COMBINED ARTIFICIAL WETLAND AND HIGH RATE ALGAL POND FOR WASTEWATER TREATMENT AND PROTEIN PRODUCTION

A. Wood, J. Scheepers and M. Hills

National Institute for Water Research, CSIR, P.O. Box 395, Pretoria, South Africa

ABSTRACT

The potential to optimize wastewater utilization, whilst achieving satisfactory nutrient removal has been investigated through a simple system combining an Artificial Wetland with a High Rate Algal Pond (HRAP). Receiving septic sewage at a surface loading equivalent to 13.5 cm/day the Wetland achieved COD removals of 59.2%, NH₄-N of 34.6%, PO₄-P of 31.9% and SS of 78%. The HRAP selectively cultivated an easily harvestable filamentous green alga through a combination of short hydraulic residence times (<3 days), and microscreens as selectors over the effluent stream. Passage of the effluent through this stage permitted COD removal to increase to 79.4%, NH₄-N to 82.8% and PO₄-P to 54.1%, whilst generating a highly proteinaceous (42% by wt) biomass at a rate of approximately 50 tons/hectare/year. This paper discusses the performance of the pilot scale facility over a twelve month period, identifying biological and operational influences on the system, and the physiological mechanics by which the wastewater treatment is accomplished.

KEYWORDS

Artificial Wetland, High Rate Algal Pond, Wastewater treatment, Protein Production.

INTRODUCTION

It is often the case that areas of the world where water is at a premium are also areas where the infrastructure for sophisticated, high technology wastewater treatment systems are not well established. Therefore, a very real need exists for simple, low cost, low technology, robust systems capable of producing high quality effluents. Oxidation pond systems are widely recognized as the accepted form of simple wastewater treatment, achieving their success through the combination of heterotrophic and photosynthetic activities in the process of nutrient removal. It is possible to systematically enhance these processes, whilst generating useful by-products, through the development of High Rate Algal Ponds (HRAP’s) and Artificial Wetlands.

High Rate Algal Ponds have been investigated since the 1960’s (Goldman, 1979; Soeder, 1980; De Pauw, 1984), but have not generally progressed beyond the pilot scale due to the inherent problems of species control, harvesting, and processing of the microalgae. An innovative development by Pretorius (1984) permits the selective cultivation of a single, easily harvestable filamentous green alga through a combination of short hydraulic residence time and microscreens operating as selectors on the effluent stream.

The reliance of the selective process on short hydraulic residence times imposes excessive organic loadings if the algal pond receives sewage directly. It is therefore necessary to pretreat the sewage prior to the algal pond. Artificial Wetlands provide a simple answer
to this requirement, by creating in effect, a low loaded biological filter of which the main function of the plants is to supply oxygen to the bacteria in the root zone (Alexander, 1986).

The combination of these two technologies offers a simple, viable and valuable water purification system particularly appropriate to the needs of rural, developing areas. This paper describes investigations undertaken at the National Institute for Water Research in South Africa to evaluate and develop this promising concept in appropriate technology.

DESCRIPTION OF THE SYSTEM

The study was based on a treatment system which consisted essentially of two similarly sized units operating in series and receiving septic sewage, one acting as a Artificial Wetland, the second as the High Rate Algal Pond (Fig. 1). Each unit was 22 m long x 11 m wide and of 400 mm nominal depth. The Artificial Wetland, having been converted from an obsolete drying bed, had slopes from the longitudinal sides towards the middle and a slope from end to end. The influent was discharged at the far end of the bed through a perforated 50 mm plastic pipe, at a rate of 25 l/min or 13.5 cm/day. The effluent from the bed is then pumped from the central sump into the algal pond.

![Fig. 1. Schematic representation of the combined Artificial Wetland, High Rate Algal Pond systems](https://iwaponline.com/wst/article-pdf/21/6-7/659/100420/659.pdf)

The wetland bed of coarse gravel media was planted with *Arundo donax* (Spanish grass) and two 2 metre bands of *Typha sp.* (cattail) at a density of 6 rhizomes/m². *Arundo donax* physically resembles *Phragmites* yet has a more vigorous growth rate, which was considered to make it potentially more efficient at oxygen transfer to the rhizosphere. The two bands of *Typha sp.* were included to act as denitrification zones, since they are reported to be less efficient at oxygenating the rhizosphere, and anoxic conditions would prevail (Alexander, 1986).

