Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2016.1144530

57 (2016) 24946–24959
November

Taylor & Francis
Taylor & Francis Group

Effect of geometry on the performance of integrated solar and hydraulic jump enhanced waste stabilization pond

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Received 7 February 2015; Accepted 17 January 2016

ABSTRACT

The effect of surface area geometry on the performance of the integrated solar and hydraulic jump enhanced waste stabilization pond (ISHJEWSP) on the treatment of sewage wastewater was studied. The set-up consisted of eight numbers of experimental ponds with varying width. The enhanced ponds were constructed to enable the initiation of hydraulic jump. Three sets of these experimental ponds were constructed with varying locations of the points of initiation of hydraulic jump. The enhanced ponds were fitted with tilt frame, wrapped with aluminium foil paper. Wastewater samples collected from the inlet and outlet for varying inlet velocities were examined for physicochemical and biological characteristics for a period of nine months. The parameters examined were temperature, pH, detention time, dissolved oxygen, total coliform count, total suspended solids, E coli, algae concentration and biochemical oxygen demand. The efficiencies of the ISHJEWSPs with respect to these parameters fluctuated with variations in geometry, with the smallest ISHJEWSP in width giving the highest treatment efficiency. The research revealed that an ISHJEWSP with Length (L):Width (W):Depth (D) ratio of 1.0:0.3:0.2 is on average 1.1 times efficient than the solar enhanced pond (pond B); 1.3 times efficient than the hydraulic jump enhanced pond (pond C), 1.7 times efficient than the conventional WSP with the same L:W:D ratio for coliform removal. The use of flat plane reflector (aluminium foil paper) appeared to be a low-cost and practical system suited to raising the average temperature of the ISHJEWSP (Pond D) over those of the conventional WSP (Pond A) between 2.43 and 3.23°C within the period of the study. The results clearly shows that a designer looking for optimum geometry must avoid relatively low values of surface area aspect ratio (Length/Width) as this will reduce the specific effect of the solar reflector in the ISHJEWSP except where the solar reflector width spans the entire width of the ISHJEWSP. However, this must be balanced with other considerations such as ease of maintenance, construction cost and availability of land.

Keywords: Geometry; Performance; Solar radiation; Hydraulic jump; Width

1. Introduction

The usefulness of the waste stabilization pond (WSP) in wastewater treatment is not in doubt. However, WSPs are limited in application by their large area requirement [1]. Also, there is the challenge of the availability land. The use of solar radiation for the treatment of chemically and biologically contaminated water is not a new phenomenon [2–7]. Solar radiation removes a wide range of organic chemicals

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and pathogenic organisms by direct exposure, is relatively inexpensive, and avoids the generation of harmful by-products of chemically driven technologies [2].

The integrated solar and hydraulic jump enhanced waste stabilization pond (ISHJEWSP) is introduced as a new technology that incorporates solar reflector and the introduction of hydraulic jump through change in pond bed slope of the conventional waste stabilization pond. The essence is for the purpose of increasing the treatment efficiency of the conventional WSP and consequently, the reduction in land area requirement [8].

One of the basic objectives of science and engineering has been to utilize all the available natural resources, in order to improve man's standard of living. However, anthropogenic activities have continually resulted in the contaminations of these resources and the environment. Contaminated water causes an estimated 6–60 billion cases of gastrointestinal illness annually. The majority of these cases occur in rural areas of developing nations where the water supply remains polluted and adequate sanitation is unavailable [9]. Therefore, treated wastewater of domestic origin is now being considered and used in many countries throughout the world as an additional renewable and reliable source of water which can be used for various purposes [10,11]. Treated wastewater reuse makes a contribution to water conservation and expansion of irrigated agriculture, taking on an economic dimension. It also solves disposal problems aimed at protecting the environment and public health and prevents surface water pollution [12]. The benefits and the potential health and environmental risks resulting from wastewater reuse and the management measures aimed at using wastewater within acceptable levels of risk to the public health and environment are well documented [13,14]. Therefore, wastewater reuse requires effective treatment and measure to protect public health and the environment at a feasible cost [15,16].

Waste stabilization ponds (WSP) are very effective in the removal of faecal coliform bacteria [17]. It consists of a large, shallow earthen basin in which wastewater is retained long enough for natural purification processes to provide the necessary degree of treatment. Its efficiency depends on the availability of sunlight and high ambient temperature which are the prevailing climate conditions in most African communities [18].

Solar radiation is becoming increasingly appreciated because of its influence on living matter and the feasibility of its application for useful purposes. It is a perpetual source of energy, along with other forms of renewable energy, has a great potential for a wide variety of application because it is abundant and accessible [19,20]. The bacteria inactivity rate in a contaminated water sample is proportional to the intensity of sunlight and atmospheric temperature and inversely proportional to the water depth [21].

A hydraulic jump occurs when liquid at high velocity discharges into a zone of lower velocity, a rather abrupt rise (a step or standing wave) occurs in the liquid surface. Air bubble entrainment in a hydraulic jump starts for $Fr_1 > 1–1.3$ [22–24]. A hydraulic jump is characterized by strong energy dissipation and air entrainment [25]. The occurrence of hydraulic jump results in the increase in dissolved oxygen thus increased rate of microbial activities in the pond thereby increasing the pond performance.

In the past, researches have been conducted to improve pond efficiency, thereby maximizing land use by solar enhanced wastewater treatment in waste stabilization ponds [26–31].

In addition, higher pond depths have been investigated for reduction of the pond surface area [32–34]. Agunwamba [34] investigated the effect of tapering on WSP performance. However, the effect of geometry on the performance of integrated solar and hydraulic jump enhanced waste stabilization pond has not been reported.

The aim of this study is to use the ISHJEWSP to increase the efficiency of treatment of the WSP without increasing the surface area requirement. The specific objectives were to: investigate the effect of change in width on the treatment efficiency of the ISHJEWSP, determine the effect on the increase in intensity of solar radiation on the treatment efficiency of wastewater in the ISHJEWSP.

2. Materials and methods

2.1. Description of area of study

The treatment plant at the University of Nigeria, Nsukka consists of a screen (6 mm bar racks set at 12 mm centres) followed by two Imhoff tanks, each measuring about 6.667 m × 4.667 m × 10 m, and two facultative waste stabilization ponds. Sludge is discarded from the imhoff tank once every 28 days onto the drying beds, so that the beds are loaded at 40-d interval. The beds have a total area of 417 m^2. Although its efficiency has deteriorated, its effluent is used for uncontrolled vegetable irrigation by some village dwellers. The poor effluent quality is also partly attributable to overloading because of population growth.

2.2. Description of experimental set-up

Experimental research and design were adopted. The experimental set-up consisted of one sewage storage tank (1.2 m × 1.2 m × 0.6 m) and an overhead storage tank (1.5 m × 1.5 m × 1.2 m) as shown in Tables 1–3 and Fig. 1 below. Three sets of experimental ponds with varying locations of change in pond bed slope were constructed using metallic tanks with each set consisting of eight experimental ponds (A, B, C, D, E, F, G, H) with varying width. Six out of the eight ponds were constructed with tilt frames of size 1.0 m × 0.3 m, fixed at varying angles in accordance with the relative position of the sun per week. The tilt frames were made of the flat wooden board wrapped with aluminium foil paper to serve as solar reflectors. The foil paper was to act as solar reflector, with each of the six ponds having one reflector each at the outlet position (west facing). The two tanks were filled to supply the eight ponds with sewage effluent from the imhoff tank of the University of Nigeria wastewater treatment plant, Nsukka. Half inch diameter inlet pipes were fitted centrally to the experimental ponds. The outlet pipes were centrally fitted to the experimental ponds. To control the inflow and outflow, valves were fitted to the inlet and outlet pipes of the experimental ponds. Wastewater samples collected from the inlet and outlet for varying inlet velocities and varying locations of point of initiation of hydraulic jump were examined for physicochemical and biological characteristics within a period of 12 months. The parameters examined were temperature, pH, detention time, dissolved oxygen (DO), total coliform count (TCC), total suspended solids (TSS), E coli, algal concentration and biochemical oxygen demand (BOD). All the analyses were carried out using appropriate water testing meters and in accordance with the standard methods [36].

