mg, Cu, Ca, Mn, Al, Zn, Mo, Co) and vitamins (biotin, niacin, pyridoxine, lactoflavin, thiamine, pantothenic acid) were tested for enhancing chemical oxygen demand (COD) and toxicity removal in activated sludge treating trade effluent. Rapid respirometry screening indicated that micronutrient addition could not ameliorate macronutrient deficiencies, but could significantly improve the degradation of hard COD in the wastewater (up to 4.24 kg COD/kg MLSS/d, i.e. 320% of the control) with no significant effect on the air requirement of the sludge. Several positive effects led to the conclusion that micronutrients have the potential to optimise the process performance of activated sludge plants treating industrial wastewater. Porous pots were used to further trial eight of the micronutrients. The retention of biomass in the pots was increased in all cases. Improvements in the degradation of COD (up to 260% of the control) were observed while biological oxygen demand (BOD) degradation was not affected. This implied the use of recalcitrant substrate components as a food source. Toxicity tests showed that the effluents from the experimental porous pots were less toxic than the control effluents. The effects of niacin addition in activated sludge treatment of industrial waste at pilot-scale were: improved sludge handling, increased COD, ammonia, suspended solids and phosphorus removal. Several industrialists saw micronutrient addition as a route to successful adaptation of processes to accommodate toxicity-based legislation.

Keywords Amtox™; direct toxicity assessment; industrial wastewater; recalcitrant compounds; trace elements; vitamins

Introduction The possible introduction of direct toxicity assessment (DTA) into the UK has brought about the need for investigating enhanced chemical oxygen demand (COD) and toxicity removal. DTA is the consideration of the effluent as a whole in terms of the impact it may have on receiving waters and is designed to provide a simple and easily understood measure for the protection of aquatic life from potentially harmful effluent discharges. It allows for the control of toxic discharges, the setting of toxicity reduction targets and provides for the assessment of improvements in the quality of receiving waters (Environment Agency, 1996). Currently, any individual or company that discharges effluent is bound under Section 7 of the UK Environmental Protection Act (EPA), 1990 (HMSO, 1990) to use the best available technique not entailing excessive cost (BATNEEC) to “render harmless any materials released into environmental media”. In addition, it is an offence under section 85 of the Water Resources Act (WRA), 1991 (HMSO, 1991) “to cause or knowingly permit any poisonous, noxious or polluting matter or any solid waste matter to enter controlled waters”. The exceptions to these rules are discharges made into a receiving water with an EPA’90 or WRA’91 authorisation or consent. Discharge consents are set out as numeric targets, usually concentrations of key chemical components. The advantages of this system lie in the ease of measurement, and hence enforcement, as well as in the capacity of the system to diagnose the source of pollutants discovered in the receiving waters. The shortfalls of numeric targets include the physical limitations (no company can measure every component of its effluent), the lack of chemical-specific toxicity data (leading to pointless measurements with no indication of polluting potential), and the complete failure to account for interactions between wastewater components. The ultimate goal for the UK aquatic
environment is the meeting of narrative targets, i.e. use-related water quality objectives (Tinsley, 1998). These targets include consent clauses but do not include any specific methods for compliance. Currently, compliance with numeric targets does not always equate to compliance with the narrative targets. The aim of the Environment Agency (EA) is to introduce DTA as an additional measure of effluent quality in order to apply a more ecologically relevant test and provide an early warning system to avert pollution incidents. DTA is a measurement of the toxicity of an entire effluent, rather than the concentration of specific effluent components. It can be used as a trigger for action to minimise lethal toxicity from point source discharges. DTA should improve the public image of industries shown to produce effluents of low toxicity but may have major impacts on those whose effluents are toxic, but have previously complied with their numeric targets.

