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Removal of diluted wastewater from a potato processing plant with laboratory-scale hybrid-constructed wetlands

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ABSTRACT

In this study, wastewater from the potato processing plant was used in hybrid-constructed wetlands (CWs) that were planted with *Cyperus alternifolius* to test its effectiveness over a 100-d period in wastewater treatment. The hybrid CWs system was constructed to place the vertical reactors after the horizontal reactors. In the study of the hybrid system, two scenarios were tested (a planted CWs and a nonplanted CWs [control]) to determine any difference between their treatment effects. Zeolite, pumice stones, and pebbles were used in the vertical reactors and zeolite alone was used in the horizontal reactors as fill materials. In the hybrid system with *C. alternifolius*, the removal efficiency of chemical oxygen demand, NH_4-N, total nitrogen, and PO_4-P were 87%, 83%, 88%, and 82%, respectively. In the control, the removal efficiency rates of the above substances were 77%, 77%, 79%, and 73%, respectively. Hybrid CWs systems were demonstrated to be effective in removing ammonia and organic matter from wastewater. In addition, the cubic model was determined to be suitable for the horizontal and vertical reactors in the planted system, while the logistic and Von Bertalanffy models were deemed suitable for the horizontal and vertical reactors, respectively, in the control.

Keywords: Potato wastewater; Hybrid system; Constructed wetlands; *Cyperus alternifolius*; Vertical flow; Horizontal flow; Growth modeling

1. Introduction

In nearly all food production businesses, the production process is formed of various phases including sorting raw materials, separating parts that cannot be processed, preparing foodstuffs properly, and packaging. This gradual production process also helps differentiate the structure of the waste. These waste management processes consist of water used for washing or rinsing, the deterioration of raw materials and unused parts, or water used for washing equipment, factory floors, and surfaces. A little amount of water is used for holding the tank [1]. Although production is similar to the one in potato processing businesses, there are various characteristics, types, and amounts of waste that is produced in the individual plants. The steps in potato processing are the entry and storage of raw materials, removal of any stones found with the potatoes, and the separation of peeling, cutting, chopping, washing, salting, and frying steps; these steps create large amounts of wastewater [2].

The wastewater from the potato processing industry is characterized by a high pollution load because of its high content of dry matter, proteins, and starch. Because of the high content of solids in the wastewaters, a primary treatment is initially applied during which one or more grid balancing tanks and predischarge units are used. The wastewaters are then biologically treated with large amounts of biodegradable organic matter [3]. In the potato processing industries, an upflow anaerobic sludge blanket reactor is generally used [1]. Aerobic systems are other biological treatment methods that are used in the treatment of wastewater from these industries. In these wastewaters, the levels of organic matter, nitrogen,

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and phosphorus are high. Various systems such as Bardenpho, A2/0, the University of Cape Town (UCT) concept, the Virginia Initiative Plant (VIP) concept, a phosphorous recovery (Pho-Strip) system, and a sequencing batch reactor (SBR) are used for nitrogen and phosphorus removal. Another method of treatment is purification by natural treatment systems. Because natural systems are economical, their use in the treatment of highly polluted wastewater is becoming widespread. The studies of wastewater from the potato processing industry indicated that the reduction of total nitrogen content is a significant benefit of these applications [2].

Constructed wetlands (CWs), which mimic natural wastewater treatment systems, are environmentally friendly, have simple construction, and require little maintenance [4–6]. CWs are human-made basins that are constructed based on specific engineering designs; these designs' ecological conditions are similar to those of natural wetlands in treating wastewater under different physical, chemical, and biological conditions [7]. CWs are used as secondary treatment plants for domestic wastewater and agricultural production, and as tertiary treatment for polishing wastewater, urban runoff, and contaminated groundwater [8–10].

All types of CWs are used in combination with a growth bioreactor [11] and all the materials and parts of wetland vegetation (roots, stems, leaves, and litter) constitute the surface for microbial attachment [12,13] Subsurface flow CWs can be designed both horizontally and vertically. Horizontal flow (HF) and vertical flow (VF) reactors can be sequentially used as hybrid CWs [14].

In wastewater treatment, the processing efficiency in these hybrid CWs is higher than in single CWs systems, especially in the removal of nutrient components. The combined use of HF and VF reactors (hybrid system) is a new application and has been recently used to optimize overall performance [15]. It was reported that using hybrid CWs is a reasonable alternative to single CWs and a more efficient wastewater treatment process with reduced water loss [16]. Hybrid CWs are usually used to treat municipal wastewater, and it was reported that the hybrid system was used in a pilot-scale plant in Mexico [17]. Another study reported that a hybrid CW was used to treat municipal sewage in Sarbsk, Poland [18].

The objective of the hybrid system is to remove organics and suspended solids (SS) from wastewater and to provide nitrification. Denitrification and further removal of organics and SS are performed specifically in an HF system [19].

In this study, a hybrid system comprising an HF reactor followed by a VF reactor was used to treat wastewater from a potato processing plant. The study used samples of the effluent from each system to examine the variations in pollutants. In addition, the most common growth models in the literature were applied in this study to determine the correct height of *C. alternifolius*, which was chosen as the wetland plant in the hybrid CWs, and the model characteristics were calculated.