2.3. Sample collection

Wastewater samples collected from the inlet and outlet for varying inlet velocities and varying locations of point of initiation of hydraulic jump were examined for physicochemical and biological characteristics within a period of twelve months. The parameters examined were temperature, pH, detention time, dissolved oxygen (DO), total coliform count (TCC), total suspended solids (TSS), E coli, algae concentration and biochemical oxygen demand (BOD). All the analyses were carried out using appropriate water testing meters and in accordance with the standard methods [36].

3. Results and discussion

3.1. Effect of pond width on treatment efficiency

3.1.1. Temperature

Temperature has been found to be one of the most important variables affecting biological processes [17,37]. The changes in temperature resulted in the variation of such parameters as dissolved oxygen, pH, E coli, total suspended solids, biochemical oxygen demand, algal concentration with width as shown in Figs. 1–36. The temperature was higher in pond F, the smallest width pond [37] than the other experimental ponds (Figs. 2, 14 and 26). This is due to its high reflector surface area to volume ratio. An increased surface area to volume ratio also means increased exposure to the environment [38].

The maximum and minimum temperature values for Pond D corresponding to Set 1, Set 2, and Set 3 are 34.5 and 28.0°C, 36.5 and 30.2°C, 37.5 and 29.5°C, respectively. Also, the maximum and minimum temperature values for Pond A corresponding to Set 1, Set 2 and Set 3 are 32.5 and 25.1°C, 34.0 and 27.2°C, 35.0 and 26.5°C, respectively.

3.1.2. Dissolved oxygen

The dissolved oxygen in pond F was higher than others (Figs. 1, 13 and 25). This is due to its high

Table 1
Detailed description of various ponds due to width effect [8]

Experimental Ponds	Size	Characteristics	Purpose
A	1 × 0.3 × 0.2	No solar reflector, no change in slope	Control
B	1 × 0.3 × 0.2	No change in slope with reflector	Measure the effect of solar reflector
C	1 × 0.3 × 0.2	Change in slope without reflector	Measure the effect of hydraulic jump
D	1 × 0.3 × 0.2	Solar reflector and change in slope	Measure the effect of solar reflector and hydraulic jump
E	1 × 0.4 × 0.2	Solar reflector and change in slope	Measure the effect of width
F	1 × 0.2 × 0.2	Solar reflector and change in slope	Measure the effect of width
G	1 × 0.5 × 0.2	Solar reflector and change in slope	Measure the effect of width
H	1 × 0.6 × 0.2	Solar reflector and change in slope	Measure the effect of width

Table 2
Detailed experimental characteristics of the various ponds due to variations in location of jump [8]

Experimental Set-up	Number of Experimental Ponds	Characteristics (location of point of initiation of hydraulic jump from the inlet)	Purpose
Set 1	8	0.5 m	Effect of location of point of initiation of hydraulic jump
Set 2	8	0.4 m	Effect of location of point of initiation of hydraulic jump
Set 3	8	0.3 m	Effect of location of point of initiation of hydraulic jump

Table 3
Detailed experimental characteristics of the various ponds due to varying inlet Froude number [8]

Experimental Set-ups	Number of Experimental Ponds	Characteristics (Froude Number)	Purpose
Set 1	8	1.1	Effect of inlet Froude number
	8	1.2	Effect of inlet Froude number
	8	1.3	Effect of inlet Froude number
Set 2	8	1.1	Effect of inlet Froude number
	8	1.2	Effect of inlet Froude number
	8	1.3	Effect of inlet Froude number
Set 3	8	1.1	Effect of inlet Froude number
	8	1.2	Effect of inlet Froude number
	8	1.3	Effect of inlet Froude number

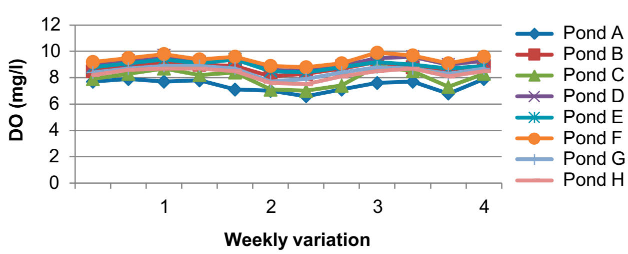

Fig. 1. Weekly DO variation in ISHJEWSPs effluent with time (Set 1, V_1).

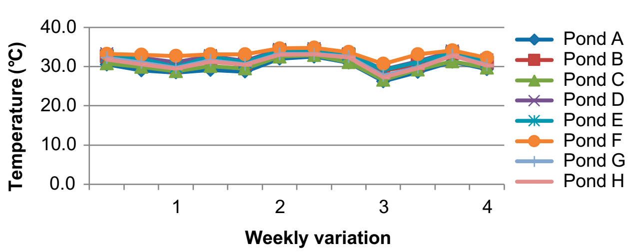

Fig. 2. Weekly temperature variation in ISHJEWSP with time (Set 1, V_1).

reflector surface area to volume ratio that exposes the wastewater to specific solar intensity; consequently the high algal bloom in pond F [26]. After sunrise, the dissolved oxygen level gradually rises, in response to photosynthetic activity, to a maximum in the mid-afternoon, after which it falls to a minimum during the night when photosynthesis ceases and respiratory activity consumes oxygen [39]. The main mechanism of oxygenation in pond systems is the oxygen provided by the algal population [39,40]. The DO concentration can rise to more than 20 mg/l (i.e. highly supersaturated conditions) and the pH to more than 9.4. These are both important factors in the removal of faecal bacteria and viruses [41]. High dissolved oxygen values have been reported in WSPs [42].

The maximum and minimum dissolved oxygen values for Pond D corresponding to Set 1, Set 2 and Set 3 are 9.8 and 8.5 mg/l, 10.4 and 8.7 mg/l, 10.6 and 8.8 mg/l, respectively. Also, the maximum and minimum dissolved oxygen values for Pond A corresponding to Set 1, Set 2 and Set 3 are 8.4 and 6.6 mg/l, 8.3 and 7.0 mg/l, 8.5 and 6.8 mg/l, respectively.

3.1.3. pH

The pH of the experimental ponds shows marked variation with width. The pH increased with decrease in width of the ponds (Figs. 3, 15, and 27). The pH in pond F, the smallest width pond, was higher than in the other experimental ponds [26,37]. Photosynthesis controls pH values. The increase in temperature and algae concentration as the width decreases results in a corresponding increase in photosynthetic activities. High pH values above 9 occur in ponds due to rapid photosynthesis by the pond alga which consumes CO_2 faster than it can be replaced by bacterial respiration; as a result, carbonate and bicarbonate ions dissociate [17,39]. Both anaerobic and facultative ponds operate most efficiently under slightly alkaline conditions [43]. High pH values have been reported in WSPs [42,44,45]. Values of pH up to 11 are not uncommon in WSP's, with the highest levels being reached in the late-afternoon [17].