Activated sludge treatment of waste is an aerated oxidation process. It is one of the best established and most widespread biological wastewater treatment processes in the developed world for both domestic and industrial wastewaters (Clark and Stephenson, 1998), and as such its adaptability to accommodate new demands in effluent quality is of great importance. The process relies on the suspension of a microbial population mixed with wastewater under aerobic conditions. Microbial growth brings about the removal of organic matter from the waste as the compounds in the feed are oxidised by the micro-organisms present in the sludge. The end results are microbial biomass and products of oxidation such as CO$_2$, NO$_3^-$, SO$_2^{4-}$ and PO$_3^{3-}$. Activated sludge plants have been used to treat a wide range of industrial wastes by effectively accelerating natural processes involving chemical, biological and physical agents. A typical activated sludge plant can be schematically represented (Figure 1). The aeration in an activated sludge plant speeds up the growth of the bacteria present at the outset and increases the number of collisions between flocs and hence their chance of aggregation into larger flocs containing non-living particles. This process occurs within a set range of environmental conditions, which limit the activity of the organisms responsible for the treatment process. For this reason, biological wastewater treatment requires certain environmental parameters such as dissolved oxygen (DO) levels, mixing regime, provision of nutrition, trace element and vitamin supply and physical conditions such as temperature and pH. The residence time of the cells within the plant must be sufficient to allow reproduction to occur in order for the influent waste to be treated effectively. As reproduction rates depend on growth and hence on metabolic rate, nutrient paucity (and associated slow cell growth) coincide with poor waste treatment.

![Figure 1 Schematic representation of a typical activated sludge plant](https://iwaponline.com/wst/article-pdf/41/12/223/427137/223.pdf)
The overall aim of this biological treatment process is to make carbon the limiting factor and hence nutrition must be balanced to achieve the lowest possible quantities of carbon in the effluent (Speitel and Segar, 1995). Until recently, activated sludge process performance has been measured in terms of the minimum effluent biological oxygen demand (BOD) and suspended solids (SS). However, increasing emphasis on effluent toxicity and the removal of priority pollutants has highlighted the need to remove COD and recalcitrant organic compounds (or “hard COD”), in particular from industrial wastewater streams. Enhanced COD removal is possible by changing operating procedures, but such techniques can often produce inconsistent results (Singleton, 1994). Environmental factors can affect biodegradation by changing the availability of nutrients and target compounds, thus preventing the growth of micro-organisms (Daubaras and Chakrabarty, 1992). Recalcitrance is a problem in industrial wastewater treatment owing to an abundance of xenobiotic compounds which resist degradation; it can arise from inappropriate conditions, inadequate nutrients and the supply of a substrate which does not activate the appropriate enzymes (Eckenfelder and Musterman, 1994). The availability of nitrogen and phosphorus can be limiting factors in the degradation of hydrocarbons and supplements where concentrations are low can lead to improved wastewater treatment (Leahy and Colwell, 1990). Nutrient augmentation includes the addition of substances such as micronutrients which increase cometabolism or which induce degradative genes (Singleton, 1994). The role of micronutrients in aerobic biological wastewater treatment is not well defined. To achieve sufficient treatment of industrial wastewater, it is necessary to supply activated sludge with the micronutrients that enable the strains capable of degrading the recalcitrant compounds to thrive and produce a low COD effluent, free of recalcitrant components. COD consists of hard COD, the recalcitrant fraction, and “soft COD”, which is more readily degradable. Enhanced COD removal indicates increased degradation of recalcitrant compounds, which are often responsible for the toxicity of a wastewater stream. Recent research into advanced COD removal has focused on changes in operating conditions (Franta et al., 1994), but this normally results in higher investments and operating and maintenance costs, but not always in lower effluent COD. The overall aim of the work here is to discover how micronutrients may provide a method for establishing low effluent toxicity and COD concentrations, thus allowing wastewater treatment to develop in response to the ever-increasing environmental legislation to which it is subject.

Micronutrient screening
This research addresses the need for low-cost optimisation of aerobic biological treatment of recalcitrant industrial wastewater. The wastewater used throughout this study was taken from the return activated sludge line of an activated sludge plant that pre-treats pH-balanced, screened wastewater from a chemicals manufacturer and discharges it to a municipal wastewater treatment works. The general aims were to increase process performance, increase and stabilise the maintenance of mixed liquor suspended solids (MLSS) concentrations and to anticipate the future need for improved toxicity removal. Micronutrients dosed directly into the MLSS appeared to be a potential option. The results of a postal survey (Burgess et al., 2000) supported these initial aims. The survey data suggested strongly that new developments in the optimisation of biological treatment processes would greatly increase the ability of wastewater treating industries to accommodate new, toxicity-based targets for effluent quality.