The HRAP was of a meandering channel configuration, with the selective screen system incorporated into the effluent control arrangement. Mixing was provided by paddle wheel, with the excess algal biomass being independently wasted over a 250 μm inclined polypropylene screen.

The operation of the selective screen system consistently selects for the filamentous alga *Stigeoclonium* sp. to the virtual exclusion of other species (Hensman, 1985). The *Stigeoclonium* sp. is naturally a benthic alga, yet under the conditions created in the pond, develops as spherical clusters of 5 to 10 mm in diameter of short filaments radiating from a central nucleus. In order to achieve greatest nutrient removal and algal productivity, the HRAP wastage rate was controlled to maintain a level of approximately 150 mg/l in suspension.
ANALYSES

Effluent samples were taken of the septic tank, the wetland, and the algal pond three times a week. These were analysed gravimetrically for suspended solids through Whatman GFC filter papers. The filtrate was analysed for ammonia, orthophosphate, nitrate and nitrites combined, by Technicon CSM6 Autoanalyzer. Unfiltered COD was determined titrimetrically after dichromate reflux according to Standard Methods (1980).

The dissolved oxygen, temperature and pH levels within the HRAP were monitored daily at 08h00, 10h00, 12h00 and 15h00.

RESULTS AND DISCUSSION

For the sake of clarity, the results and discussion are presented separately for the two stages of the system.

Artificial Wetland Results

Passage of the effluent through the Wetland resulted in substantial pollutant removal, through the combined activities of the macrophytes, microorganisms and substrata. The results are presented for the operational period between August 1986 and September 1987. Figures 2 and 3 illustrate the pollutant levels. Table 1 indicates mean pollutant levels for the period, and percentage removals efficiency.

Fig. 2. Influent and effluent levels of Ammonium and Phosphorus of the Artificial Wetland

Fig. 3. Carbonaceous removal, as COD, through the Artificial Wetland
In considering the results, it should be borne in mind that the requirement of the algal selection system for short hydraulic residence times, and the decision not to modify the drainage arrangement of the obsolete gravel bed limited the optimization of both loading rates and flow distribution through the wetland, which affected total treatment potential.

Previous to planting the macrophytes the gravel bed had been operated simply as a flow through coarse filtration stage. This achieved COD removal of 21%, (from 220 to 173 mg/l), suspended solids of 60.5% (from 86.1 to 34 mg/l) Ammonia increased 7.3% (from 34.6 to 37.1 mg/l) and phosphate 12.5% (from 6.74 to 7.58 mg/l). At this time vegetation developing in the bed was regularly removed and therefore contributed little to the treatment capacity of the system. In fact, substrata compaction resulted, leading to flow disruptions and short-circuiting directly to the sump. It can be seen therefore that the establishment of the Artificial Wetland has significantly improved the treatment efficiency, increasing the COD removal to 59%, NH₄-N to 35%, PO₄-P to 32% and suspended solids to 78%, despite the high loading rates and the operational arrangement.

The mechanics of this improved treatment is through the establishment of an active macrophyte community and rhizosphere, which provided sites for microbiological attachment, contributed oxygenation, and encouraged permeability through compacted areas as well as acting as a filter to the suspended particulate matter.

As the suspended matter was filtered out by the system, the bacterial mass within the wetland increased, and directly enhanced the microbial nutrient removal capacity and physico-chemical binding. This, in association with the establishment of a mature macrophyte community is indirectly the basis of improved treatment capacity with ageing of the systems, and the requirement for a settling-in period of 2-5 years before a wetland bed is fully developed for wastewater treatment as suggested by Brix (1987).

Despite the fact that COD and ammonium removals were significantly improved by the wetland, with effluent COD levels consistently below 100 mg/l and ammonia below 30 mg/l, the inability to achieve total organics removal and nitrification is a reflection of the high surface loading rate and incapacity of the macrophytes to meet the oxygen demand. Although laboratory studies are presently investigating actual oxygenation rates, in practice it has been found that the Arundo does not actively oxygenate a large rhizosphere. Root penetration was limited to the surface zone i.e. <300 mm, whilst the root structures, when removed from the bed, were found to be predominantly black, indicating that reducing conditions prevail even around the rhizomes. This idea was supported by the observation that rhizomes placed in small containers of effluent rapidly turned black, whilst rhizomes of Typha, Scirpus and Phragmites generated aerobic conditions and encouraged nitrification.