2. Materials and methods

2.1. Wastewater from the potato processing plant

The wastewater that was fed into the systems was supplied by BOLPAT A.Ş, Bolu, Turkey, and stored in a refrigerator at 4°C under controlled conditions. The wastewater was then stored in a feed tank before being dosed into the reactor systems intermittently. The mean wastewater characteristics are given in Table 1. The raw wastewater was diluted to a ratio of 1:5 using tap water before being introduced into the system due to reliability and economic concerns, and to prevent any possible consequences from toxicity on the plants in the reactor.

2.2. Hybrid systems

The study was carried out on hybrid CWs made from PVC material formed by sequential placement of pilot-scale HF and VF reactors. The HF reactors are 33 cm long, 14.8 cm wide, and 16 cm high, with a working height of 12.3 cm. VF reactors are circular systems, with internal diameters of 20.2 cm and a working height of 21 cm. To take samples from the outlet water, the researcher used 1.25 cm mini ball valves 3.4 cm high in the HF reactors and 4.8 cm high in the VF reactors. The planted HF and VF reactors were designated as HF_P and VF_P; the unplanted HF and VF reactors were designated as HF_{UP} and VF_{UP}. The planted hybrid system was defined as HS_P and the unplanted hybrid system as HS_{UP}. The two hybrid systems are shown in Fig. 1.

In HS_P, HF_P contained 61 rhizome/m^2 *C. alternifolius* and the VF_P reactor contained 93 rhizome/m^2 *C. alternifolius.* In HS_{UP}, the HF_{up} and VP_{up} were left empty for being used as the control system.

Wastewater from the potato processing plant was fed into the systems intermittently (5 min feedings/h) using the peristaltic pump (Ismatec VC 280), which enabled the pores within the bed media to be filled with air that was then trapped by the subsequent dose of liquid between feedings.

Table 1
Diluted wastewater characterization

Parameter	Mean
COD (mg/L)	450.5 ± 0.70
NH_4-N (mg/L)	18.5 ± 2.12
NO_3-N (mg/L)	3.85 ± 0.63
NO_2-N (mg/L)	1.16 ± 0.11
TN (mg/L)	9.9 ± 0.14
PO_4-P (mg/L)	1.965 ± 0.02
pH	8.215 ± 0.03
ORP (mV)[a]	–69.95 ± 35.0
EC (µS/cm)[b]	949 ± 357.7

[a]EC: electrical conductivity.
[b]ORP: oxidation reduction potential.

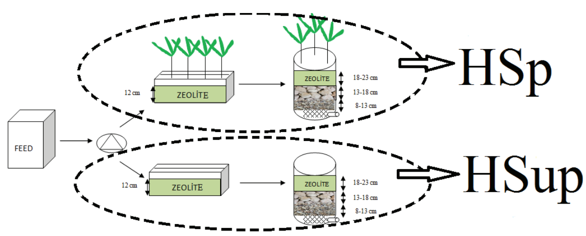

Fig. 1. Design of hybrid constructed wetland.

In the horizontal flow systems (HF), the wastewater which is fed in the inlet continues its way under the surface of the bed in a more or less horizontal path until it reaches the outlet zone. In the VF systems, however, the wastewater is fed on the whole surface area through a distribution system and passes the filter in a more or less vertical path [20].

Wastewater was input at a rate of 1.2 L/d (0.5 L/h) and passed through the system with total hydraulic retention times of 6 d for both HS_p and HS_{UP}. The systems were allowed to adapt for 7 d and then operate for the following 93 d. Gravel, zeolite, and pomza were used as the fill materials in the reactors. Zeolite (clinoptilolite) was used in addition to the commonly used zeolite and pomza media to improve the removal mechanisms (i.e., ion exchange and adsorption) in both the HS_p and HS_{UP} systems. The characteristics of the reactors are provided in Table 2.

2.3. *Cyperus alternifolius*

Cyperus alternifolius, also known as umbrella papyrus, is a dark-green plant 20–30 cm long and 1–2 m tall with leaves 5–50 cm wide that is usually found in nutrient-rich lakes and rivers. It is so named umbrella papyrus because its leaves have the shape of an umbrella outward. As a tropical plant, *C. alternifolius* generally inhabits moist environments and can live in water up to 15–20 cm deep. Without sufficient water, the plant turns yellow and goes through a dormancy period until recontact with water, which initiates the growth by creating new extensions from the root zone [21].

Cyperus spp. has been used successfully in small-scale gravel bed CWs in Australia and New Zealand [22]. As identified by Hocking [23], the attributes that make *Cyperus* spp. a potentially useful plant for CWs are their year-round growth in warm temperate regions (withstanding moderate frosts), tolerance of hyper-eutrophic conditions and salinity, ease of propagation, and apparent lack of the potential for serious weed invasions [22–25].