Atomic emission spectrophotometry using an Inductively Coupled Plasma Atomic Emission Spectrophotometer (Thomas Jarrell Ash, Plasma 300) was used to identify the missing or deficient trace elements in the industrial waste as compared to theoretical trace metal requirements of activated sludge micro-organisms. The concentrations of available
nitrogen, phosphorus and sulphur were also measured and compared with the theoretical requirements of bacteria for these nutrients. The theoretical vitamin requirements and their doses were taken from the literature. This procedure produced a list of micronutrients requiring supplementation (Table 1).

A series of respirometer screening tests was performed using the parameters of COD removal efficiency and oxygen uptake of activated sludge receiving the chemical wastewater supplemented with doses of micronutrients. The tests were looking for micronutrients that showed a potential for maximising COD removal without compromising the condition and sustainability of the biomass. The first phase of testing (Burgess et al., 1999a) involved balancing the nitrogen and phosphorus content of the wastewater before addition of micronutrients. Six trace metals and six vitamins were used as chemical additives dosed into the mixed liquor. Control sludge batches (receiving no micronutrient supplements) attained an average COD removal rate of 1.941 kg COD/kg MLSS/d. Dosing micronutrients into the mixed liquor produced COD removal rates of up to 2.240 kg COD/kg MLSS/d. The greatest improvement in wastewater treatment was attained by the addition of 1.0 mg/l niacin to the wastewater, resulting in an unchanged oxygen uptake rate (0.011 kg O₂/kg MLSS/d) and increased COD removal (2.240 kg COD/kg MLSS/d). The results suggested that the vitamins biotin, pantothenic acid and niacin were required by activated sludge bacteria and that calcium enhanced the stimulatory effects of niacin and manganese.

The second screening phase (Burgess et al., 1999b) was performed without N and P balancing. This meant the effluent was phosphorus-limited, according to the standard ratios for COD:N:P. Six trace metals and three vitamins were used as chemical additives dosed into the mixed liquor. All of the supplements resulted in increased COD removal rates. Control sludge batches (receiving no micronutrient supplements) attained an average COD removal

<table>
<thead>
<tr>
<th>Micronutrients</th>
<th>Range of theoretical micronutrient requirements (mg/l)</th>
<th>Concentration of micronutrients detected in the wastewater (mg/l)</th>
<th>Dose added (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>15.0 minimum¹</td>
<td>32.00</td>
<td>none</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>3.0 minimum¹</td>
<td>1.69</td>
<td>1.30</td>
</tr>
<tr>
<td>Sulphur</td>
<td>1.0 minimum¹</td>
<td>100.0</td>
<td>none</td>
</tr>
<tr>
<td>Calcium</td>
<td>0.4–1.4</td>
<td>0.44</td>
<td>1.0</td>
</tr>
<tr>
<td>Potassium</td>
<td>0.8–3.0</td>
<td>95.0</td>
<td>none</td>
</tr>
<tr>
<td>Iron</td>
<td>0.1–4.0</td>
<td>1.20</td>
<td>none</td>
</tr>
<tr>
<td>Magnesium</td>
<td>0.4–5.0</td>
<td>10.0</td>
<td>none</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.01–0.5</td>
<td>&lt;1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Copper</td>
<td>0.01–0.5</td>
<td>&lt;1.0</td>
<td>none</td>
</tr>
<tr>
<td>Aluminium</td>
<td>0.01–0.5</td>
<td>0.02</td>
<td>1.0</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.01–0.5</td>
<td>&lt;1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>0.2–0.5</td>
<td>&lt;1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>Cobalt</td>
<td>0.1–5.0</td>
<td>&lt;1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Biotin</td>
<td>0.05–0.1</td>
<td>–</td>
<td>1.0</td>
</tr>
<tr>
<td>Niacin</td>
<td>0–10</td>
<td>–</td>
<td>1.0</td>
</tr>
<tr>
<td>Thiamine (B1)</td>
<td>0.3–1.2</td>
<td>–</td>
<td>1.0</td>
</tr>
<tr>
<td>Lactoflavin (B2)</td>
<td>0.5–2.0</td>
<td>–</td>
<td>1.0</td>
</tr>
<tr>
<td>Pyridoxine (B6)</td>
<td>0.1–10</td>
<td>–</td>
<td>1.0</td>
</tr>
<tr>
<td>Pantothenic acid</td>
<td>0.01–2.0</td>
<td>–</td>
<td>1.0</td>
</tr>
</tbody>
</table>