An explanation of the reduced oxygenation capacity may be found in the fact that Arundo donax is not naturally an aquatic macrophyte, preferring to inhabit the drier bank areas of streams and wetlands. It is therefore conceivable that its above ground development is sufficient to supply ample oxygen for the metabolism of the plant and that subsurface oxygenation is not as physiologically established as other aquatic macrophyte species. The necessity for planting the correct macrophyte is demonstrated by the variation in wastewater treatment potential reported between species, in relation to their abilities to transfer...
Artificial wetland and high rate algal pond

Oxygen from the shoots to the rhizospheres (Gersberg, 1986; Finlayson, 1983). *Phragmites* and *Schoenoplectus* have been recognised as suitable candidate species, whilst *Arundo* appears to be less attractive from the present study.

The improvement in nitrogen and phosphorus removal was partially a result of changes in the operational regime, such as recycle of oxygenated effluent from the algal pond, and partially the contribution of the macrophytes and substrata with regard to oxygenation, filtration, microbiological activity and assimilation into biomass.

In an established artificial wetland nutrient assimilation could account for approximately 150-200 mg N and 30-40 mg P/m²/day (Gersberg 1983). In the present study where nutrient loading rates averaged 4.15 g N and 1.1 g P/m²/d, the biomass uptake could only account for minimal nutrient removal, whilst there can be net release of nutrients at the end of the growing season due to the bacterial decomposition of plant biomass and humus within the substrata (Rodgers, 1985). Although this was not specifically monitored, the die-back of the macrophytes was substantial, and in association with reduced bacterial metabolism, contributed to the higher levels of nutrients in the effluent from the bed during the winter conditions.

The actual removal of phosphate through the wetland therefore occurred through physico-chemical precipitation, and binding with the substrata rather than biological assimilation. This was only enhanced by the gradual build-up of both vegetation and humus, and operational adjustments.

Nitrogen removal occurred principally through nitrification and subsequently denitrification, with minor contributions from assimilation and precipitation. Nitrification was limited by the ability of the nitrifying organisms to compete for available oxygen, whilst denitrification was limited by the extent of prior nitrification and supply of carbon sources. Residual nitrate in the effluent usually corresponded to low COD levels where denitrification was restricted, whilst residual ammonia corresponded to inefficient COD removal, and hence increased demand for available oxygen.

The nitrogen removal was then directly influenced by the hydraulic and organic loading rates. In this instance, a hydraulic loading rate of 13.5 cm/d at an average organic loading of 30 g COD/m²/d was too excessive to achieve total COD removal let alone encourage substantial nitrification and subsequent denitrification. It is apparent that for reliable nitrogen removal it is the requirement for efficient nitrification that imposes an upper limitation on the hydraulic loading of the bed, via the oxygenation capacity of the macrophytes in the system, after having satisfied the carbonaceous oxygen demand.

Batch fed pot experiments consisting of a range of macrophyte species planted in a substratum of waste power station ash and receiving either settled sewage or stabilization pond effluent at controlled retention times, demonstrated that nutrient removal can be highly efficient at reduced loading rates, Table 2. In comparing *Arundo donax* directly, the effluent concentrations of COD, NH₄-N and PO₄-P at a loading rate of 28 mm/day were 25 mg/l, 1.3 mg/l and 0.8 mg/l respectively from settled sewage, percentage removals being 92%, 94% and 92%. At a loading of 84 mm/d for stabilization pond effluent the levels stood at 23 mg/l COD, 0.45 mg/l NH₄-N and 0.3 mg/l PO₄-P.

**TABLE 2** Nutrient Levels in the Effluent and Removal Efficiencies for Various Macrophyte Species Receiving either Stabilization Pond Effluent or Settled Sewage at Nominal Loadings of 8.4 and 2.8 cm/d Respectively.

