Water Sustainability using Pond-In-Pond Wastewater Treatment System: Case Studies

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Wastewater is an easily accessible but highly underutilized resource that could meet irrigation needs while conserving freshwater for future generations and is increasingly recognized as an essential and economical strategy in areas with water scarcity. This paper presents case studies on the Pond-In-Pond (PIP) configuration where PIP is an integration of two types of pond -- anaerobic and aerobic -- and consists of a deeper inner section entirely submerged within the outer pond. Performance data from existing PIP, or PIP-like systems dated back to 1960s', were collected and analyzed; and the results from the PIP systems investigated resulted in an average BOD removal of over 80% with a deviation of less than 10%. Consequently, the PIP unit alone ensured a level of treatment required for effluent reuse in crop irrigation for typical municipal wastewater with influent BOD in the range of 200 to 300 mgL^{-1}. Moreover, the combination of PIP with other processes in a treatment system has the capability of treating high-strength wastewater for other uses such as aquaculture, fishery, and others--including stream discharge. The PIP is a potentially viable and sustainable technology for low-cost wastewater treatment especially for reuse purposes due to the savings in capital costs, operations and maintenance costs, and revenue from reclamation of the effluent.

Keywords: pond-in-pond, natural treatment system, BOD removal, reuse, irrigation, sustainability

1. Introduction

While the world's population is increasing, the per capita freshwater resources are decreasing. Current understanding of our freshwater resources indicates that the planet's sustainable limit will be reached by about the year 2030 for food production and 2040 for potable water [1]. The climate-driven changes in evaporation, precipitation, and runoff have created additional stress on water availability in many parts of the world. The changes in climatic factors are expected to amplify levels of water scarcity by up to 40%, with an additional 15% of the global population expected to suffer water shortages if the world warms by just 2 °C [2].

Water is not distributed evenly among the population of the world; and, thus, the available water varies greatly among regions and so does the level of water scarcity. Regions at risk from water scarcity include parts of the southern United States, the Mediterranean, and the Middle East. Countries like Jordan, Israel, and Iraq have faced up to a 45% reduction in their available per capita water supply in the last few decades [1]. For instance – countries like Jordan with a population expected to continue to rise and the primary source of water affected by climate change will soon be in the category of absolute water scarcity. Absolute water scarcity is identified as a commonly used threshold when available water per capita is less than 500 cubic meters of water per year [3]. With the current trends, the per capita water supply for Jordan will fall from the current 145 m^3/yr to only 91 m^3/yr by the year 2025 [4]. Similar situations are expected to occur in other countries in Africa, the Middle East, and much of the southern United States.

In the United States, reduced surface water available for crop irrigation has resulted in an increased dependency on groundwater. Thus, the easily accessible sources of quality groundwater in the United States have been heavily consumed, and developing new sources is difficult and costly--if even possible. After successive droughts in California, crop production has been substantially limited [5]. Additionally, Peterson et al. [6] project a 16-28% increase in the frequency of drought in the southwestern United States; and, average temperatures are projected to increase in coming decades [7] with precipitation not expected to increase proportionately [8]. Based on current population growth and finite natural resources, incorporating water reuse technology is a necessity. As Fedler [9] noted, "It is not a matter of *if* we will utilize reuse technology in the future; it is a matter of *when* we will use it to sustain economic growth and minimize environmental impacts."

1.1 Water Use in Agriculture

Irrigation is a major consumer of fresh water around the world. If no sustainable approaches are adopted, there will be insufficient water available. Nearly 70% of the fresh water consumed worldwide is by food production systems [10]. In the United States, 42% of the total freshwater consumed is used for crop irrigation [11]. Higher crop yields must occur in the future if countries are to meet the increasing need for food. Thus, the strain on freshwater resources will continue to increase unless changes occur. While options are limited for developing new water supplies, many sources of wastewater are readily available and are produced within the proximity of the crop production operations. If municipalities recycled their wastewater for irrigation rather than using fresh water, that same volume of freshwater would then be available for public consumption. Currently, the United States collects and treats about $45x10^9$ m^3/yr ($1.2x10^{12}$ gallons/yr) of municipal wastewater of which less than 6% is reclaimed for beneficial purposes [12]. Yet, if this water was reclaimed for crop production, approximately 10 million hectares (25 million acres) could be irrigated, representing about half of the irrigated crop area in the United States [1]. The reclamation rate is even less in the global context with only approximately 3% of municipal wastewater being recycled [13].

If our crop production systems can adapt to using reclaimed water, we will be able to sustain and possibly increase crop production for a much longer time [1] while continuing to provide adequate drinking water. In addition, the use of reclaimed water for irrigation improves the environment because it reduces the amount of waste (treated or untreated) discharged into water courses. Further, it provides savings in the cost for treating wastewater for municipalities as treatment requirements for reuse are less stringent than stream discharge. If 10% of the wastewater in United States was treated to meet regulatory requirements for land application to crops (typically effluent BOD < 60 mgL^{-1}), the estimated saving in operations and maintenance costs for wastewater treatment systems alone could be about $3 billion annually compared to stream discharge. Additionally, reducing the number of new treatment plants required, billions more in capital costs could be saved in the future as the population continues to grow.

1.2 Wastewater Treatment System

In the case of technologies available, there is a plethora of systems, from simple ponds to complicated mechanical systems that could be used for wastewater treatment. It is well understood from past and current analyses that pond treatment systems are much lower in cost compared to conventional mechanical systems such as activated sludge systems, biofiltration systems, oxidation ditches, rotating bio-disc systems, and membrane processes because of the amount of mechanical equipment involved in the conventional systems [[14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25]]. Additionally, some pond systems can provide the organic removal with a level of effluent BOD less than 60 mgL^{-1}. The most appropriate design is one that will produce an effluent that meets the recommended microbiological and chemical quality guidelines both at low cost and with minimal operational and maintenance requirements [[26], [27]]. Traditional ponds used for treating municipal wastewater range from aerobic to facultative to anaerobic based on their geometry, hydraulic flows, dominant biological reactions occurring in the ponds, and their overall goals [28]. Several procedures have been developed to design the various types of ponds. These methods include area-loading, first-order plug flow, first-order complete mix, dispersion model [[29] [30], [31], [32]], and several regression models such as those proposed by McGarry, Gloyna, and Larsen [[33], [34], [35]]. Many of these pond designs have been in existence for decades; yet, there is a lack of specific design guidelines for pond treatment systems, and selection of a design procedure is difficult to ascertain [36].