2.4. Chemical analyses

Two days of each week during the 100-d processing period, water samples were taken from the outlets of the HS_P and HS_{UP} systems and from the supply tank. Physical and chemical parameters comprising levels of chemical oxygen demand (COD), ammonium (NH_4-N), total nitrogen (TN), orthophosphate (PO_4-P), nitrite (NO_2-N), nitrate (NO_3-N), electrical conductivity (EC), pH, and oxidation reduction potential (ORP) were monitored. EC, pH, and ORP analyses were performed using a Thermo Scientific Orion 5 Star Multi Analyzer. NH_4-N, TN, PO_4-P, NO_2-N, and NO_3-N analyses were conducted using a Pharo 100 Spectrophotometer (Merck, USA) in accordance with American Public Health Association (2005) standards. Table 3 presents the overall treatment performance of the hybrid CWs.

Table 2
Hydraulic characteristics of the reactors systems

			Hydraulic retention time (HRT) (d)	Organic loading rate (kg COD/m³ d)	Filling volume (L)	Number of plant rhizomes/m²
System	HS_p	HF_p	2.5	0.180	3	61
		VF_p	3.3	0.135	4	93
	HS_{up}	HF_{up}	2.5	0.180	3	–
		VF_{up}	3.3	0.135	4	–

Table 3
Overall treatment performance of a hybrid constructed wetland

Parameters	Planted hybrid system (HS_p)				Unplanted hybrid system (HS_{up})			
	Inflow	Outflow HF_p	Outflow VF_p	Removal %	Inflow	Outflow HF_{up}	Outflow VF_{up}	Removal %
pH	8.19	7.5 ± 0.17	7.4 ± 0.20	n.a	8.19	7.9 ± 0.10	7.9 ± 0.09	n.a
ORP (mV)	–94.7	–89.9 ± 2.04	–87.0 ± 3.81	n.a	–94.7	–89.74 ± 2.89	–88.6 ± 3.63	n.a
EC (μS/cm)	696	695 ± 55.20	746 ± 101.41	n.a	696	684 ± 41.45	587 ± 83.91	n.a
Turbidity (NTU)	20	6.68 ± 1.37	4.86 ± 0.76	75.65	20	7.14 ± 1.19	6.74 ± 1.77	68.79
COD (mg/L)	451	110.48 ± 37.19	55.58 ± 21.18	87.67	451	172.13 ± 28.28	103.58 ± 19.83	77.03
TN (mg/L)	9.8	1.86 ± 0.76	1.37 ± 1.08	88.49	9.8	2.27 ± 1.26	1.59 ± 1.33	79.35
NH_4-N (mg/L)	17	3.3 ± 1.92	3.3 ± 1.67	83.7	17	3.8 ± 1.98	3.4 ± 1.67	77.6
NO_2-N (mg/L)	1.08	0.32 ± 0.16	0.18 ± 0.08	n.a	1.08	0.39 ± 0.22	0.28 ± 0.16	n.a
NO_3-N (mg/L)	4.3	2.9 ± 0.36	2.3 ± 0.28	n.a	4.3	3.7 ± 0.40	2.7 ± 0.38	n.a
PO_4-P (mg/L)	1.98	0.74 ± 0.10	0.90 ± 0.16	82.50	1.98	0.34 ± 0.15	0.51 ± 0.17	73.83
SS (mg/L)	0.134	0.052 ± 0.012	0.070 ± 0.014	54.10	0.134	0.048 ± 0.014	0.056 ± 0.019	46.08

The surface area and structural morphologies of the materials were analyzed effectively using the JSM-6390LV (JEOL, USA) scanning electron microscope (SEM). The SEM images of the fill materials that were used in the study were taken after the 100-d experimental period to examine the suitability of the produced biofilm on the material surfaces. For the analysis, the fill materials were poured into strips using carbon adhesive tape and placed in the SEM chamber, where photographs were taken and recorded.

2.5. Statistical analyses

Discriminant function analysis was conducted to evaluate the wastewater treatment performance of the HS_P and HS_{UP} reactors. One-way analysis of variance at a significance level of 0.05 was conducted to the removal efficiencies for the 100-d monitoring period for each of the water quality parameters. Statistical analyses were conducted using SPSS 23 (IBM Corporation, Armonk, NY, USA). The statistical results are presented in the following form: (ANOVA; $F_{0.95}$ [d.f.; dn]; p) where $F_{0.95}$ = 95% confidence limit, d.f. = degrees of freedom, and dn = sample size.

2.6. Growth modeling

In this study, statistical modeling was used to examine plant growth. The study used R-R v 3.3.2 after determining these models. The mean squared error (MSE), Akaike information criterion (AIC), and Bayesian information criterion (BIC) were considered in the modeling process. R^2 was used to determine the most suitable model since this value is a measure of how the model can explain the dependent variable based on the independent variables.

The equations and parameters of proportional, linear, quadratic, quadratic zero, parabola, cubic, exponential, restricted exponential, logistic, Von Bertalanffy, Gompertz, Richards, and hyper-Gompertz that were used to compare plant height growth values in the HF_P and VF_P systems are provided in Table 4. The letters a, b, c, and d in the models show the model coefficients.

3. Results and discussion

The treatment of wastewater from potato processing plants was investigated in hybrid CWs. The levels of COD, NH_4-N, NO_3-N, NO_2-N, TN, PO_4-P, SS, pH, ORP, EC, and turbidity after processing were the parameters that were investigated in the study. Table 6 presents a summary of the input and output concentrations and percent recovery efficiencies of all the pollution parameters that were examined.