<table>
<thead>
<tr>
<th>Species</th>
<th>COD mg/l</th>
<th>% Rem</th>
<th>NH₄-N mg/l</th>
<th>% Rem</th>
<th>PO₄-P mg/l</th>
<th>% Rem</th>
<th>NO₃-N mg/l</th>
<th>% Rem</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stabilization</td>
<td>Typha</td>
<td>16.3</td>
<td>54</td>
<td>0.5</td>
<td>61</td>
<td>0.8</td>
<td>51</td>
<td>1.3</td>
</tr>
<tr>
<td>Pond</td>
<td>Scirpus</td>
<td>17.1</td>
<td>51</td>
<td>0.4</td>
<td>74</td>
<td>0.7</td>
<td>54</td>
<td>0.7</td>
</tr>
<tr>
<td>Effluent</td>
<td>Phragmites</td>
<td>16.2</td>
<td>54</td>
<td>0.3</td>
<td>76</td>
<td>0.8</td>
<td>46</td>
<td>0.8</td>
</tr>
<tr>
<td>Arundo</td>
<td>23</td>
<td>35</td>
<td>0.45</td>
<td>0.6</td>
<td>67</td>
<td>0.3</td>
<td>81</td>
<td>0.4</td>
</tr>
<tr>
<td>Settled</td>
<td>Typha</td>
<td>20</td>
<td>94</td>
<td>1.2</td>
<td>94</td>
<td>0.6</td>
<td>92</td>
<td>0.5</td>
</tr>
<tr>
<td>Sewage</td>
<td>Scirpus</td>
<td>21</td>
<td>93</td>
<td>0.7</td>
<td>97</td>
<td>1.0</td>
<td>88</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>Phragmites</td>
<td>16.3</td>
<td>95</td>
<td>1.5</td>
<td>93</td>
<td>1.1</td>
<td>86</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>Arundo</td>
<td>25</td>
<td>92</td>
<td>1.3</td>
<td>94</td>
<td>0.5</td>
<td>94</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**Downloaded from iwaponline.com/wst/article-pdf/21/6-7/659/100420/659.pdf**
Recycle of HRAP Effluent to the Wetland

The photosynthetic activity in the algal pond was capable of generating peak dissolved oxygen (DO) levels in excess of 20 mg/l, Table 3. It was therefore considered potentially beneficial to recycle an equal volume of the oxygenated effluent from the pond back to the artificial wetland.

This is indicated on Fig. 2, and can be seen to have resulted in reduced nutrient levels in the effluent from the bed. Despite the fact that additional oxygen was being introduced, the apparent enhanced nutrient removal was a dilution effect rather than biological or physico-chemical. In actual terms, the recycling of effluent only served to increase the surface loading, decreasing the retention time within the bed, encouraging short-circuiting, dislodging the microbial community, and reducing the efficacy of the total arrangement, and was hence ceased. This does not preclude the potential to recycle this oxygen saturated effluent for alternative purposes such as fish production and irrigation.

HIGH RATE ALGAL POND

Nutrient removal through the HRAP, unlike the Artificial Wetland, is principally a function of assimilation into algal-bacterial biomass, with some contribution from precipitation, sedimentation and volatilization as a result of photosynthetically induced pH shifts to the alkaline, and presence of contributing ions.

The nutrient levels within the pond and concentration of algae during the study are illustrated in Figures 4 and 5. Figure 5 also illustrates certain of the operational upsets to the algal system which will be dealt with later.

![Fig. 4. Effluent nutrient levels of the High Rate Algal pond](image)

![Fig. 5. Suspended solids (Algal Biomass) of the High Rate Algal Pond](image)

The maximum potential production of algae which could be obtained from the monthly average...
values of irradiance for South Africa according to Sandbank (1984) would be approximately 27 g/m²/d. In the present study a mean production between 15 and 20 g/m²/d was achieved, which amounts to approximately 50 tons/ha/y taking into account the operational and biological upsets during the period. The inability to practically accomplish maximum levels of algal production, and thereby increase nutrient removal potential, is considered to be due to such factors as nutrient limitation (principally NH₄-N and light to the culture), predation, and bacterial encroachment.

The amount of nitrogen and phosphorus which may be removed from the effluent by algal assimilation mechanisms is dependent upon the intracellular content of the algal biomass and the amount of biomass which may be abstracted daily as productivity or yield (Hensman 1986). The composition of the Stigeoclonium was found to be 12% nitrogen and 1.1% phosphorus by weight. An annual average production of 20 g/m²/d would therefore remove 2.4 g N/m²/d and 220 mg P/m²/d. At a nominal pond depth of 400 mm this would approximate to 6 mg N/l and 0.55 mg P/l. In practice an average of 19.4 mg/l reduction in ammonium-N occurred, 10.5 mg/l being accounted for as nitrate through nitrification, resulting in a net loss of 8.9 mg N/l, whilst phosphate loss through the pond amounted to 1.9 mg/l. The discrepancy in balancing the nutrients indicates the role played by physico-chemical mechanisms associated with algal activity.