The maximum and minimum pH values for Pond D corresponding to Set 1, Set 2 and Set 3 are 10.9 and 7.2, 11.0 and 8.3, 11.2 and 8.4, respectively. Also, the maximum and minimum pH values for Pond A corresponding to Set 1, Set 2 and Set 3 are 8.8 and 6.3, 9.0 and 6.5, 9.2 and 6.5, respectively.

3.1.4. Algae concentration

The results obtained for algae concentration are presented in Figs. 4, 16, and 28. The results show that algae concentration increases as the width decreases. As expected, this was due to the smallest sized pond being warmest throughout the average day [26,37]. Algal activity is also retarded at low temperatures. Even under conditions of high solar radiation, intensity of algal growth is affected by low temperatures [46]. The concentration of algae in a facultative pond depends on loading and temperature, but is usually in the range 500–2000 μg chlorophyll *a* per litre [39]. High alga values have been reported in WSPs [42,44,45].

The maximum and minimum algae concentration values for Pond D corresponding to Set 1, Set 2 and Set 3 are 376.6 μg of chlorophyll a per litre and 182.6 μg of chlorophyll a per litre, 510.8 μg of chlorophyll a per litre and 216.5 μg of chlorophyll a per litre and 575.4 μg of chlorophyll a per litre and 194.4 μg of chlorophyll a per litre, respectively. Also, the maximum and minimum algae concentration values for Pond A corresponding to Set 1, Set 2 and Set 3 are 166.9 μg of chlorophyll a per litre and 76.71 μg of chlorophyll a per litre, 243.4 μg of chlorophyll a per litre and 121.0 μg of chlorophyll a per litre and 263.9 μg of chlorophyll a per litre and 98.9 μg of chlorophyll a per litre, respectively.

3.1.5. Total coliform count

Pond F with the least geometry had the least coliform than the other experimental ponds (Figs. 9, 21, and 33). Comparing pond F which had the smallest dimension for all the cases, the results show that the average efficiency of coliform removal was higher in Pond F. This was followed by Pond D, E, B, G, H and C as shown in Figs. 10, 22, and 34 for Set 1. For Sets 2 and 3, Pond F had the highest treatment efficiency followed by Pond D, Pond B, Pond E, Pond G, Pond H and Pond C. Pond A had the least efficiency of treatment for all sets. This is due to its high reflector surface area to volume ratio. An increased surface area to volume ratio also means increased exposure to the environment [38]. Good linear relationships between the numbers of FC in a pond and the direct and indirect (via increases in algal biomass and pH) effects of sunlight have been reported [44,45].

The maximum and minimum total coliform values for Pond D corresponding to Set 1, Set 2 and Set 3 are 460 per 100 ml and 28 per 100 ml (58–92%), 460 per 100 ml and 28 per 100 ml (58–94%) and 460 per 100 ml and 28 per 100 ml (58–94%), respectively. The average efficiencies of total coliform removal for Pond D corresponding to Set 1 (V_1, V_2, V_3), Set 2 (V_1, V_2, V_3), Set 3 (V_1, V_2, V_3) are 82.3, 80.7, 86.6, 83.9, 85.7, 88.7, 88.7, 83.2 and 83.5%, respectively. Also, the maximum and minimum coliform values for Pond A corresponding to Set 1, Set 2 and Set 3 are 1,100 per 100 ml and 120 per 100 ml (0–81%), 1,100 per 100 ml and 120 per 100 ml (0–89%) and 1,100 per 100 ml and 120 per

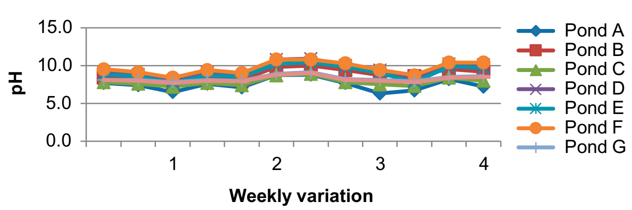

Fig. 3. Weekly pH variation in ISHJEWSP with time (Set 1, V_1).

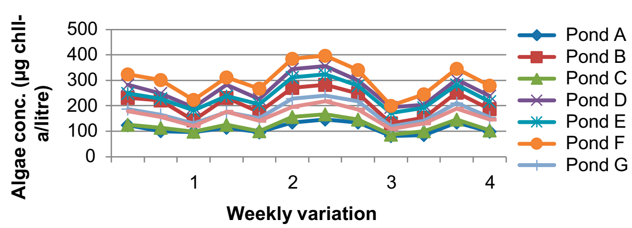

Fig. 4. Weekly algae concentration variation in ISHJEWSP with time (Set 1, V_1).

100 ml (0–86%), respectively. The average efficiencies of total coliform removal for Pond A corresponding to Set 1 (V_1, V_2, V_3), Set 2 (V_1, V_2, V_3), Set 3 (V_1, V_2, V_3) are 49.2, 40.3, 51.9, 51.3, 52.4, 52.6, 52.6, 51.3 and 51.7%, respectively.

3.1.6. Biochemical oxygen demand

The results obtained revealed there was a higher degree of removal of BOD in Pond F because of its small width and the use of solar reflector which increased the temperature leading to increased microbiological activities. This was followed by Pond D, Pond E, Pond B, Pond G, Pond H, Pond C and A as shown in Figs. 8, 20 and 32 for Set 1. For Sets 2 and 3, Pond F had the highest treatment efficiency followed by Pond D, Pond B, Pond E, Pond G, Pond H and Pond C. Pond A had the least efficiency of treatment. The weekly variations of BOD corresponding to Set 1 are shown in Figs. 7, 19, and 31.

The maximum and minimum BOD values for Pond D corresponding to Set 1, Set 2 and Set 3 are 80 mg/l and 30 mg/l (63–90%), 65 mg/l and 25 mg/l (74–91%) and 90 mg/l and 20 mg/l (74–93%), respectively. The average efficiencies of BOD_5 removal for Pond D corresponding to Set 1 (V_1, V_2, V_3), Set 2 (V_1, V_2, V_3), Set 3 (V_1, V_2, V_3) are 81.1, 79.2, 81.3, 83.2, 84.8, 85.4, 86.7, 82.6 and 83.5%, respectively. Also, the maximum and minimum BOD_5 values for Pond A corresponding to Set 1, Set 2 and Set 3 are 190 and 120 mg/l (29–60%), 190 and 120 mg/l (25–75%) and 210 and 115 mg/l (38–59%), respectively. The average efficiencies of BOD_5 removal for Pond A corresponding to Set 1 (V_1, V_2, V_3), Set 2 (V_1, V_2, V_3), Set 3 (V_1, V_2, V_3) are 43.8, 41.6, 44.5, 45, 46.5, 48.5, 50.8,44.9 and 45.9%, respectively.

3.1.7. Total suspended solids

Pond F with the least geometry had the least suspended solid than the other experimental ponds (Figs. 5, 17, and 29). For the different samples collected over the duration of this study, it was observed that Pond F (0.2 m width) had more treatment compared with the other ponds (Figs. 7, 19, and 31). The results thereby imply that the efficiency of the ISHJEWSPs decreased by an increase in width. This was followed by Pond D, Pond E, Pond B, Pond G, Pond H, Pond C and Pond A for Set 1. For Sets 2 and 3, Pond F had the highest treatment efficiency followed by Pond D, Pond B, Pond E, Pond G, Pond H and Pond C. Pond A had the least efficiency of treatment.