Design parameters for ponds are limited primarily to the area-loading criteria. The area-loading criteria is, at best, a rule-of-thumb design process with numerous contradictions [[29], [37], [38]]. The practice of using the organic loading rates and retention times based upon a regional determinant (North to South) has often been reported as not continuously meeting effluent standards [29]. The regression equations [[33], [34], [35]] established using the pond dimensions are adequate for preliminary design; however, serious considerations on flow dynamics and environmental conditions are required for their use on a larger scale since extrapolation is not recommended. Design approaches based on first-order kinetic rates [[30], [39]] and dispersion numbers [[31], [32]] would, ideally, serve as the best design approach; yet, the use of such models is often limited due to difficulty in obtaining needed design parameters, which are usually obtained only after performance data from the installed ponds are collected. The latest advances in pond design with the application of computational fluid dynamics models [[40], [41], [42], [43], [44], [45], [46]] and integrated models [47] have helped design engineers better understand the flow dynamics and the effects of pond configuration on treatment performance [[48], [49], [50]]. However, the applicability of such mechanistic models is questioned due to the lack of model validation and the computing power requirements [47]. Also, there exist contradictory viewpoints regarding pond dimensions as it relates to performance [36]. Some researchers claim pond dimensions such as length-to-width ratio and depth have no effect on pond performance [[51], [52]]; whereas, others say that the length-to-width ratio and depth are major design factors [[43], [53]]. Likewise, there is lack of consensus on the effects of baffles on pond performance [[42], [46], [48], [54]]. This clearly illustrates that existing knowledge on the design of ponds is inadequate. Several researchers [[29], [36], [55], [56], [57]] have discussed the different pond systems, existing design criteria and their limitations.

Each of the traditional ponds -- aerobic (or aerated aerobic), anaerobic, and facultative -- has advantages and limitations. Table 1 summarizes the advantages and limitations for these three major pond systems [[23], [55], [58], [59]]. Aerobic ponds, without aerators, require a larger amount of land compared to all other ponds because of the shallow depths. Aerators help reduce the land area, but they produce high concentrations of suspended solids in the effluent and require energy to complete the treatment process. In addition, the short retention times associated with aerobic treatment do not provide enough time for adequate coliform removal via solar radiation. The anaerobic and even the facultative ponds have a potential problem with odors due to high organic loadings typically used in those ponds. One possible solution to the inherent problems with the traditional ponds is to integrate the best functions of each into a single pond to allow the symbiotic relationships of related microorganisms to proceed without inhibition. A detailed discussion on need and importance of such integrated systems can be found in Adhikari and Fedler [36].

Table 1: Summary of advantages and limitations of Aerobic, Facultative, and Anaerobic pond systems [Source: [23], [55], [58], [59]]

Operational Factor	Aerobic	Facultative	Anaerobic
Energy requirements	High	Low to medium	Low
Land requirements	High, unless mechanically aerated	Medium	Low
Capital Cost	High	Low	Low
Operation & Maintenance Cost	High to Low	Low	Low
Extent of loading possible	Low to moderate	Moderate to high	High
Pathogen removal	High	Medium	Low
BOD removal	Low	Medium to high	Medium
Sludge production	High	Low	Very low
Odor problems	Low	Medium	High
Waste strength	Low to medium	Medium to high	High
Depth	Very shallow (<1.2 m)	Shallow (1.2 -2.4 m)	Deep (>3 m)

Hydraulic retention time	15-20 days	5-30 days	15-30 days
Energy production	No	Yes	Yes

An integrated, single-pond system, known as Pond-In-Pond (PIP), provides a treatment process that combines the best functions of the aerobic and anaerobic ponds. PIP systems, however, have not been discussed in detail in terms of performance primarily due to a lack of data. Thus, the objectives of this paper are to 1) gather performance data from existing PIP systems and other ponds that are similar in configuration to the PIP, thereby producing a larger dataset, and 2) evaluate the performance of the PIP configuration for reuse systems based on the data collected from existing operations. Since little research on PIP configurations has occurred over the past several decades, this research went back to the 1960's to obtain sufficient data for a more complete analysis of performance for PIP-like designs while considering newer approaches to designing typical ponds.

2. Pond-In-Pond Configuration

The first known combined pond was in Desert Lake Village near Boron, California in 1957 [60]. In that system, a small, deeper sub-basin was placed within one corner of the overall basin. This concept was further refined to include a slightly deeper section of the pond for confining the influent [[28], [36], [61], [62], [63]]. The combined ponding unit with a depth of around 3 m (9.85 ft) and retention time of up to 30 days provided effluent BOD concentrations less than the required standards for reuse in land application (typically 60 mgL^{-1}) [[23], [28], [36], [64], [65]]. These combined systems require less capital, energy, and operation and maintenance costs than typical mechanical systems [[14], [15], [23], [36], [66]] and require less land, produce fewer odors, and fill in with sludge much more slowly than traditional ponds [67]. Since the initial treatment pond is submerged within an outer pond, the term Pond-In-Pond (PIP) was adopted as a simple descriptor for the system.

The Pond-In-Pond (PIP) is a treatment technology in which two types of ponds--anaerobic and aerobic--are combined into a single pond [[28], [36], [68]]. This configuration integrates the functions of each pond type into a single pond in which the top aerobic surface allows for photosynthetic oxygenation resulting in lower odor levels compared to traditional ponds, and the bottom zone provides the anaerobic environment required for more complete conversion of complex organic matter. The basic premise of the PIP was to provide a protective zone for the anaerobic organisms to perform without interruption as shown in Figure 1. The inner pond of the PIP includes a berm at the top on all sides which serves as a barrier to mixing that can be caused by seasonal temperature stratification of the water and subsequent wind [[36], [68], [69]].

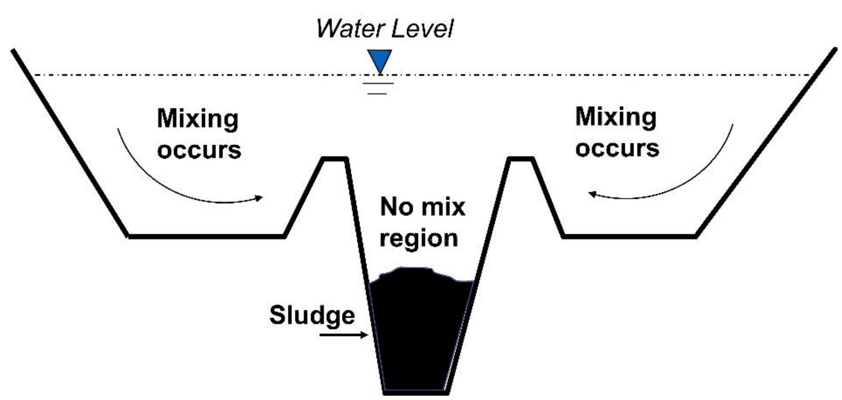

Figure 1: Configuration of Pond-In-Pond to prevent mixing [Source: Adhikari & Fedler *[36]*]