As algal photosynthesis proceeds and CO₂ is abstracted, bicarbonate is used in preference to carbonate alkalinity, depressing total alkalinity and causing the pH to rise. This action decreases the solubility of a number of salts of phosphate, principally calcium, which precipitate from solution (Hensman, 1986).

Although the carbon content of the influent COD did introduce buffering capacity and CO₂ via the action of the heterotrophic bacteria, the algae were capable of increasing the pH within the pond to levels in excess of pH 10 (Table 3). Hensman (1986) reported Stigeoclonium growing on secondary effluent to raise the pH typically from 7.5 to a peak of 9.0, resulting in the reduction in soluble PO₄-P from 10 mg/l to a mean of 4.4 mg/l, whilst a pH of 9.8 was considered sufficient to precipitate phosphate to 1.0 mg/l. In the present study where the mean PO₄-P concentration from the Artificial Wetland was 6 mg/l, it may be assumed that a pH of 9.2 would have been sufficient to remove phosphate to such low levels. The fact that phosphate in the HRAP effluent averaged 4 mg/l despite high pH was a result resolubilization of phosphate during periods of lower pH, i.e. at night, and the sampling in the morning. High pH levels such as those experienced can also result in the ammonium nitrogen being transformed into ammonia gas which can be volatilized to the atmosphere.

Mechanics of the HRAP

The physiological mechanics of the HRAP relies on the maintenance of a symbiotic relationship between bacteria (responsible for the eventual aerobic degradation of organics), and the algae photosynthesising according to light energy inputs. This appears to be strictly related to the lower COD range of concentration where the algal component is dominant. Higher loadings encourage bacterial development, decrease light penetration and thus directly and indirectly upset the sensitive symbiosis.
The ability of *Stigeoclonium* to remove wastewater nutrients is demonstrated by the batch experiments illustrated in Figure 6. Outdoor, stirred reactors containing a media of raw sewage and humus tank effluent in a 1:2 ratio, were inoculated with *Stigeoclonium* and sampled on a daily basis. Nutrients were directly assimilated into biomass and lost through the volatilization and precipitation mechanisms as the pH rose into the alkaline. The decline in growth rate as the algal concentration increased was a response to diminishing light penetration through the culture and nutrient limitation through pH conditions.

![Figure 6. Nutrient uptake by a developing culture of *Stigeoclonium*](image)

![Figure 7. Nutrient uptake by an established culture of *Stigeoclonium*](image)

Figure 7 illustrates the reaction of an established continuously fed *Stigeoclonium* culture to the interruption of feeding raw sewage. The ammonia level rapidly reduced as nitrate increased. This was indicative of enhanced nitrification afforded by reduced carbonaceous load, rather than assimilatory uptake. Since nitrate is not the preferred nitrogen source for algal synthesis, the nitrification is principally effected by the nitrifying bacteria population in suspension and attached to the filamentous clusters.

Although nitrification, as such, should not have an adverse effect upon the algae, growth limiting conditions in respect of ammonia-N could ensue. In this study, and elsewhere (Hensman 1986) it was observed that cultures demonstrating maximum nitrification were prone to cluster breakdown and fragmentation of the filaments.

The preferential assimilation of ammonium over nitrate was demonstrated by the removal of nitrate being delayed until ammonium was reduced to minimal levels. The continued growth of the algal culture at levels of phosphate below 0.2 mg/l was indicative of its ability to supply basal metabolic needs either through the activation of enzymatic pathways to enhance the extraction of low levels of phosphate, or the release of stored reserves of phosphate under stress conditions.

**Algal Biomass**

The algal biomass harvested from the pond was simply sterilized by the mixing of 0.25% formaldehyde solution and sun dried, prior to processing as animal feed. The addition of a dry chopped straw support enhanced the drying ability, removed the requirement for mixing with other feed components, and assists in the acceptability of the biomass to higher animals. Alternatively, the biomass can be combined with carbohydrates (maize meal), minerals, oils, etc. in order to compile a nutritionally balanced diet which can be pelleted.

The composition of the algal biomass was 42% protein, 5.6% fibre, 2.6% fat, 15% ash. However, as with many plant protein sources the amino acid composition indicated a slight deficiency in the sulphur amino acids, constraining the algae biomass to act as a supplement rather than replacement to the conventional fish or soya meal proteins. Algal feeding studies have indicated that HRAP biomass may replace of the order of 10% of the protein...
requirements for higher animals, 60-80% for fish (Brune, 1978; Sandbank, 1980; Mokady, 1980; Saxena, 1983).