3.1. Environmental conditions

During the 100-d working period, the temperature under laboratory conditions was maintained at a mean value of 22°C ± 2.54°C. The oxidation–reduction potential was stable throughout the entire monitored period at all outflow samples. In HS_P and HS_{UP} systems, the input redox potential was –94.7 mv whereas the output and input redox potentials in the HS_P system at the HF_P and VF_P reactors were –89.9 ± 2.04 and –87 ± 3.81 mv, respectively. In the HS_{UP} system, the redox potentials in HF_P and VF_{UP} reactors were –89.74 ± 2.89 and –88.6 ± 3.63 mv, respectively. The researcher expected these conditions to be formed in later stages due to the constant saturation of both of the units to water. The average redox potential in the hybrid systems indicated that these systems contained less anaerobic medium than the other systems.

3.2. Treatment performance

3.2.1. Removal of organics and suspended solids

The efficiency for CWs removing organic matter is primarily in response to the amount of biodegradation, prolongation of hydraulic dwell time, or reduction in the hydraulic load [27]. At the beginning of all operations, 451 mg/L COD was intermittently fed into the hybrid systems. Output concentrations from the HF_P–VF_P (horizontal flow planted-vertical flow planted) and HF_{UP}–VF_{UP} (horizontal flow unplanted-vertical flow unplanted) reactors were 110.48 ± 37.19, 55.58 ± 21.18, 172.13 ± 28.28, and 103.58 ± 19.83 mg/L, respectively. The overall treatment efficiencies of HS_P and HS_{UP} were 87.67% and 77.03%, respectively (Fig. 2) (F [1, 56] = 79.340, $p < \alpha$, $\alpha = 0.05$). The level of COD that was removed in the hybrid system of Vymazal [26] was 84%, a value very similar to the one that was observed in our study. Melian et al. [16] reported COD removal at 78% (365 mg/L COD) from the domestic wastewater in the hybrid CWs in which VF and HF reactors were used sequentially. Borin et al. [27] conducted a study of piggery wastewater using VF and HF hybrid systems, and reported a COD removal of 79%. Hua et al. [15] obtained a COD removal at 90% efficiency in septic tank outlet wastewater in the hybrid system in which HF and VF reactors were used sequentially.

Table 4
Equations of applied models in plant growth

Growth model	Equation
Proportional	$y = at$
Linear	$y = at + b$
Quadratic	$y = at^2 + bt + c$
Quadratic zero	$y = at^2 + bt$
Parabola	$y = at^2 + c$
Cubic	$y = at^3 + bt^2 + ct + d$
Exponential	$y = ae^{bt}$
Restricted exponential	$y = a - be^{-ct}$
Logistic	$y = \frac{abe^{ct}}{ae^{ct} + b - a}$
Von Bertalanffy	$y = \left(\frac{a}{b} - \frac{1}{b}e^{-\frac{bt}{3} - \frac{cb}{3}}\right)^3$
Richards	$y = \frac{a}{\left(1 + be^{-cdt}\right)\frac{1}{d}}$
Gompertz	$y = a * \exp(-e^{-(t-c)/b})$

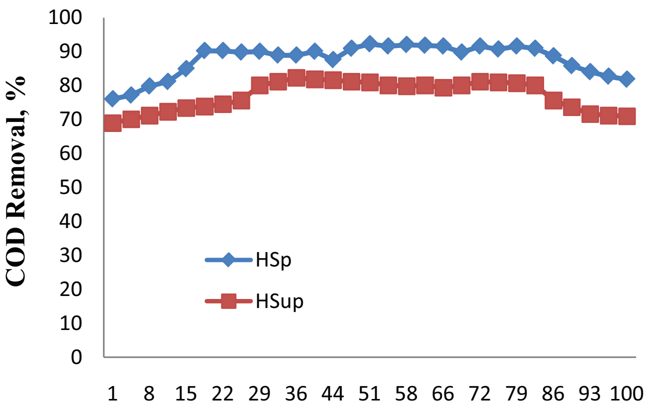

Fig. 2. Removal COD HS_p/HS_{up}.

The study by Tuttolomondo [28] and Korkusuz et al. [29] were found to have higher removal efficiency for planted units than unplanted units for COD.

The difference in COD removal efficiency between HS_P and HS_{UP} was 10.64%. As a result, it is believed that plants in the HS_P system produce continuous oxygen by photosynthesis, and that the oxygen is transported to the plant's roots, which results in a higher percentage of COD removal. It has been reported that oxygen transfer to the rhizosphere from plant roots affects COD removal [29]. Because there was no plant in the HS_{UP} system, COD removal was less efficient. Based on this result, this study puts forward that the plants will have a positive effect on the elimination of COD, and that higher amounts of organic matter in wetlands will be removed over time by the growing plants. This allows the formation of biofilms in the system [30]. During the study period, an average of 79% COD removal was observed in the HS_P system between days 1 and 15, and 88% COD removal was observed between days 15 and 100. This 9% difference indicates that the majority of biofilm formation occurs during the first 15 d. The presence of plants in HF_P–VF_P systems supports biofilm formation at the water surface and interfaces with roots and fill material [31]. The SEM images in Fig. 3 support this conclusion.