The PIP system provides more efficient conversion of organic matter. The deeper section of the inner pond allows for a greater retention time of solids so that hard to degrade compounds can degrade more completely under anaerobic conditions. The greatest part of the sludge is converted to gaseous form leaving behind only fixed solids at the bottom, which is accounted for in the design life of the pond. Thus, the PIP offers an advantage over other pond systems by eliminating the need for periodic (typically around 5 years) removal of sludge. Handling of sludge build-up in the bottom of the ponds has been one of the major issues in traditional pond systems, as it reduces the volume for treatment and, thus, the retention time. The configuration of the pond within a pond with the berms around the inner pond serves as a baffle within the pond and thus induces flow diversion which was found to be beneficial from several studies [[19], [42], [43], [44], [45], [46], [70]] using a computational fluid dynamics (CFD) analysis on baffled ponds. CFD models simulate the fluid flow more precisely and offer flexibility in understanding the effects of external factors such as wind, thermal stratification, baffles [[49], [71]], along with the pond inlet/outlet configurations and determination of potential dead zones [[48], [50]] within the pond. The CFD models showed that the use of baffles and inlet/outlet configurations has significant effects on pond performance and flow efficiency, respectively. This has allowed designers to more fully understand why Stone [60] added the flow diversions to the process. Also, the configuration of the PIP allows for a reduction in the total area required for wastewater treatment compared to traditional ponds, which reduces the capital cost.

3. Pond-In-Pond: Case Studies

The PIP system provides more efficient conversion of wastewater, including high-strength waste, to end products. In addition, it requires essentially no energy input, except for pumping of the waste into the system if gravity flow is not possible [[28], [36]]. The following section presents the case studies on such systems. The case studies discussed in this paper are selected to cover the wide applicability of these systems.

3.1 Sewage Treatment Facility in Desert Lake Village near Boron, California

The Desert Lake Village system was built in 1957 to serve a planned community of approximately 250 homes and other facilities in the community such as hotel units, a shopping center, and a school. The system consists of a primary basin followed by secondary and tertiary basins that could be run in series as shown in Figure 2. The primary basin was designed similar to the concept of the PIP, in which a deeper sub-basin was placed inside the larger pond [60]. The larger, outer pond has the wetted area of 1.82 hectares (4.5 acres) and a minimum liquid depth of 0.9 m (3 ft) with a 0.6 m (2 ft) freeboard. The smaller sub-basin has an area of 2,090 m^2 (22,500 ft^2) and a water depth of 2.1 m (7 ft), and the raw sewage was discharged into the deeper sub-basin. No performance data has been reported for this system, but Stone [60] reports that the system was working effectively.

Based on experience of five similar installations, Stone [60] recommended the use of increased depths for the inner basin. The deeper basin improved the depth diffusion of raw sewage providing greater algal and bacterial activity and treatment efficiency than a shallow basin of equivalent area. In addition, greater depths provided better control of swamp-type vegetation and better inhibition of insect breeding. This arrangement also greatly reduced the excavation cost [60]. The total cost for installing the system including the pumping plant, automatic controls, fencing, piping, and all other components was less than $15,000. The annual operating cost was less than $1,000 a year. The operating costs for individual septic tanks and leach systems in nearby communities with similar population and sewage characteristics was approximately $15,000 annually.

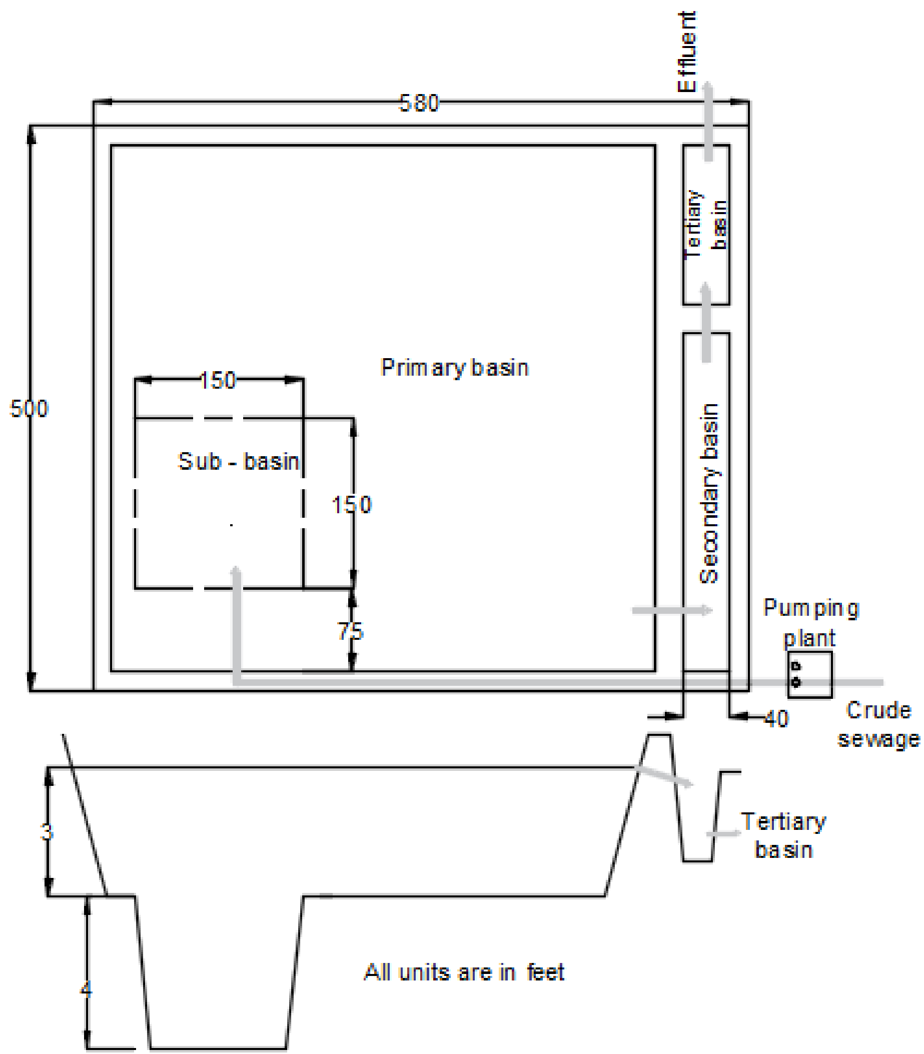

Figure 2: Plan view (top) and longitudinal cross-section (bottom) of sewage treatment facility in Desert Lake village near Boron, California (adapted from Stone *[60]*)

3.2 Advanced Integrated Wastewater Ponding System (AIWPS), California

The first advancement to the concept of the PIP was adopted by Oswald [68] when he placed a deeper section within a larger outer pond and added berms around the inner pond. Oswald [68] integrated his PIP into an overall system and called it the Advanced Integrated Wastewater Ponding System (AIWPS) that was developed to provide stream discharge of the municipal effluent. This system consisted of four ponds in series as shown in Figure 3 and was designed for treating municipal wastewater for stream discharge. The first pond in the series is the PIP (referred to as an Advanced Facultative Pond-AFP). The PIP has aerobic conditions on the surface and anaerobic at the bottom and consists of a deeper digestor pit inside a typical facultative pond in which the sludge is digested under anaerobic conditions.