In order to further optimize the utilization of the wastewater the effluent from the HRAP may be used directly for irrigation or pass to additional ponds for fish production, prior to irrigation. The wastewater could then yield further fish protein sources in the order of 10 tons/ha/yr, as well as subsequent terrestrial crops. Either way, the residual nutrients are put to constructive use rather than destructive discharge, in the generation of essential protein sources.

Phenomena Detrimental to the Algal Cultivation

During the experimental period occasional upsets to the biological and operational components detrimentally affected the performance of the system which warrant some consideration and comment.

Amongst the foremost were the ravages of the algal culture by Chironomid larvae, not as direct consumption, but rather by utilizing the filamentous clusters for the synthesis of cocoons prior to their final metamorphosis into adult insects. The phenomenon was so intense that an algal culture of 150 mg/l could be almost totally removed from suspension within 2 to 3 days, to lie as a gelatinous mass on the bottom of the pond writhing with worms (larvae). The reproduction rate of the insects during the summer months was so great that destruction of the culture could occur every 3 to 4 weeks.

Insecticide addition was capable of overcoming this problem, but was undesirable both for the expense and the contamination of the biomass. Biological control in the form of Carp, *Tilapia* and *Clarias* was found to be successful, permitting a stable algal culture to be maintained until a failure in the distribution of septic sewage to the artificial wetland resulted in excessive carbonaceous loadings to the pond. This oxygen demand led to anaerobic conditions developing overnight, suffocating the carp and *tilapia* and permitting larval development in the ensuing weeks to attack the algae. *Clarias*, being capable of air breathing were not directly affected by the anaerobic conditions, but being exploratory in nature were found to have disappeared from the low walled pond. Some replacements were made later in the study and appear to be maintaining a balanced ecosystem once again.

Another detrimental biological factor was the occurrence of excessive bacterial encroachment onto the filamentous algae, turning the algal culture from that of clusters between 5 and 10 mm diameter to finer brown clusters of 0.5 to 2 mm in diameter which tended to settle from suspension.

It had been observed previously that excessive carbonaceous loadings could lead to the swamping of the culture with bacteria, and ultimate destruction of the algal population. This was thought to have been the cause of the first decline following short-circuiting problems in the wetland where COD levels were as high as 280 mg/l. However, a subsequent decline was thought to have been more through the excessive development of nitrifying microorganisms upon the algal clusters. The influent COD was not particularly high, whilst nitrification within the pond was substantial, with ammonia levels below 2 mg/l and nitrate levels about 15 mg/l. As mentioned previously, *Stigeoclonium* cultures demonstrating significant nitrification suffered physiological upset with concomitant breakdown of colony structure.

It is apparent therefore that some care is required in operating the combined system in order to achieve the full potential that is indicated.

CONCLUSIONS

The combination of two low technology, low cost, robust and simple systems has proved successful in the treatment of sewage effluent, whilst generating by-products in the form of the macrophytes and high protein algal biomass. Pollutant removal through the Artificial Wetland amounted to 59.2% COD, 34.6% NH4-N, 31.9% PO4-P and 78% suspended solids. This was despite that fact that the Artificial Wetland was newly planted, and therefore had not reached a mature stand with regard to root penetration and proliferation, the dominant species planted *Arundo donax* does not appear ideal for oxygenation, and that hydraulic and organic loadings were not optimized. The removal mechanics were principally carbonaceous
oxidation, nitrification, denitrification, precipitation, sedimentation and filtration respectively, with minor nutrient removal accounted for via assimilatory processes.

Passage of the effluent from the Wetland through the High Rate Algal Pond increased the pollutant removals to 79.4% COD, 82.8% NH₄-N and 54.1% PO₄-P, whilst generating in the order of 42% Protein algal biomass. The removal mechanics through this stage were principally assimilation into the biomass with contributions from precipitation, sedimentation and volatilization as a consequence of the photosynthetically induced pH shift into the high alkaline. Biological problems in the form of culture crashes through Chironomid larval activity can be overcome through the presence of fish species, whilst bacterial encroachment can be overcome by ensuring low organic loading to the pond.

The effluent from the combined systems still contains residual nutrients which can be further employed for fish production or irrigation to further optimize the utilization of the wastewater for food production.

REFERENCES