¹ From suggested COD:N:P ratio of 100:10:1, Beardsley and Coffey, 1985
rate of 1.335 kg COD/kg MLSS/d. Dosing micronutrients into the mixed liquor produced improved COD removal rates. The largest improvement in COD removal was attained by the addition of pyridoxine to the wastewater, resulting in a slightly greater oxygen uptake rate (0.036 kg O₂/kg MLSS/d) and a COD removal rate of 4.239 kg COD/kg MLSS/d, a threefold increase compared with the control. All of the vitamin supplements resulted in improved COD removal. The results suggested that the vitamins niacin, lactoflavin and pyridoxine were required by activated sludge biomass under phosphorus-limited conditions. In general, the data indicated that while micronutrient addition could not ameliorate macronutrient deficiencies, certain micronutrients were able to improve significantly the degradation of COD in the wastewater with little or no effect on the oxygen demand of the sludge. It was concluded that micronutrient supplements had the potential to optimise biological treatment of industrial wastewaters which are nutrient-limited or changeable.

Biodegradability testing

After the micronutrient screening, larger scale degradability tests were used to ascertain the levels of BOD and COD removal achievable, the effects of micronutrients on the sludge population, and the potential of micronutrient additions to remove toxic components from the industrial wastewater. Small scale activated sludge reactors were used to test trace elements and vitamins over periods of six sludge ages.

The bench scale work demonstrated how trace elements could provide a method for establishing low effluent COD concentrations and removing recalcitrant constituents from industrial wastewaters (Burgess et al., 1999c). The research focused on the impact of trace metal supplementation to industrial waste in terms of the performance of activated sludge reactors treating a high-strength, recalcitrant effluent. A four-lane porous pot testing facility (USEPA, 1996; Painter and King, 1978) fed with the industrial wastewater was employed to ascertain the optimal trace element type and level of macronutrient availability. Supplements of a wide range of micronutrients were supplied to the porous pots, and their ability to improve the biodegradation of the wastewater was assessed in terms of BOD and COD. The data were normalised so that the control pot from each experiment was assigned the value of 100, and the test pot data varied accordingly. Retention of biomass in the reactors was increased in all cases, in excess of 100% with specific trace metals. Improvements in the degradation of COD were observed (Figure 2), while BOD removal efficiency was not affected proportionally. This implies increased use of recalcitrant substrate components as a food source. Results from this study demonstrated significant improvements in the process’s ability to biodegrade recalcitrant COD.

Figure 2 Normalised COD removal data for porous pots dosed with trace metals and vitamins
Note: toxicity tests. Composite samples of selected effluents were taken over three days and tested for toxicity to nitrifying bacteria using 2h toxicity tests in an Amtox™ (PPM Ltd., Ammonia Toxicity Monitor Version 1.01F), with 80ml immobilised nitrifying cultures (PPM Ltd., Wild Type Immobilised Nitrifiers) and a baseline removal limit of 60%. Amtox™ has been discussed in the literature (Hayes et al., 1998) and is under consideration for use as a tool in DTA. As the Amtox(tm) uses ammonia removal efficiency of nitrifiers to measure toxicity, the results are indicative of the potential impact the sampled wastewater may have on a sewage treatment works. The toxicity of the sampled wastewater is represented by the loss of ammonia removal efficiency over the test period. A non-toxic wastewater will allow the removal efficiency to remain above the baseline for the duration of the test.