HS_P and HS_{UP} have a total retention period of 5.8 d, which is effective in removing COD. By providing a long retention time in CWs, microorganisms could reduce the concentration of organic matter in the wastewater by using it for metabolic activities with a requirement of COD [32]. Sarmento et al. [33] stated that the retention period was 3 d and that higher amounts of organic matter removal are directly related to longer retention periods. Rampsarad and Philip [34] observed that COD removal efficiency increased when the retention time was increased from 8.9 to 14.3 d.

The mean value of the SS concentration in the diluted wastewater that was fed into the hybrid system was 0.134 mg/L. The mean values of output concentrations from the reactors were 0.052 ± 0.012 and 0.070 ± 0.014 mg/L for HF_P–VF_P, respectively, and 0.048 ± 0.014 and 0.056 ± 0.019 mg/L for HF_{UP}–VF_{UP}, respectively.

SS recovery efficiency of HS_P and HS_{UP} systems was 54.10% and 46.08%, respectively (Fig. 4). There was no significant difference between the exposures ($F_{0.95}$ [1, 14] = 1.254; $p > 0.05$), and SS removal in the HS_P system was 8% higher than that in the HS_{up} system. This difference was associated with the length of the root structures and was effective in removing SS. In addition, according to this result, plants appear to play an important role in eliminating SS [35]. Burgoon et al. [36] conducted a CWs treatment of wastewater from potato processing plants using *Typha latifolia* and obtained 86% SS recovery from the system.

3.2.2. Removal of TN, NH_4-N, and NO_3-N

The mechanisms that ultimately remove nitrogen from wastewaters involve mainly ammonia volatilization, denitrification, plant uptake (with biomass harvesting), ammonia adsorption, and organic nitrogen burial. Ammonification and nitrification processes convert only nitrogen among the other nitrogen forms; however, these processes do not remove nitrogen from the wastewater [37].

Of all these mechanisms, nitrification and denitrification are the most effective ones for removing ammonia. In hybrid systems, nitrification occurs in VF and denitrification occurs in HF. It is also known that plant species used in both single CWs and hybrid CWs systems affect these processes [15]. Vymazal [26] stated that placing HF before VF reactors decreases NH_4-N removal; however, the recovery efficiency was increased in this study by using zeolite as a fill material, which is known to be effective in NH_4-N removal.

At the beginning of all operations, 17 mg/L NH_4-N was intermittently fed into the hybrid CWs. Output concentrations from HF_P–VF_P and HF_{UP}–VF_{UP} reactors were 4.6 ± 1.83, 2.8 ± 1.09, 5.9 ± 1.73, and 3.8 ± 1.58 mg/L, respectively. The treatment performances of the two hybrid CWs for HS_P and HS_{up} were 83.7% and 77.6%, respectively (F [1, 56] = 8.264, $p < \alpha$, $\alpha = 0.05$) (Fig. 5). High NH_4-N removal in the HS_P and HS_{UP} reactors is believed to be the result of nitrification in these systems. There is approximately 6% difference in NH_4-N removal from the HS_P and HS_{UP} systems, which is not significant. In the HS_P reactor, it is believed that the plants in the environment contribute to the nitrification process by oxygen transfer from the roots into the atmosphere. An aerobic environment is required for nitrification to take place, and the effect of plant root growth on the transport of oxygen to the rhizosphere is high. NH_4-N removal depends on pH [27]. In this study, the pH ranged from 7.5 to 7.9. If the pH value is <8, evaporation from the NH_4-N medium is neglected [38].

There were 1.08 mg/L NO_2-N and 4.3 mg/L NO_3-N in the wastewater fed into the reactors. In the HS_{UP} system, the NO_2-N and NO_3-N concentrations in HF_{UP} and VF_{UP} were 0.32 ± 0.16, 0.18 ± 0.08, 2.9 ± 0.16, and 2.3 ± 0.28 mg/L, respectively. In the HS_{UP} system, the NO_2-N and NO_3-N concentrations in HF_{UP} and VF_{UP} were 0.39 ± 0.22, 0.28 ± 0.16, 3 ± 0.40, and 2.7 ± 0.28 mg/L, respectively. These values demonstrate that ammonia is effectively converted into nitrite and nitrate. It has been observed that NO_3-N concentrations are higher in the HS_P and HS_{UP} reactor systems than NO_2-N concentrations (Fig. 6). The increase in nitrate concentration can be associated with the nitrification process because CWs provide increased wastewater oxygenation. In addition, the system is intermittently fed so that there is a large supply of oxygen in the substrate. By applying wastewater into the system, oxygen in the bed mass is increased [33].