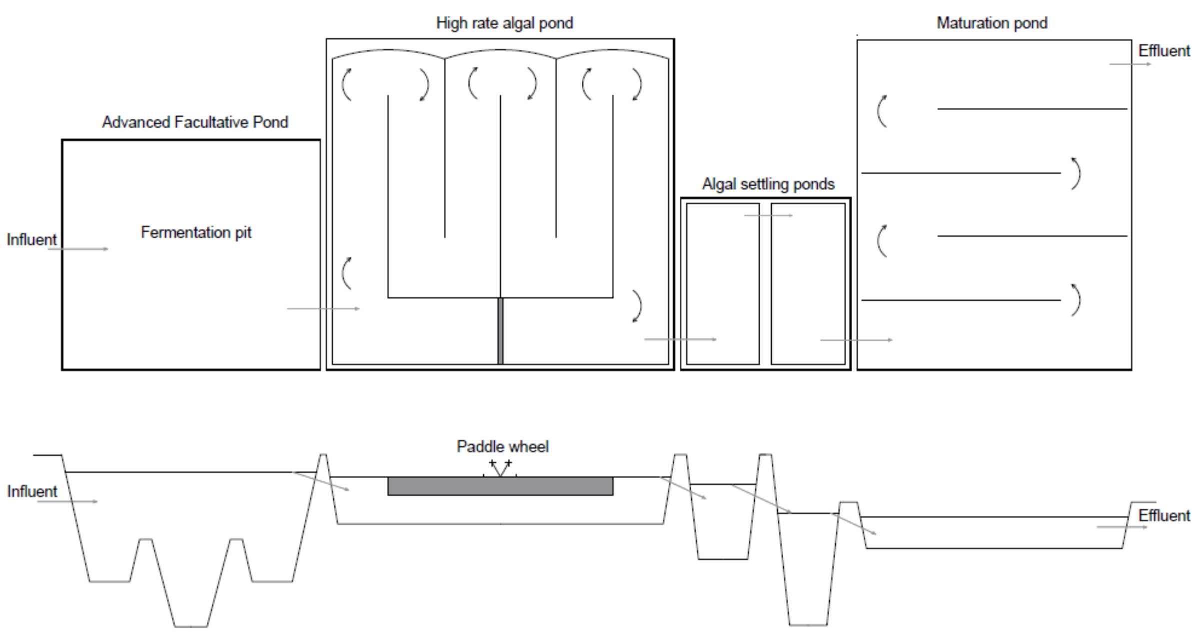

Figure 3: Plan view (top) and longitudinal cross-section (bottom) layout of Advanced Integrated Wastewater Ponding System (AIWPS) [Source: Shilton *[72]*]

Performance data from the AIWPS systems at multiple locations in California (CA) is presented in Table 2. It illustrates that the PIP component can remove influent BOD in the range from 70% to above 90%. The effluent BOD from the PIP unit in all four locations is below the 60 mgL^{-1} typically used for reuse in irrigation. Thus, it is possible for the PIP to stand alone as a single pond for treating municipal wastewater sufficiently for reuse as crop irrigation water. In addition, this design minimized the sludge handling requirements. The system in St. Helena (Table 2) operated for over 20 years without sludge removal [63]. Likewise, the Hollister system operated for 10 years without sludge removal, and was found to be of sufficient capacity for at least another 10 years by Oswald [63].

Table 2: Performance of PIP and AIWPS at multiple locations

System	Influent BOD (mgL^{-1})	Pond-In-Pond (PIP)			Advanced Integrated Wastewater Ponding System (AIWPS)	
		Retention time (days)	Effluent BOD (mgL^{-1})	% Removal	Effluent BOD (mgL^{-1})	% Removal
St. Helena, CA*	223	20	17	92	7	97
Hollister, CA*	194	32	43	78	7	96
Delhi, CA*	224	-	56	75	4	98
Bolinas, CA†	160	-	47	70	14	91

*Data obtained from Tuba & Victor [73]

† Data obtained from EPA [55]

3.3 Advanced Integrated Wastewater Ponding System (AIWPS), Ethiopia

The pilot-scale AIWPS facility was installed at the Modjo Tannery in Ethiopia to study the seasonal and diurnal variations of pH, dissolved oxygen (DO), and temperature within the AIWPS. The system was comprised of a PIP (originally referred to as AFP) followed by a secondary facultative pond (SFP) and a maturation pond (MP). The PIP was square in shape with 3 m (9.8 ft) for both length and width and 3.5 m (11.5 ft) depth and consists of a cylindrical submerged pit of 1.6 m (5.2 ft) in diameter and 5 m (16.4 ft) deep. The vertical variations in pH, temperature and dissolved oxygen (DO) for the PIP were minimal as compared to the variations in the SFP and MP [74], which indicates the use of the protected, deeper pond in the PIP system is appropriate. The pH varied between 8 and 8.4 at the surface of the water to 7.2 at the bottom, 9 near the surface to 8.2 at the bottom, and 9.4 at the surface to 8.4 at the bottom for PIP, SFP and MP, respectively. The temperature for the PIP varied by 2 ℃ along its depth with 20-24 ℃ near the surface to around 18-22 ℃ near the bottom, whereas the temperature gradient for SFP and MP was 5-8 ℃ and 3-5 ℃, with near surface temperatures about 26 ℃ and 29 ℃, respectively. Likewise, the DO for the PIP was less than 0.2 mgL^{-1} throughout its depth, while the DO varied between 20 mgL^{-1} at the surface to nearly zero at the bottom for both the SFP and MP.

The Modjo Tannery system was operated under three different feed flows. The raw waste was passed through successive bar screens and was retained for 1 day in a two-chamber horizontal settling tank (HST) prior to the PIP unit. The performance data in Table 3 (data extracted from Tadesse et al. [74]) shows that the BOD removal for the system was above 90% for all three cases. Among all the AIWPS components, the PIP unit had the highest removal efficiencies with 89, 73 and 82 percent for feed phase I, II, and III, respectively [74].