Parallel to the trace element work, vitamins were dosed continuously in the bench scale activated sludge simulations. Measuring BOD₅ and COD removal, oxygen uptake and MLSS monitored the effect on process efficiency. After 48 days of chemical treatment the COD removal of the niacin-treated simulation was significantly higher than that of the control (removal rate kg/kg MLSS/d = 260% of control). BOD removal from treated and control samples was not significantly different. The best results in terms of sustained improvements in BOD removal efficiency were observed in the reactors dosed with phosphorus/pyridoxine and phosphorus/niacin. The porous pot receiving pyridoxine alone removed less of the influent BOD than the control and the two pots supplied with the lower doses of phosphorus/niacin and phosphorus/niacin/calcium were no more efficient than the control: these additions produced higher maximum BOD removal, but more variable reactor performance. The trends in COD removal efficiency were similar for each of the test porous pots, indicating that the phosphorus plus niacin dosed reactor performed significantly better than all of the others during the dosing period.

Toxicity tests were performed using an Amtox™ toxicity monitor. The toxicity of the porous pot effluents was expected to correlate quite closely with the mean effluent COD concentrations, but this was not the case. All of the effluents from the experimental reactors were less toxic than the control reactor effluent samples. Supplements of molybdenum/lactoflavin and phosphorus/niacin allowed the effluent to be considered to be non-toxic, as the ammonia removal efficiency of the bacteria exposed to these effluents remained above the baseline level of 60% removal (Figure 3). The results indicated that the most promising micronutrient addition (phosphorus and niacin mixture) warranted investigation at pilot-scale, where their effects on sludge handling and nitrification could be assessed in addition to BOD, COD and SS removal.

Pilot scale trial and industrial application
The overall effects of nutrient addition in activated sludge treatment of industrial waste that were demonstrated at pilot-scale can be summarised as: improved sludge handling and...
increased COD, ammonia, SS and phosphorus removal. The results of phosphorus and niacin dosing at pilot-scale confirmed the trends in MLSS maintenance and COD, BOD and ammonia removal observed at bench-scale. Since effluent toxicity at bench-scale was seen to be positively correlated with effluent pH and COD concentrations, and negatively correlated with effluent ammonia (within the range 18–25 mg/l), it was reasonable to infer that the same correlations apply at pilot-scale. If this is the case, the higher pH and COD concentration observed in the effluent from the control rig of the pilot system effluent implied greater toxicity in the control effluent than in that of the test plant, and the results obtained imply enhanced toxicity removal by the activated sludge and demonstrate the improved degradation of recalcitrant compounds indicated by increased COD removal which is not associated with increases in BOD removal (Table 2). The net effect was stimulation of the activated sludge micro-organisms with no inhibitory effects from micronutrient addition over a longer test period observed.

The work at all scales indicated that micronutrient addition could be a valuable tool for companies wishing to improve the levels of COD and toxicity removal from industrial wastewaters attainable by biological treatment processes. However, technical merit alone is not enough for a technology to become common practice, so an assessment was made of the