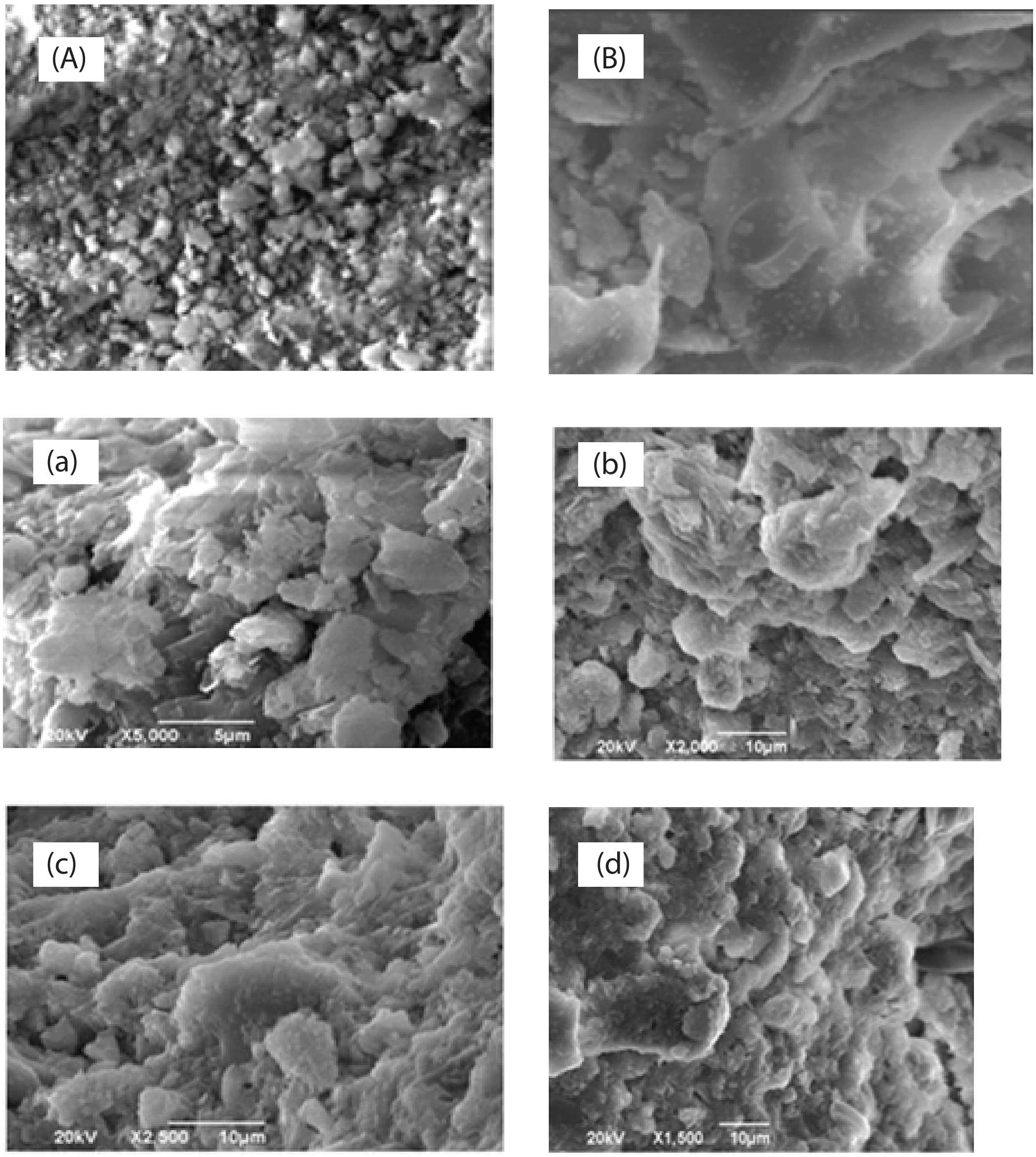

Fig. 3. SEM images of HS_p and HS_{up} systems: (A) zeolite blank image, (B) pumice stone blank image; (a) VF_p, (b) HF_p, (c)VF_{up}, and (d) HF_{up}.

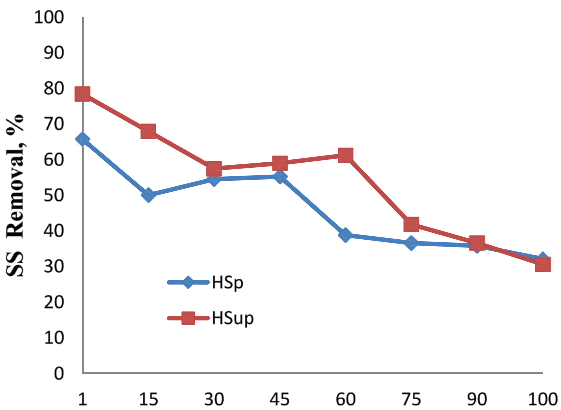

Fig. 4. Removal SS HS_p/HS_{up}.

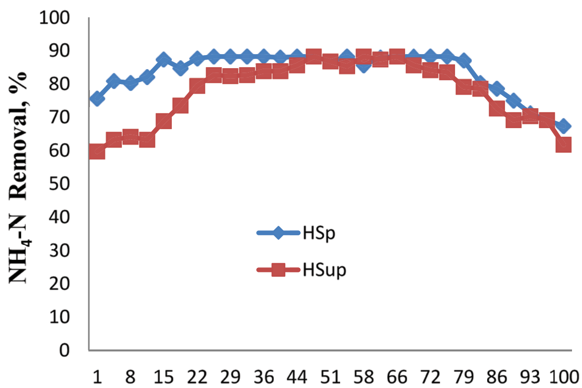

Fig. 5. Removal NH_4-N HS_p/HS_{up}.