Table 3: Mean removal performances of the HST, PIP, and AIWPS

Feed phase	Feed Flow (l/d)	Raw tannery wastewater (mgL^{-1})	HST* Effluent BOD (mgL^{-1})	Pond-In-Pond (PIP)			Overall removal (AIWPS†) (%)
				Influent BOD (mgL^{-1})	Retention time (days)	Effluent BOD (mgL^{-1})	
I††	500	3580	2225 (38)	2225	8	250 (89)	99
II††	800	3075	2075 (33)	2075	5	560 (73)	92
III††	1275	2810	2142 (24)	2142	3	396 (82)	94

[*] Horizontal Settling Tank

[†] Advanced Integrated Wastewater Ponding Systems

[††] Data obtained from Tadesse et al. [74]

Values in parentheses are % removals.

3.4 Integrated Facultative Pond, Lubbock, Texas

The system built at the Animal Science farm of Texas Tech University was designed to treat the waste from 1,000 head of cattle and a 280-sow farrow-to-finish piggery operation, which was preceded by a screening process [75]. The system was established primarily to evaluate 1) the potential contamination of the underlying subsurface beneath the digestor pit without a liner and 2) energy recovery through methane capture (not presented here). However, the study brings forth several merits of using the PIP system in high-strength wastewater treatment and provides an argument for adopting the PIP design approach for water reuse purposes.

The system consisted of a 6 m (19.6 ft) deep inner pond integrated with a 3.1 m (10 ft) deep outer pond, followed by shallow ponds for production of aquatic plants and fish. The effluent from these ponds was collected in a storage basin and used in a slow-rate land application system. In addition to treatment of wastewater within the limits of required effluent BOD for land application of livestock wastewater, the aquatic plants and fish produced in the other ponds provided the ability to produce additional revenue for an industry that would utilize the technology. This technology could provide an annual revenue of over $ 5 US million from the cattle feedlots located in Texas when accounting for the energy and nutrients available [[28], [75], [76]]. Additional revenue is possible from the crops produced when the effluent is applied on a land application system. Thus, the integrated system has capabilities of meeting the required BOD standards for reuse while providing economic returns.

3.5 Municipal Wastewater Treatment System, Dove Creek, Colorado

The treatment facility at Dove Creek, Colorado serves approximately 700 people with an average annual influent BOD of approximately 250 mgL^{-1}. The system is similar to the Pond-In-Pond concept as it consists of a deep sludge cell preceding the aerobic cell. The anaerobic pit is approximately 6.1 m (20 ft) deep and the aerobic portion has a depth of about 4 m (13 ft). The pond system is then followed by a free water surface wetland.

The performance data was measured in the wetland following the pond system, and no effluent data is available for the individual ponds. The wetland, however, was used only for the polishing of the effluent; thus, a major fraction of treatment is expected to have occurred in the pond system. The final effluent BOD was approximately 30 mgL^{-1} for most of the period between 2000-2006, except for a few exceedances during start-up and during winter months [55]. The high quality effluent from the system could possibly be due to the additional aeration provided to the aerobic cell as mentioned in the EPA report [55].

3.6 Municipal Wastewater Treatment System, Colorado City, Texas

A PIP system in Colorado City in West Texas was designed for treating municipal wastewater for a population of 10,000 with an average annual influent BOD of approximately 280 mgL^{-1} and has been in operation for more than 15 years. The system consists of two PIP units in parallel, each with a surface area of approximately 24,000 sq. m. (6 acres), a 3:1 side slope, and a retention time of 22 days. The depth of the inner pond is 4.6 m (15 ft), and the outer pond is 3 m (10 ft) deep.

The performance data for the last 10 years of operation from 2010 through 2019 show that the system is performing within its design limits of an effluent BOD of less than 60 mgL^{-1}. The detailed analysis of the performance data has been provided in Adhikari and Fedler [36] , and it was observed that the overall average annual and monthly effluent BOD were approximately 40 mgL^{-1}. This clearly shows that the PIP system effluent can be used for water reuse systems. Table 4 and Table 5 present the annual and monthly average effluent BOD, respectively, for the Colorado City system.

Table 4: Annual average effluent Biological Oxygen Demand (BOD) [Source: Adhikari & Fedler *[36]*]

Year	Effluent BOD (mgL^{-1})	Year	Effluent BOD (mgL^{-1})
2010	45	2015	69*
2011	44	2016	36
2012	45	2017	23
2013	50	2018	23
2014	58	2019	26

*Year 2015 have some data that are more than two standard deviations from the mean.

Table 5: Monthly average effluent Biological Oxygen Demand (BOD) [Source: Adhikari & Fedler *[36]*]

Months	Effluent BOD (mgL^{-1})	Months	Effluent BOD (mgL^{-1})
Jan	40	Jul	35
Feb	42	Aug	27
Mar	59	Sep	33
Apr	66*	Oct	30

May	55	Nov	42
Jun	37	Dec	44

*59 mgL^{-1} when year 2015 is excluded from analysis.

3.7 Other Systems

In addition to the case studies discussed in this paper, similar systems are in practice at several other locations in United States and other nations [55]. Some of the reported systems in United States are in Napa - CA, Ridgemark Estates - CA, Hilmar - CA, and some recently built systems in West Texas. Likewise, these systems have been reported in other countries such as India, New Zealand, and Australia. These systems are not discussed in this paper due to unavailability of sufficient data.

3.8 Advantages and Limitations

Pond systems are simple, low-cost, and reliable wastewater treatment systems that have been used for many years to treat wastewater. Wastewater reuse in irrigation has two major objectives: it improves the environment because it reduces the amount of waste (treated or untreated) discharged into water courses, and it conserves water resources by lowering the demand for freshwater consumption for crop production [[77], [78]]. In addition, use of reclaimed water in irrigation has several other benefits such as 1) the reclaimed water contains valuable nutrients for crop production thus providing nutrient-rich water year around [[9], [65]], 2) the reduced need for commercial fertilizers, 3) the potential increase in crop yields, and 4) the income generation [28]. Also, the sludge produced from pond treatment systems can be used in agriculture with benefits obtained from the nutrients and organic matter contained in sludge

[79]. The fertilizer and organic matter content of sludge offer resource and energy conservation and maintenance of soil fertility.

The PIP configuration offers the advantage of being a stand-alone unit as opposed to other pond systems requiring multiple units of anaerobic, aerobic, and/or maturation ponds. Therefore, much less land area is required. When the inner pond depth is increased, there is increased solids retention time thereby providing more efficient conversion of wastewater to end products. In addition, the PIP configuration minimizes the need for sludge removal. Table 6 presents the performance data for different PIP systems used for treating different influent types, in which the average BOD removal for all systems combined was above 80%.