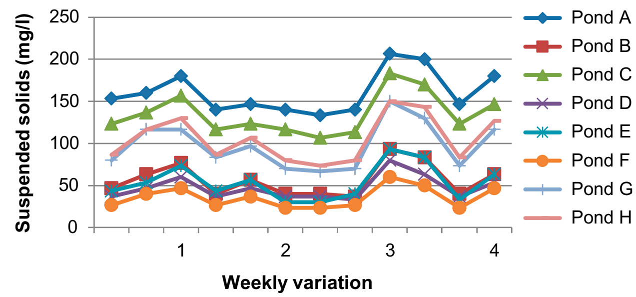

Fig. 5. Weekly suspended solids variation in ISHJEWSP with time (Set 1, V_1).

The maximum and minimum TSS values for Pond D corresponding to Set 1, Set 2 and Set 3 are 80 and 30 mg/l (73–89%), 73 and 20 mg/l (75–92%) and 77 and 17 mg/l (73–93%), respectively. The average efficiencies of TSS removal for Pond D corresponding to Set 1 (V_1, V_2, V_3), Set 2 (V_1, V_2, V_3), Set 3 (V_1, V_2, V_3) are 82.4, 82.1, 83.3, 84.9, 86.7, 88.2, 89.1, 83.9, and 85.1%, respectively. Also, the maximum and minimum TSS values for Pond A corresponding to Set 1, Set 2 and Set 3 are 213 and 130 mg/l (31–53%), 190 and 100 mg/l (35–58%) and 190 and 97 mg/l (34–62%), respectively. The average efficiencies of TSS removal for Pond A corresponding to Set 1 (V_1, V_2, V_3), Set 2 (V_1, V_2, V_3), Set 3 (V_1, V_2, V_3) are 39.7, 38.8, 42.7, 44.4, 46.1, 48.9, 51.2, 42.6 and 44.8%.

3.1.7. E coli

Similar to the results obtained for the total coliform count, Pond F which had the smallest dimension for all the cases had the highest average efficiency of E coli removal. This was followed by Pond D, Pond E, Pond B, Pond G, Pond H, Pond C and A as shown in Figs. 12, 24, and 36 for Set 1. For Sets 2 and 3, Pond F had the highest treatment efficiency followed by Pond D, Pond B, Pond E, Pond G, Pond H and Pond C.

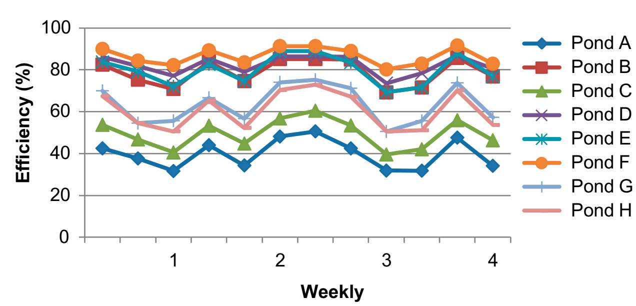

Fig. 6. Efficiency of suspended solids removal with time (Set 1, V_1).

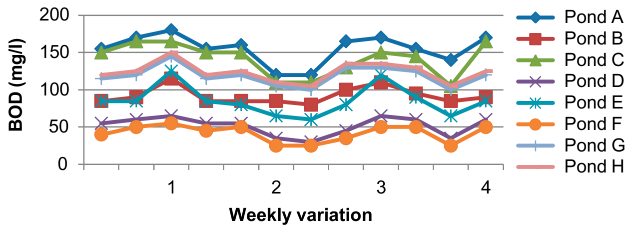

Fig. 7. Weekly BOD variation in ISHJEWSP with time (Set 1, V_1).

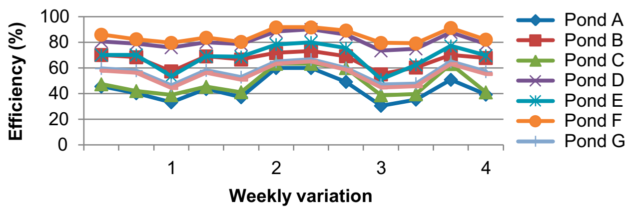

Fig. 8. Efficiency of BOD removal with time (Set 1, V_1).

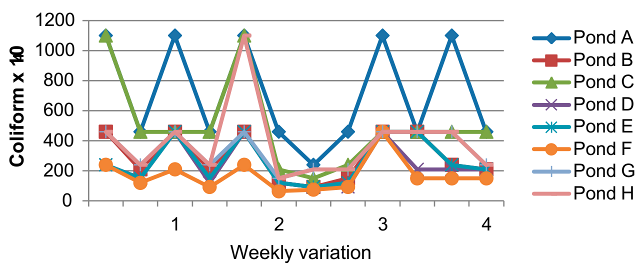

Fig. 9. Weekly coliform variation in ISHJEWSP with time (Set 1, V_1.

Pond A had the least efficiency of treatment. The weekly variations of E coli corresponding to Set 1 are shown in Figs. 11, 23, and 35.

The maximum and minimum E coli values for Pond D corresponding to Set 1, Set 2 and Set 3 are 210 per 100 ml and 14 per 100 ml (54–94%), 210 per 100 ml and 14 per 100 ml (54–94%) and 210 per 100 ml and 14 per 100 ml (74–94%), respectively. The average efficiencies of E coli removal for Pond D corresponding to Set 1 (V_1, V_2, V_3), Set 2 (V_1, V_2, V_3), Set 3 (V_1, V_2, V_3) are 81.9, 80.3, 84.1, 82.1, 83.1, 85.6, 85.8,81.9 and 83.1%, respectively Also, the maximum and minimum E coli values for Pond A corresponding to Set 1, Set 2 and Set 3 are 460 per 100 ml and 28 per 100 ml (0–88%), 460 per 100 ml and 23 per 100 ml (0–90%) and 460 per 100 ml and 23 per 100 ml (0–90%), respectively. The average efficiencies of E coli removal for

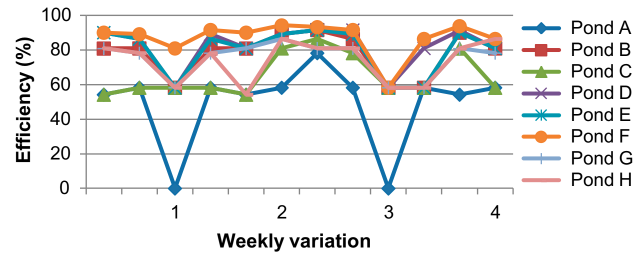

Fig. 10. Efficiency of coliform removal with time (Set 1, V_1).

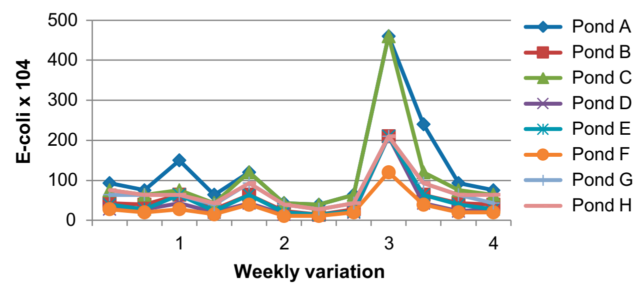

Fig. 11. Weekly E coli variation in ISHJEWSP with time (Set 1, V_1).

Pond A corresponding to Set 1 (V_1, V_2, V_3), Set 2 (V_1, V_2, V_3), Set 3 (V_1, V_2, V_3) are 43.6, 37.6, 48.3, 45.3, 47.1, 49.9, 49.4, 47.3 and 47.8%, respectively.