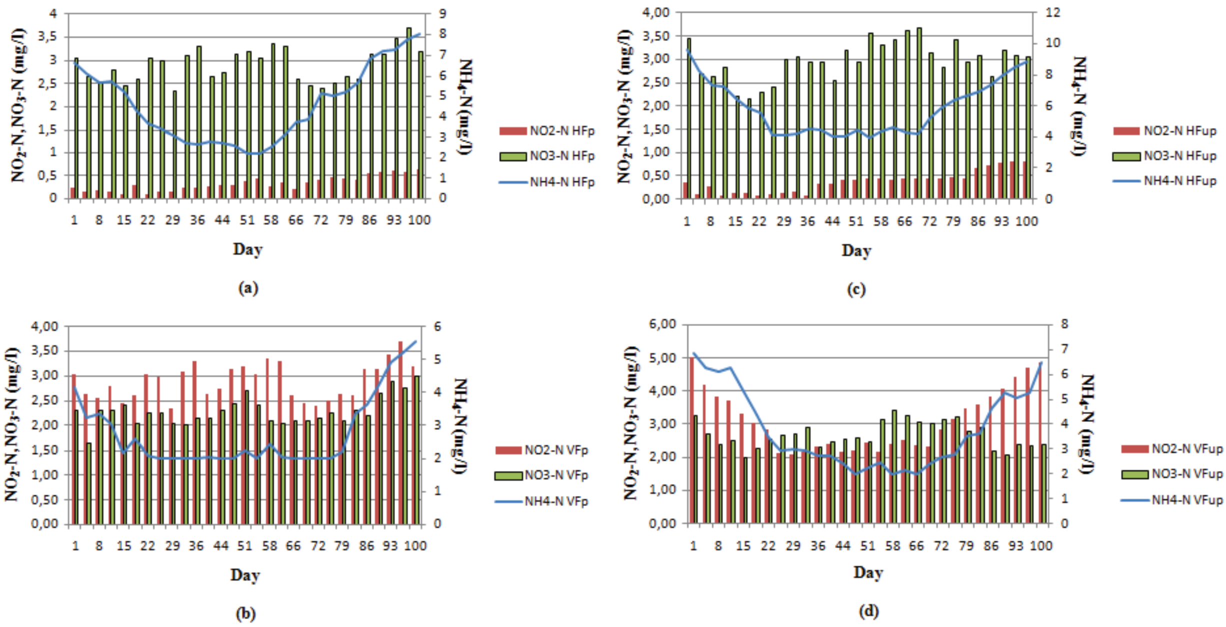

Fig. 6. Change of NH_4-N, NO_3-N, NO_2-N concentrations in HS_p and HS_{up} systems: (a) HF_p reactor, (b) VF_p reactor, (c) HF_{up} reactor, and (d) VF_{up} reactor.

TN removal is directly proportional to pH and temperature [7]. The average total nitrogen concentration in the wastewater fed into the system over 100 d was 9.8 mg/L. TN removal rates for HS_p and HS_{UP} reactors were 88.49% and 79.35%, respectively (Fig. 7). A significant difference was observed when comparing TN removal in the two hybrid systems ($F_{0.95}$ [1, 56] = 11.699; $p < 0.05$). This difference is believed to be the result of nitrification through HS_P. For nitrification, oxygen must be present in the system and it is transferred to the rhizosphere of the plant. This leads to an increase in total nitrogen removal; therefore, it can be concluded that plants are an effective part of the wastewater treatment process in CWs [33].

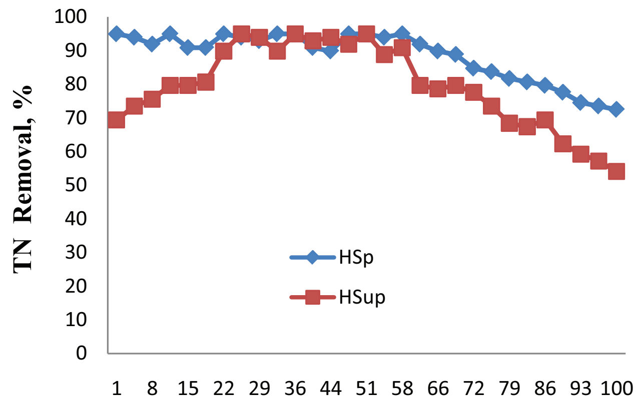

Fig. 7. Removal TN HS_p/HS_{up}.

3.2.3. Phosphate removal

PO_4-P removal mechanisms in wetland systems involve plant uptake, adsorption, and precipitation. A higher potential adsorption is observed in HF systems, as opposed to VF systems, because the substrate is constantly in contact with the water. These processes lead to higher PO_4-P removal efficiency in HF systems than in VF systems [39]. The free orthophosphate, which algae and microorganisms can easily absorb, binds the organic and inorganic phosphorus cycle in CWs [37]. The fill material that is used for phosphorus removal is important; therefore, choosing a suitable filler is important for high PO_4-P adsorption capacity [42]. Long-term phosphorus removal in CWs is achieved by Al–Fe compounds and plant residues, with little phosphorus uptake by plants [40].