Table 6: Performance from the PIP configurations at multiple locations

System	**Influent BOD (mgL^{-1})**	**Effluent BOD (mgL^{-1})**	**% Removal**
St. Helena, CA*	223	17	92
Hollister, CA*	194	43	78
Delhi, CA*	224	56	75
Bolinas, CA*	160	47	70
Colorado City, TX*	250	39	84
Dove Creek, CO*	250	37	85
Ethiopia†	2147	402	81

* Municipal wastewater
† Industrial wastewater

Despite simple construction, the PIP-type systems still lack specific design guidelines, especially the depth for the anaerobic pit, the shape with respect to influent and effluent pipes, and the heights of the berms surrounding the anaerobic pit. All the case studies and the previous research show an improved performance with deeper ponds as opposed to shallow ponds, but no optimal depth has been determined. The systems are designed with depths ranging between 3 m (10 ft) to more than 6 m (20 ft) with performance not increasing proportionately. A study on AIWPS pond design for the last few decades shows an increasing trend in the adopted depths from about 3 - 4 m (9 – 13 ft) to about 6 - 7 m (19 - 23 ft) in more recent years [55]. The increase in depth helps reduce the area requirement thereby lowering the capital cost; however, more research is required to study the effects of depth on pond performance. Lastly, very few systems are in operation and lack adequate performance data to evaluate the applicability of such systems under different environmental conditions. The biological activity slows during cold weather conditions thus inhibiting anaerobic reactions. This could potentially lead to longer retention times or higher rates of sludge accumulation. The applicability of such systems in low temperature environments is yet to be fully explored due to the limited data available within colder climates.

4. Performance Data Analysis

The performance data gathered from the existing systems shows that the PIP configuration can provide effluent within the required limits for reuse in land application. Figure 4 shows the influent and effluent BOD and percentage BOD removal for systems treating municipal wastewater. The performance data from six different systems shows that the effluent BOD is below 60 mgL^{-1} for all cases with an average BOD removal rate of more than 80%. Likewise, results from similar observations for systems treating high strength industrial waste, as shown in Figure 5, show that the systems, on average, removed approximately 80% of the BOD.

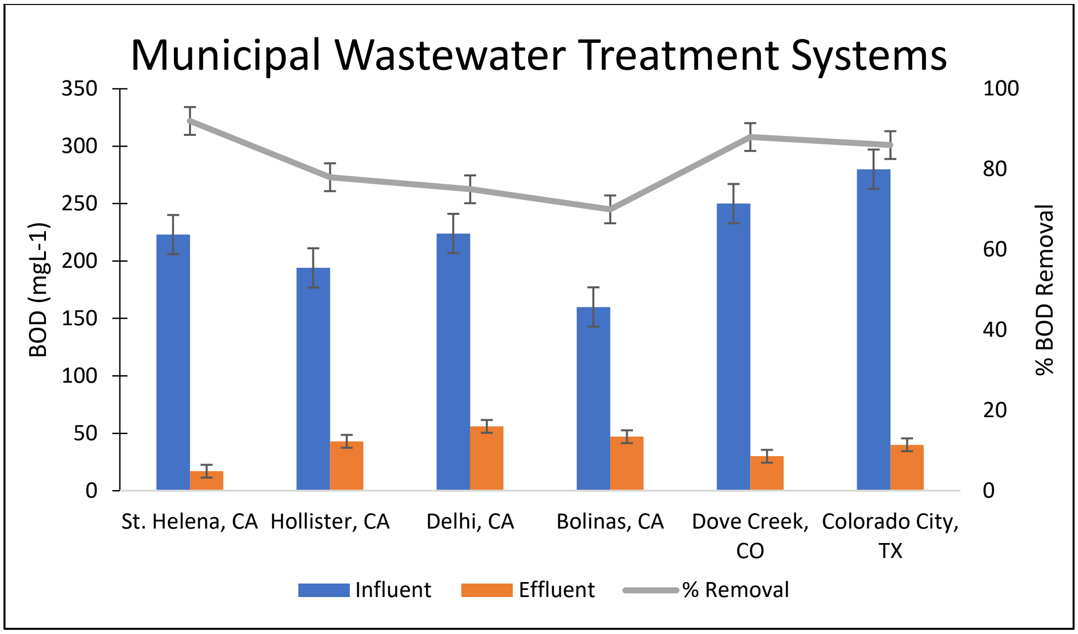

Figure 4: Influent BOD, Effluent BOD and percent BOD removal for PIP configuration treating municipal wastewater.

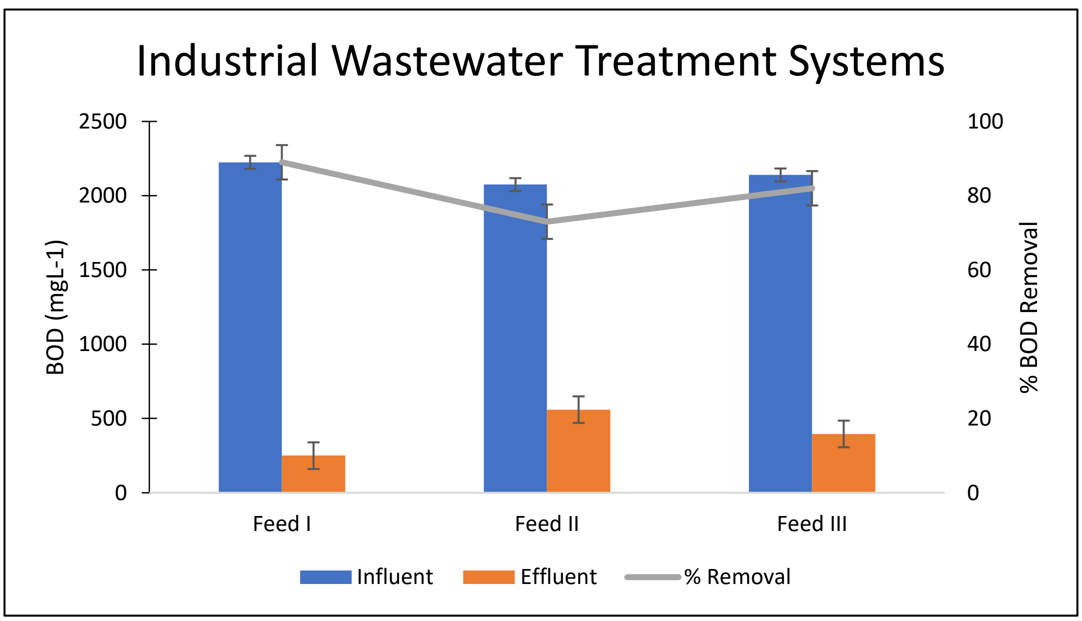

Figure 5: Influent BOD, Effluent BOD and percent BOD removal for PIP configuration treating industrial wastewater [data obtained from (Tadesse et al., 2004)]

Furthermore, variability in influent and effluent BOD shows that regardless of incoming influent BOD strength, the effluent from these systems treating municipal wastewater are always within the typical standards for reuse as shown by the box and whisker diagram[1] in Figure 6. The influent BOD for municipal wastewater shows a large variability with values ranging between 160 mgL^{-1} to 280 mgL^{-1}. Both the mean and median BOD is approximately 225 mgL^{-1}. The effluent, however, ranges between 17 mgL^{-1} to a maximum of 56 mgL^{-1} with an average effluent BOD of approximately 39 mgL^{-1}.