Figures depicting the results of the effect of pond width on treatment efficiency for Set 2 and Set 3 are intentionally omitted due to their voluminous number of pages requirement.

3.2. Effect of solar radiation on treatment efficiency

Generally, the efficiencies of treatment of the parameters increased with an increase in the solar radiation. Amongst ponds B, D, E, F, G and H, pond F, which had the smallest width, had the highest treatment efficiencies of coliform, BOD, E coli and sus-

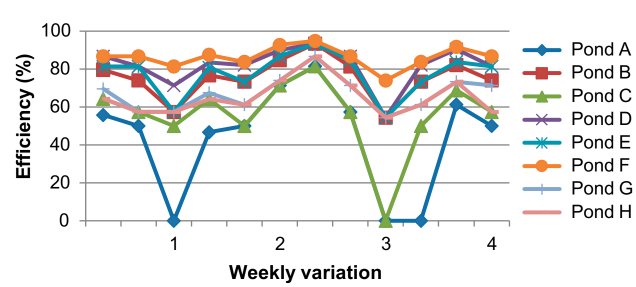

Fig. 12. Efficiency of E coli removal with time (Set 1, V_1).

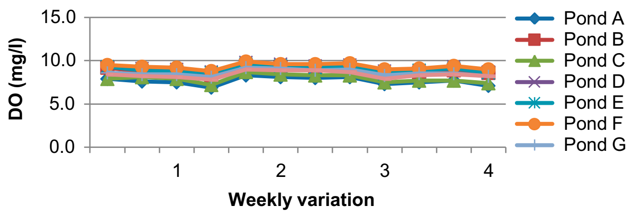

Fig. 13. Weekly DO variation in ISHJEWSPs effluent with time (Set 1, V_2).

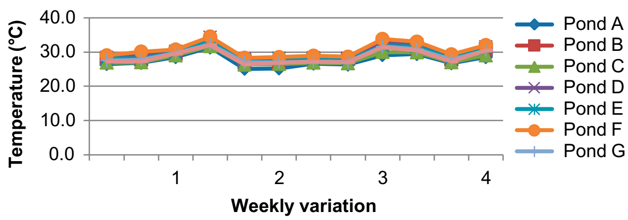

Fig. 14. Weekly temperature variation in ISHJEWSPs effluent with time (Set 1, V_2).

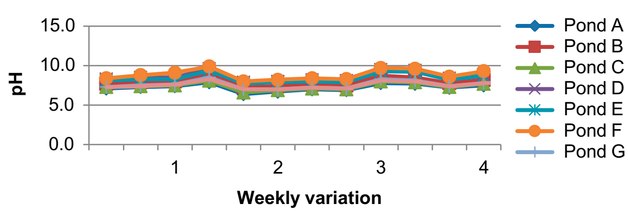

Fig. 15. Weekly pH variation in ISHJEWSPs effluent with time (Set 1, V_2).

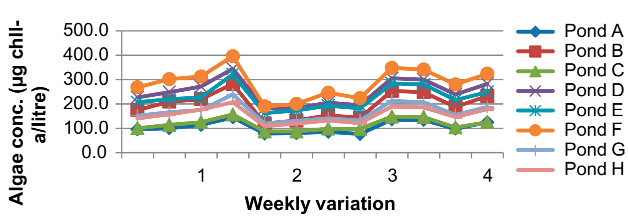

Fig. 16. Weekly algae concentration variation in ISHJEWSPs effluent with time (Set 1, V_2).

pended solids removal as shown in Figs. 37–48. For the three sets, these corresponding results were corroborated by the higher maximum temperature in Pond D (34.5, 36.5 and 37.5.0°C) than Pond A (32.5, 34.0 and 35.0°C) [47].

Figures depicting the results of the effect of solar radiation on treatment efficiency for Set 2 and Set 3

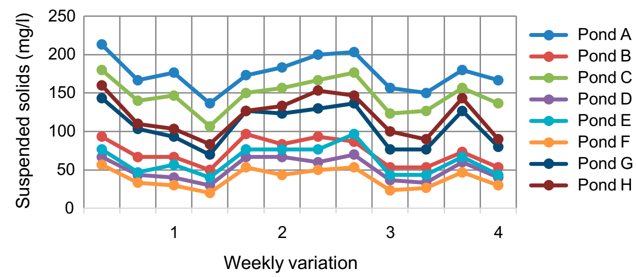

Fig. 17. Weekly suspended solids variation in ISHJEWSP with time (Set 1, V_2).

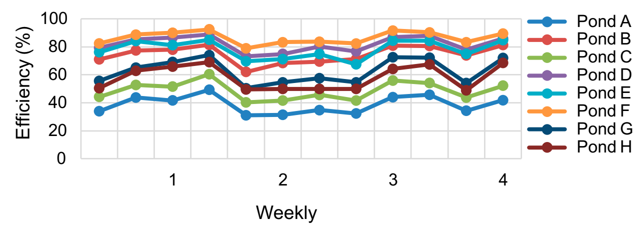

Fig. 18. Efficiency of suspended solids removal with time (Set 1, V_2).

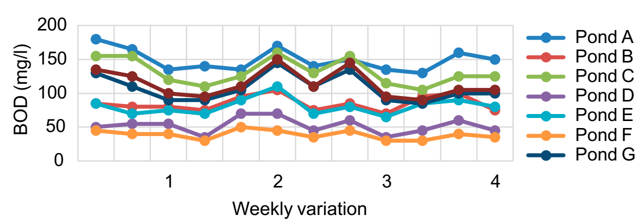

Fig. 19. Weekly BOD variation in ISHJEWSP with time (Set 1, V_2).

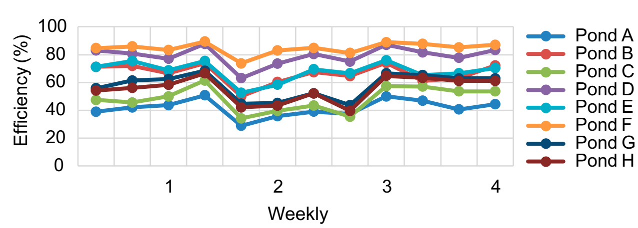

Fig. 20. Efficiency of BOD removal with time (Set 1, V_2).

are intentionally omitted due to their voluminous number of pages requirement.

The aforementioned efficiencies were calculated using the relationship:

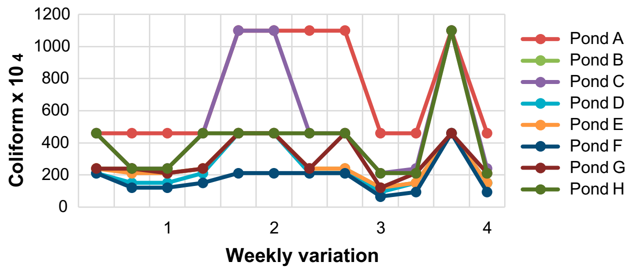

Fig. 21. Weekly coliform variation in ISHJEWSP with time (Set 1, V_2).

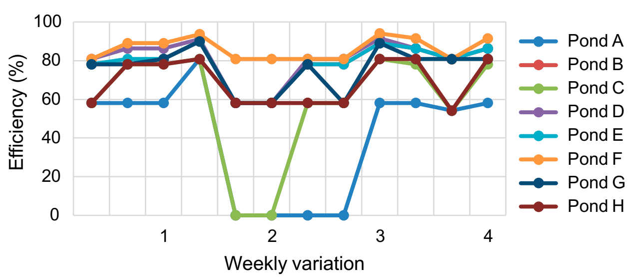

Fig. 22. Efficiency of coliform removal with time (Set 1, V_2).