<table>
<thead>
<tr>
<th>BOD_5</th>
<th>COD</th>
<th>NH_3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>Test</td>
<td>Control</td>
</tr>
<tr>
<td>Feed</td>
<td>effluent</td>
<td>Feed</td>
</tr>
<tr>
<td>Max</td>
<td>1100</td>
<td>890</td>
</tr>
<tr>
<td>Mean</td>
<td>804</td>
<td>421</td>
</tr>
<tr>
<td>Min</td>
<td>278</td>
<td>175</td>
</tr>
<tr>
<td>SD</td>
<td>287</td>
<td>231</td>
</tr>
<tr>
<td>RSD (%)</td>
<td>35</td>
<td>54</td>
</tr>
<tr>
<td>t-test</td>
<td>t=1.09, df=10, cl=1 SD</td>
<td>t=0.53, df=17, cl=1 SD</td>
</tr>
<tr>
<td>Removal efficiency (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>82</td>
<td>71</td>
</tr>
<tr>
<td>Mean</td>
<td>26</td>
<td>37</td>
</tr>
<tr>
<td>Min</td>
<td>-220</td>
<td>-51</td>
</tr>
<tr>
<td>SD</td>
<td>85</td>
<td>36</td>
</tr>
<tr>
<td>RSD (%)</td>
<td>331</td>
<td>99</td>
</tr>
<tr>
<td>t-test</td>
<td>t=1.09, df=10, cl=1 SD</td>
<td>t=1.07, df=16, cl=1 SD</td>
</tr>
<tr>
<td>Removal rate (kg/kg MLSS/d)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>0.075</td>
<td>0.029</td>
</tr>
<tr>
<td>Mean</td>
<td>0.034</td>
<td>-0.001</td>
</tr>
<tr>
<td>Min</td>
<td>0.003</td>
<td>-0.031</td>
</tr>
<tr>
<td>SD</td>
<td>0.024</td>
<td>0.017</td>
</tr>
<tr>
<td>RSD (%)</td>
<td>70.38</td>
<td>-1199.13</td>
</tr>
<tr>
<td>t-test</td>
<td>t=1.06, df=10, cl=1 SD</td>
<td>t=1.07, df=16, cl=1 SD</td>
</tr>
</tbody>
</table>
t=critical t ratio; df=degrees of freedom; cl=confidence limit; SD=standard deviation; RSD(%)=relative standard deviation
potential of micronutrient addition for industrial wastewater treatment. Work was planned to investigate the extent to which UK industry would be prepared to adopt micronutrient addition as an option for reducing wastewater toxicity in preparation for the introduction of DTA. Interviews with industrialists were used to explore the options open to companies to deal with risks, and to assess the potential value of micronutrient addition in removing the risks associated with DTA. All of the respondents had been involved in decision making for the removal of pollutive potential of industrial effluent and had participated in the nationwide process of conference and debate in the run-up to the introduction of DTA.

The interviews focused on the potential use of micronutrient addition in response to DTA. The results showed that around half of the participants had considered it as an option in the past, and the overwhelming majority of participants numbered micronutrient addition among their list of options for effluent treatment in the future. Among the comments made regarding micronutrient addition were several positive opinions: cost benefits, sustainability and performance featured strongly in the reasons to employ micronutrients, but there were also some negative comments: usually cost. Over 90% of the participants included micronutrient addition in their lists of options for adaptation to future effluent quality limits. Many participants saw themselves vulnerable to the possible changes brought about by the introduction of DTA. However, with micronutrient addition among their options, companies with the opportunity to treat or pre-treat their own effluents perceived the risk to themselves as being reduced. They saw micronutrient addition as a route to successful adaptation to DTA, based on their companies’ processes and the trials performed with micronutrient addition in biological waste treatment carried out here. If micronutrient addition is made more evident and therefore available, then toxicity-based regulation could be implemented more easily.

Conclusions
Respirometry screening can produce a comparative measure for predicting the potential of micronutrient additions, although the rates of respiration and substrate degradation can not be assumed to prevail at all scales of operation. The dosing regimes: phosphorus/biotin, phosphorus/pantothenic acid, phosphorus/manganese, phosphorus/calcium/manganese and phosphorus/ calcium/ niacin stimulated the biomass to remove COD. The addition of several mixed and single micronutrient doses to phosphorus-limited wastewater improved COD removal, but micronutrient supplements can not replace phosphorus balancing. At bench-scale, improvements in the degradation of COD and removal of toxicity were observed while BOD₅ degradation was not affected, implying the increased use of recalcitrant substrate components as a food source when a balanced phosphorus and micronutrient supply is provided. The removal of recalcitrant COD and hence of priority pollutants and toxicity can be improved without the need for expanding existing wastewater treatment or pre-treatment plants. Phosphorus/niacin dosing at pilot-scale showed that maintenance of biomass, COD, SS, phosphorus and ammonia removal can be improved. The increased COD removal is not associated with increases in BOD₅ removal and therefore demonstrates the improved degradation of recalcitrant compounds. This implies enhanced toxicity removal by the activated sludge.

Current operating levels in activated sludge plants are not perceived to be sufficient for operators to accommodate DTA. Micronutrient addition is considered to be a viable option by industrialists for accommodating DTA legislation and compliance.

Acknowledgements
The authors would like to express their thanks to the UK Engineering and Physical Sciences Research Council and Yorkshire Water Services Ltd. for financial support during this research.
References


USEPA, (1996). Fate, transport and transformation test guidelines. OPPTS 835.3220 Porous pot test. USEPA, Cincinnati, Ohio, USA.