Lastly, the BOD removal percentages for all the systems were evaluated. The PIP systems in these cases provided removal efficiency ranging from 70 to above 90% as shown in Figure 7. Moreover, all the systems, regardless of the prevalent environmental conditions and influent BOD concentrations, have shown to reduce BOD by approximately 80% on average with a deviation of less than 10%.

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[1] The central rectangle represents the interquartile range (IQR) with segment inside the rectangle representing the median. The whiskers above and below the box show the location of the maximum and minimum. And, any data points 1.5*IQR or more above the third quartile or 1.5*IQR or more below the first quartile are considered as outliers.

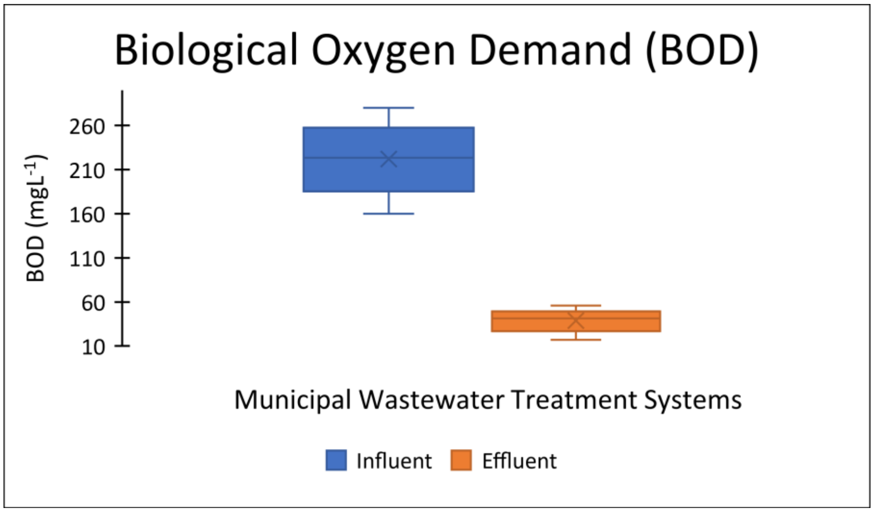

Figure 6: Variability in Influent and Effluent BOD for the PIP treating municipal wastewater

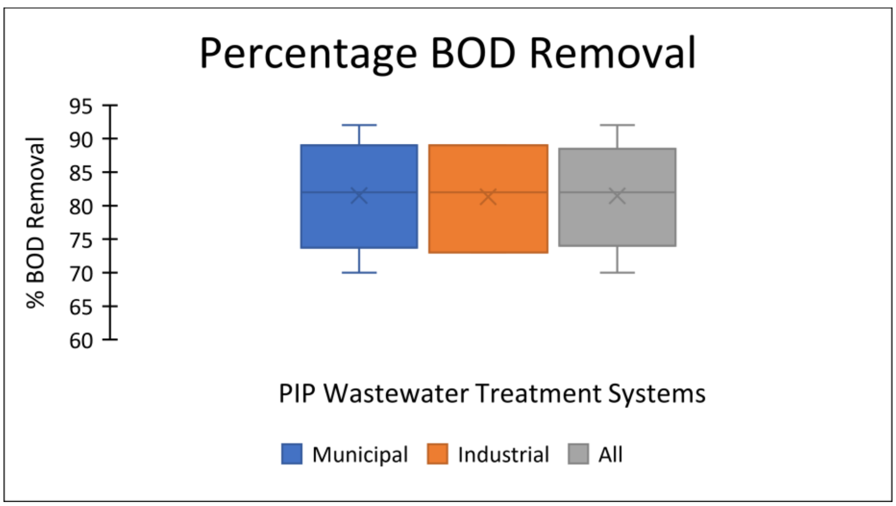

Figure 7: Variability in percentage BOD removal for PIP systems

For reuse of effluents for land application, the major concern is odor. Therefore, the BOD should be less than 100 mgL^{-1} with an extra level of precaution by limiting it to 60 mgL^{-1}. Thus, this paper only considered BOD removal for evaluating the performance of the PIP systems for water reuse.

5. Cost

Costs associated with wastewater treatment facilities fall under one of two categories: 1) capital costs and 2) operations and maintenance (O&M) costs. For the PIP system, the primary cost associated with construction of the pond includes the cost of the land, excavation, grading, berm construction, and inlet and outlet structures. Operating costs and energy requirements are minimal as the PIP does not require an external source of energy and, typically, no mechanical systems [[36], [80]].

5.1. Capital Costs

One of the major benefits of using the PIP is a reduction in land area requirements compared to other pond systems, which has been a major limitation in most multiple pond systems. The concept of using a deeper pond inside another pond eliminates the installation of multiple units and reduces the land area requirements by more than 50% which reduces capital costs. Table 7 shows the area requirements for different pond systems --aerobic, anaerobic and facultative--for the same level of treatment based on the current design criteria typically used. The results shown in Table 7 are for the following assumed characteristics of wastewater and environmental condition listed below. A similar comparison of land area requirements can also be found in EPA [55].

Design Flow rate, $Q = 3786\ m^3d^{-1}$ (1 MGD)

Influent BOD_5, $C_o = 200\ mgL^{-1}$

Desired effluent BOD_5, $C_e = 30\ mgL^{-1}$

Avg. summer temperature = 25 ^0C

Avg. winter temperature = 5 ^{0}C

Avg. annual temperature = 10 ^{0}C

Waste generation = 100 gpd/capita

Population @ 100 gpd/capita = 10,000

Table 7: Land area estimates for different pond systems

Pond Type	Design Method	Depth, m	Area, ha
Aerobic*	Wehner-Wilhelm equation	1	13.6
Facultative*	Wehner-Wilhelm equation	3	7.2
Anaerobic	Areal loading method	4	8.8
Pond-In-Pond†	Septic tank criteria††	3	3.3
Pond-In-Pond†	Anaerobic loading criteria††	3	3

*Reaction rate and dispersion numbers are assumed from existing literature.