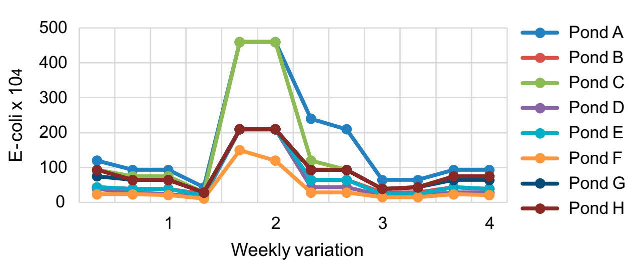

Fig. 23. Weekly E coli variation in ISHJEWSP with time (Set 1, V_2).

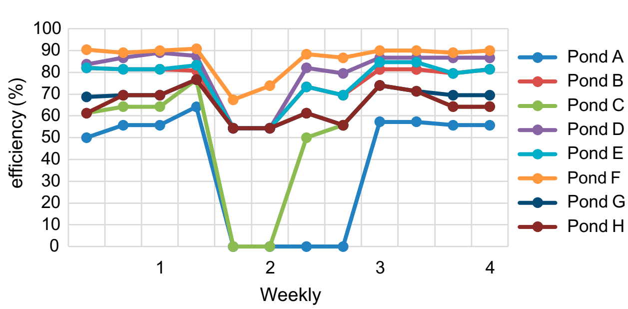

Fig. 24. Efficiency of E coli removal with time (Set 1, V_2).

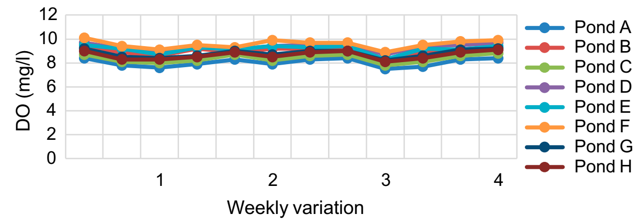

Fig. 25. Weekly DO variation in ISHJEWSPs effluent with time (Set 1, V_3).

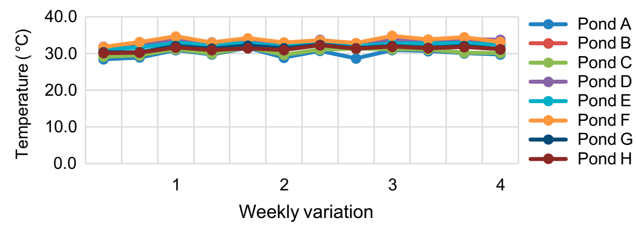

Fig. 26. Weekly temperature variation in ISHJEWSP with time (Set 1, V_3).

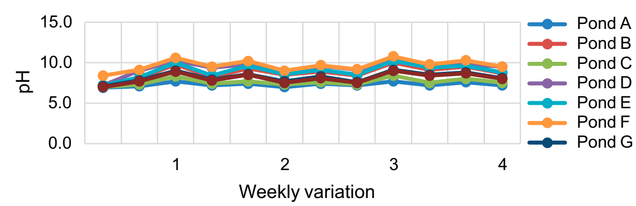

Fig. 27. Weekly pH variation in ISHJEWSP with time (Set 1, V_3).

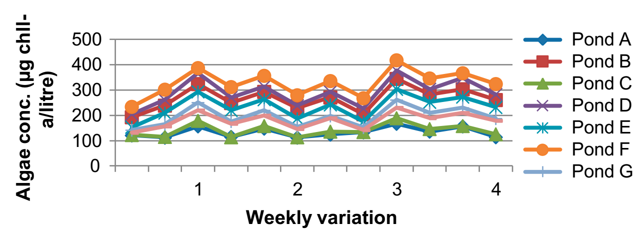

Fig. 28. Weekly algae concentration variation in ISHJEWSPs effluent with time (Set 1, V_3).

$$\text{Efficiency} = \left(\frac{\text{InputConcentration} - \text{OutputConcentration}}{\text{Input Concentration}}\right) \times 100 \quad (1)$$

Figs. 1–48 show that the use of flat plane reflector (aluminium foil paper) appeared to be a low-cost and practical system suited to raising the pond

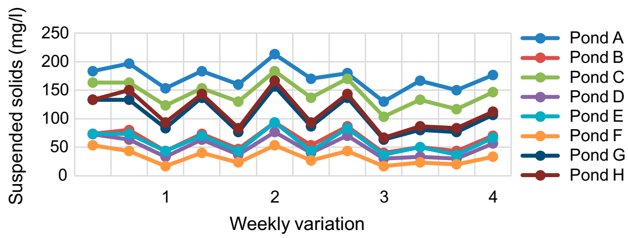

Fig. 29. Weekly suspended solids variation in ISHJEWSP with time (Set 1, V_3).

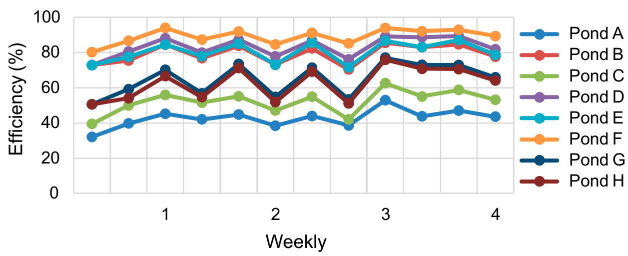

Fig. 30. Efficiency of suspended solids removal with time (Set 1, V_3).

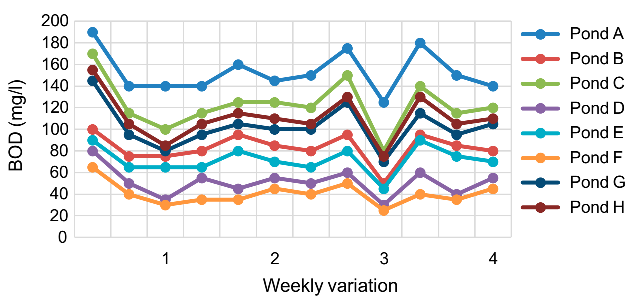

Fig. 31. Weekly BOD variation in ISHJEWSP with time (Set 1, V_3).

temperature. Test results for the months studied show that it is possible to raise the average temperature of the ISHJEWSP (Pond D) over those of the conventional WSP (Pond A) between 2.43 and 3.23˚C.

The precedence of higher solar radiation and temperature to the increase in inlet Froude number and location of point of initiation of hydraulic jump (Set 1, V_2; Set 3, V_1) imply that the efficiency of the ISHJEWSP is largely dependent on the climatic conditions; implying higher organic load assimilation during periods with high temperature and solar radiation.

The results clearly shows that a designer looking for optimum geometry must avoid relatively low values of surface area aspect ratio (Length/Width) as this will reduce the specific effect of the solar reflector in

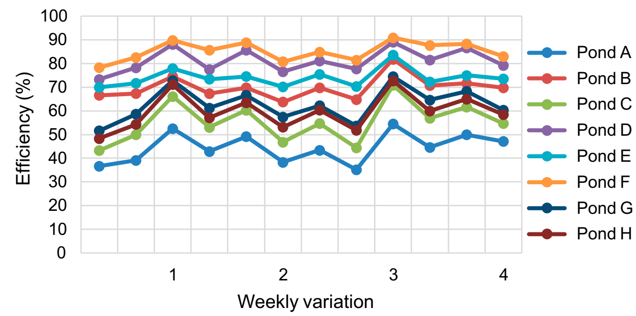

Fig. 32. Efficiency of BOD removal with time (Set 1, V_3).