†Depth shown for PIP is for the outer pond only.

†† Design guidelines can be found on Oswald [64].

Side slope used in the calculations is 2.5:1 for all ponds for consistency.

5.2. Operation and Maintenance Costs

The PIP systems are designed to operate by gravity flow and are entirely natural. The only energy used is direct solar energy, and no mechanical or electrically operated devices are required. Thus, these systems are easy to operate, do not need expert personnel, and provide a savings in energy and power requirements. Another important advantage of these systems is the small amount of sludge they produce. In these ponds, sludge undergoes continuous digestion until nothing remains except the non-degradable residue. Systems with similar configurations as the PIP have been found to run for more than 25 years without sludge removal, thereby, providing a savings in sludge handling costs and substantial benefit in terms of meeting environmental regulations for residue disposal [63].

6. Discussion

The PIP is a treatment technology in which two types of ponds--anaerobic and aerobic--are combined into a single pond. The inner deeper section provides anaerobic conditions for more complete degradation of organic matter while the outer pond provides additional treatment through the aerobic process used to control odor. The systems discussed were designed for different purposes such as stream discharge, energy and nutrient recovery, and reuse of effluent on land application sites. Regardless, all the systems have adopted the concept of the PIP as their first treatment unit and have been found to be successful in producing required quality effluent. Moreover, the performance data gathered from existing systems that date back to the 1960's show an average BOD removal of more than 80%, thereby ensuring that the PIP can adequately treat the typical municipal wastewater (influent BOD in the range of 200-300 mgL^{-1}) for reuse in land application.

- The AFP in the AIWPS system is no different than the PIP, and performance data from all systems used for treating municipal wastewater showed that the PIP can produce effluent within the BOD limits required for reuse in irrigation.

- For tannery waste, the PIP has been found to substantially remove the BOD concentration with more than 80% removal on average; however, for reuse of the effluent, additional treatment unit must follow the PIP.
- The PIP system used for treating municipal wastewater in Dove Creek, Colorado and Colorado City, West Texas produced an average annual effluent lower than the required limits of 60 mgL^{-1} desired for reuse.
- The system designed for treating cattle waste showed that it could provide revenue through the reuse of effluent for such things as producing aquatic plants and fishes and through use of the final effluent for land application.

In addition to the improved performance, the configuration of the PIP helps reduce the land area required as compared to conventional pond systems for the same level of treatment and requires minimal operation and maintenance cost. The PIP is, therefore, a lower-cost treatment system. However, poorly designed deep ponds can be more costly and can often lead to operational issues such as odor problems, short-circuiting of flows, and the need for sludge removal. These problems could be the major reasons why most authorities in the field tend to prefer shallow ponds over deeper ponds. Considerable experience from the existing systems has clearly shown the relative importance of increased depth. Thus, the PIP system, with improved understanding on pond hydraulics and pond performance and a more in-depth study on pond design and configuration, could be a beneficial system for wastewater reuse.

7. Conclusions

With the increasing population and changing climatic factors, there is a need for sustainable practices in utilizing our limited freshwater resources. Ponds have been in use for decades for treating wastewater, and several design approaches have been proposed for designing those pond systems. However, no standard design guidelines exist that adequately predict continuous performance. Additionally, there exist contradictory viewpoints regarding optimal pond dimensions and performance. This clearly illustrates that existing knowledge on the design of these ponds is inadequate. Given the wide use of ponds for wastewater treatment and the lack of appropriate design parameters, a simple, low-cost Pond-In-Pond (PIP) could be used instead.

The consistent performance data from several systems showed that the Pond-In-Pond system has the potential to be used for many types of influent ranging from municipal wastewater to industrial wastewater and animal waste. The performance data from the PIP systems examined provided an average BOD removal of greater than 80% with a standard deviation of less than 10%. Thus, for typical municipal wastewater, with an influent Biological Oxygen Demand (BOD) concentration between 200 and 300 mgL^{-1}, the PIP unit alone could provide adequate treatment required for reuse in crop irrigation. In addition, the PIP can be used in combination with other processes in a treatment system for treating high-strength wastewater and for other uses such as stream discharge, aquaculture, fishery, and others. Lastly, the savings in capital costs due to reduced area requirements, savings in operations and maintenance, and revenues from reclamation of effluent make the PIP a potentially viable and sustainable technology for wastewater treatment especially for reuse purposes.

8. Research Significance

- A single unit system (such as the PIP) can be effectively used for treating municipal wastewater when followed by reuse of the effluent. Adopting these systems for use of reclaimed wastewater in irrigation eliminates the need for treating wastewater to stream discharge quality, thus providing huge savings in capital, operations and maintenance costs, and energy requirements. For instance, in the case for the AIWPS, the effluent from the AFP portion of the system was well below 60 mgL^{-1} as is required for reuse. Treatment from the three other units of that system combined provided only about an additional 15-20% removal of BOD; however, the operation of those units is energy intensive. Thus, use of the PIP system for wastewater reuse in irrigation helps minimize cost for treatment while indirectly saving freshwater for human consumption in future years.

- Most of the municipal treatment systems are centralized and incur huge costs in transporting raw wastewater. Likewise, additional cost is required for carrying the effluent to the point of discharge. On the other hand, the PIP can be operated as a decentralized unit avoiding some of the conveyance costs. The PIP system has wide applicability in small and rural communities where the wastewater produced in the community can be treated locally and reused on adjacent farms. Adopting the PIP system for treating domestic waste will help these small communities by reducing the cost for treating their wastewater and developing economic benefit from the reuse of that water for crop irrigation.
- The PIP is an economical system because it reduces the land area requirements by approximately 50% as opposed to other pond treatment systems for the same level of treatment. In addition, the PIP facilitates energy capture since most of the sludge is converted to biodegradable end products. If the inner pond was covered, methane capture is possible which can be a source of additional revenue.

- Lastly, the PIP can be a better replacement to the existing first units in conventional ponding systems where higher quality effluent is required.

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Author Agreement/Declaration

All authors have seen and approved the final version of the manuscript being submitted. They warrant that the article is the authors' original work, has not received prior publication, and is not under consideration for publication elsewhere.

Declaration of Interest

There are no conflicts. There is no financial/personal interest or belief that could affect the research’s objectivity.

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Data used in the manuscript are gathered from previous published articles and proper citations have been made.

Disclosure Statement

No potential conflict of interest was reported by the authors.

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