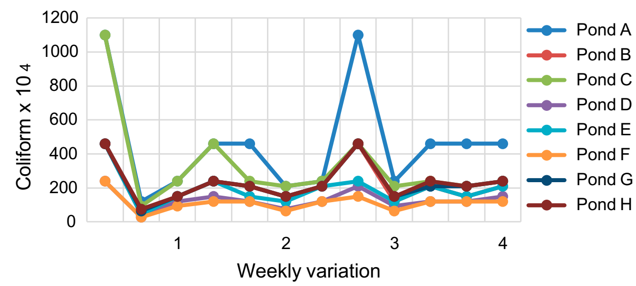

Fig. 33. Weekly coliform variation in ISHJEWSP with time (Set 1, V_3).

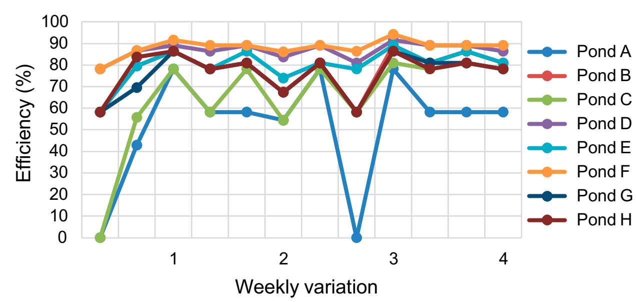

Fig. 34. Efficiency of coliform removal with time (Set 1, V_3).

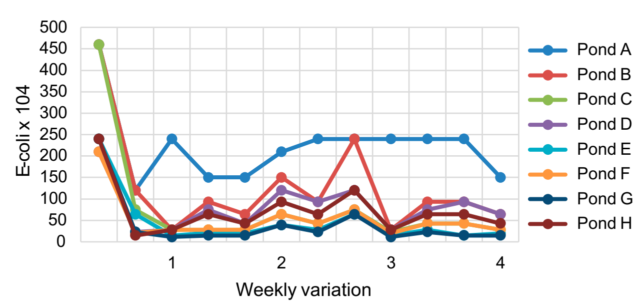

Fig. 35. Weekly E coli variation in ISHJEWSP with time (Set 1, V_3).

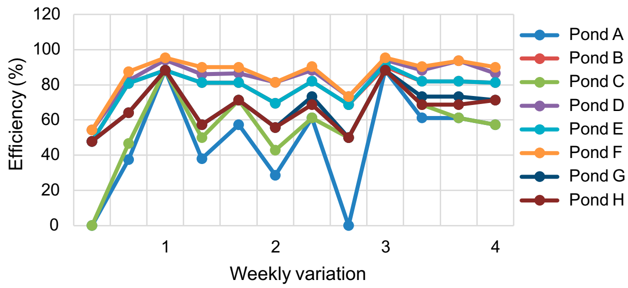

Fig. 36. Efficiency of E coli removal with time (Set 1, V_3).

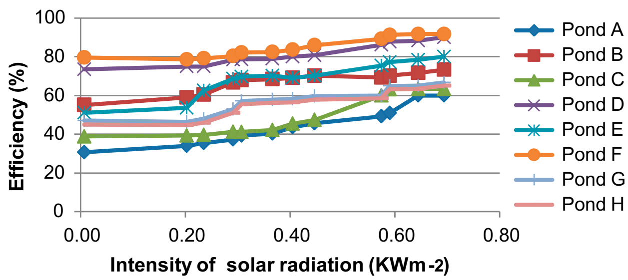

Fig. 37. Efficiency of BOD removal vs. solar intensity (Set 1, V_1).

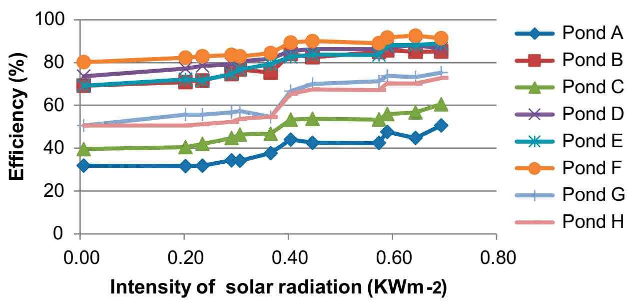

Fig. 38. Efficiency of suspended solids vs. solar intensity (Set 1, V_1).

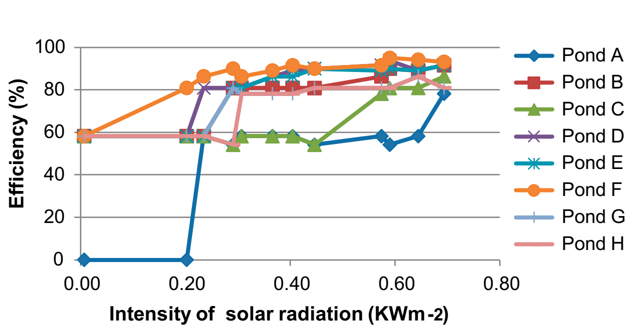

Fig. 39. Efficiency of coliform removal vs. solar intensity (Set 1, V_1).

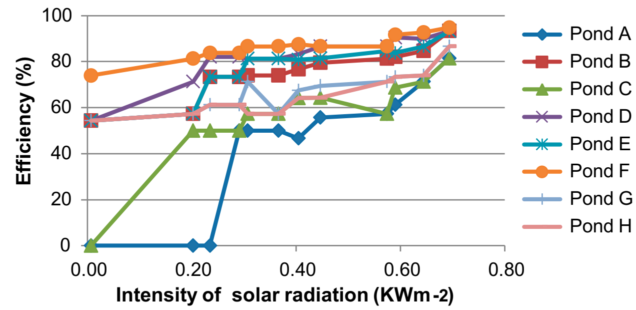

Fig. 40. Efficiency of E coli removal vs. solar intensity (Set 1, V_1).

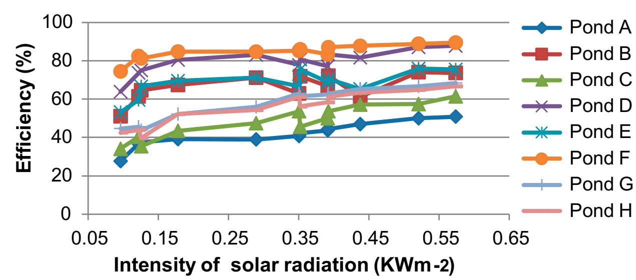

Fig. 41. Efficiency of BOD removal vs. solar intensity (Set 1, V_2).

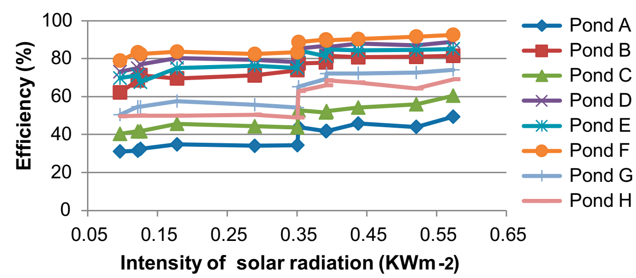

Fig. 42. Efficiency of suspended solids vs. solar intensity (Set 1, V_2).

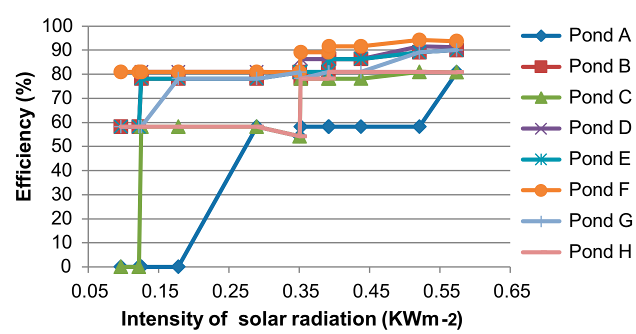

Fig. 43. Efficiency of coliform removal vs. solar intensity (Set 1, V_2).

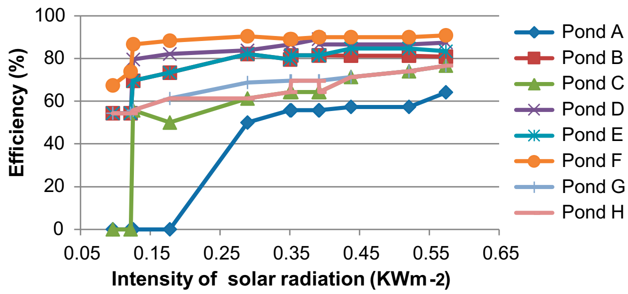

Fig. 44. Efficiency of E coli removal vs. solar intensity (Set 1, V_2).

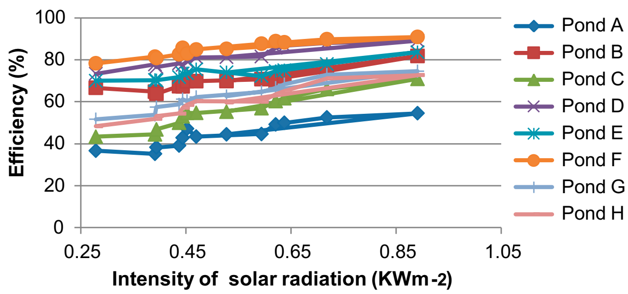

Fig. 45. Efficiency of BOD removal vs. solar intensity (Set 1, V_3).

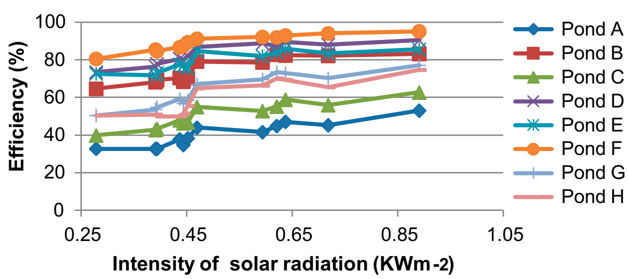

Fig. 46. Efficiency of suspended solids vs. solar intensity (Set 1, V_3).

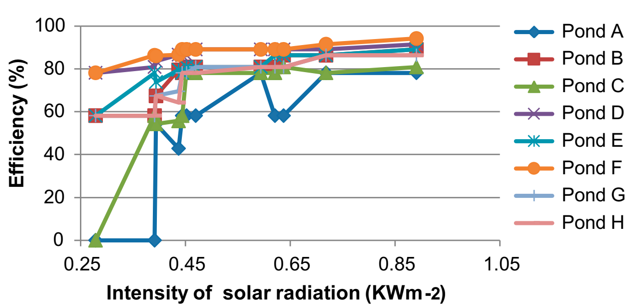

Fig. 47. Efficiency of coliform removal vs. solar intensity (Set 1, V_3).

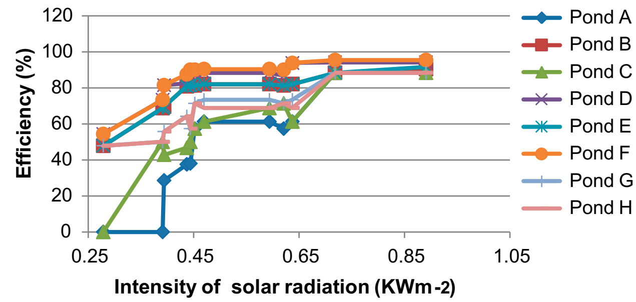

Fig. 48. Efficiency of E coli removal vs. solar intensity (Set 1, V_3).

the ISHJEWSP except where the solar reflector width spans the entire width of the ISHJEWSP. However, this must be balanced with other considerations such as ease of maintenance, construction cost and availability of land.

4. Conclusion

The efficiencies of the ISHJEWSPs with respect to the parameters of temperature, pH, detention time, DO, TCC, TSS, E coli, algae concentration and BOD fluctuated with the variations in width and intensity of solar radiation. The highest treatment efficiency was observed in the ISHJEWSP smallest in width. Also, the efficiencies of treatment of the TCC, E coli, BOD_5 and TSS increased with an increase in the solar radiation.

For width effect, samples collected from ponds A, B, C, D, E, F, G and H reveal that pond F (integrated solar and hydraulic jump enhanced—0.2 m wide) had the highest treatment efficiency. This was followed by ponds D (integrated solar and hydraulic jump enhanced—0.3 m wide), then E (integrated solar and hydraulic jump enhanced—0.4 m wide), then B (solar enhanced—0.3 m wide), G (integrated solar and hydraulic jump enhanced—0.5 m wide), H (integrated solar and hydraulic jump enhanced—0.6 m wide), C (hydraulic jump enhanced—0.3 m wide) and A (control—0.3 m wide) for set 1.

For Sets 2 and 3, the research reveals that pond F (integrated solar and hydraulic jump enhanced—0.2 m wide) had the highest treatment efficiency. This was followed by ponds D (integrated solar and hydraulic jump enhanced—0.3 m wide), then B (integrated solar and hydraulic jump enhanced—0.4 m wide), then E (solar enhanced—0.3 m wide), G (integrated solar and hydraulic jump enhanced—0.5 m wide), H (integrated solar and hydraulic jump enhanced—0.6 m wide), C (hydraulic jump enhanced—0.3 m wide) and A (control—0.3 m wide).

For all sets studied, Pond F had higher treatment efficiencies than the other enhanced ponds due to its high reflector surface area to volume ratio that exposes the wastewater to specific solar intensity; consequently the high algal bloom in pond F.

The research revealed that an ISHJEWSP with Length (L):Width (W):Depth (D) ratio of 1.0:0.3:0.2 is on average 1.1 times more efficient than the solar-enabled pond (pond B), 1.3 times efficient than the hydraulic jump (slope) enabled pond (pond C),1.7 times efficient than the conventional WSP with the same L:W:D ratio for coliform removal using foil paper as solar reflector. The use of flat plane reflector (aluminium foil paper) appeared to be a low-cost and practical system suited to raising the average temperature of the ISHJEWSP (Pond D) over those of the conventional WSP (Pond A) between 2.43 and 3.23˚C within the period of the study.

The results clearly shows that a designer looking for optimum geometry must avoid relatively low values of surface area aspect ratio (Length/Width) as this will reduce the specific effect of the solar reflector in the ISHJEWSP except where the solar reflector width spans the entire width of the ISHJEWSP. However, this must be balanced with other considerations such as ease of maintenance, construction cost and availability of land.

Acknowledgements

Part of the results presented in this paper rely on TRODAN data collected and managed by the Centre for Atmospheric Research, National Space Research and Development Agency, Federal Ministry of Science and Technology, Anyigba, Nigeria. We thank the Centre for Atmospheric Research and their partners for promoting high standards of atmospheric observatory practice as well as the Federal Government of Nigeria for continuous funding of the Nigerian Space program (www.carnasrda.com).

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