In this study, the mean PO_4-P concentration input into the system was 1.98 mg/L. The means of reactor output concentrations were 0.74 ± 0.10 and 0.90 ± 0.16 mg/L for HF_P–VF_P, and 0.34 ± 0.15 and 0.51 ± 0.17 mg/L for HF_{UP}–VF_{UP}. The means of PO_4-P removal efficiency in the HS_P and HS_{UP} systems were 82.50% and 73.83%, respectively (Fig. 8).

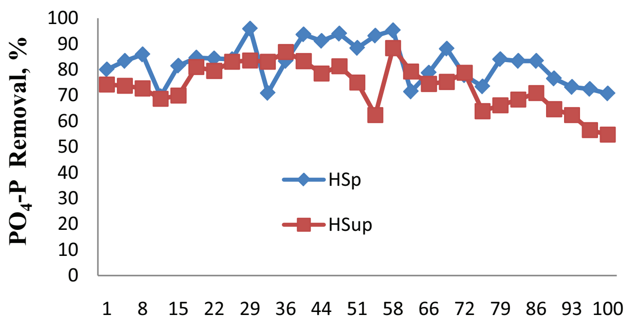

Fig. 8. Removal PO_4-P HS_p/HS_{up}.

There was a significant difference in the PO_4-P removal efficiency in both hybrid systems. ($F_{0.95}$ [1.56] = 15.308; $p < 0.05$). This approximately 9% greater efficiency in the HS_P reactor is believed to be the result of using zeolite with high adsorption capacity. On the other hand, Tao et al. [41] reported that a plant with *C. alternifolius* was associated with a very low level of phosphorus removal.

In their studies, Reddy et al. [42], and Yalcuk et al. [43] reported that they achieved 87% and 95.93% PO_4-P removal, respectively, when they used zeolite as fill material in their CWs; therefore, it can be suggested that zeolite greatly contributes to PO_4-P removal.

3.3. Modeling plant growth

During the 100-d operation period that involved the use of *C. alternifolius* in the HF and VF reactors in the hybrid CWs, 13 growth models were examined and their model coefficients were determined.

Tables 5 and 6 show the regression analysis from the data that were obtained from the HF_p and VF_p reactors. According to these criteria, AIC and BIC values are preferred in models with low MSE, while corrected R^2 values are preferred in those with high R^2. The models with R^2 and corrected R^2 values equal to zero or negative are excessively incompatible. According to these criteria, the Von Bertalanffy model is the most suitable model for the VF_p reactors, and the logistics model is the most suitable one for HF_p reactors.

Tables 7 and 8 show the estimated coefficients of the regression models that were created based on the data set from the HF_p and VF_p reactors, respectively. Figs. 9 and 10 provide graphical representations of the predicted values of the regression models that were generated using data sets from HF_p and VF_p reactors, respectively. From the graphs, it was observed that there is a harmonious relationship between the actual and predicted values for the linear, quadratic, quadratic zero, cubic, restricted exponential,

Table 5
Performance metrics for the HF_p reactor model

Growth model	MSE	R^2	Corrected. R^2	AIC	BIC
Proportional	283.232	0.220	0.142	105.810	106.780
Linear	39.788	0.890	0.866	84.257	85.712
Quadratic	5.675	0.984	0.979	62.888	64.828
Quadratic zero	47.278	0.870	0.821	86.327	87.782
Parabola	109.901	0.697	0.630	96.449	97.904
Cubic	4.848	0.987	0.979	62.997	65.422
Exponential	68.896	0.810	0.768	90.846	92.301
Restricted exponential	5.538	0.985	0.981	62.595	64.534
Logistic	3.905	0.989	0.985	58.403	60.342
Von Bertalanffy	4.087	0.989	0.985	58.949	60.889
Gompertz	247.733	0.317	0.062	110.203	112.627
Richards	362.976	0.000	–0.571	116.787	119.696

Table 6
Performance metrics for the VF_p reactor model

Model	MSE	R^2	Corrected. R^2	AIC	BIC
Proportional	223.555	0.209	0.130	102.970	103.940
Linear	26.584	0.906	0.885	79.418	80.873
Quadratic	3.814	0.987	0.981	58.120	60.060
Quadratic zero	41.668	0.853	0.797	84.811	86.266
Parabola	79.053	0.720	0.658	92.496	93.951
Cubic	2.438	0.991	0.986	54.747	57.172
Exponential	47.974	0.830	0.793	86.503	87.957
Restricted exponential	2.752	0.990	0.988	54.202	56.141
Logistic	3.936	0.986	0.981	58.496	60.436
Von Bertalanffy	2.688	0.990	0.987	53.921	55.861
Gompertz	241.681	0.145	–0.176	109.906	112.331
Richards	282.629	0.000	–0.571	113.784	116.694

logistic, and Von Bertalanffy models in line with the data set from the VF_p reactor; whereas we determined that there is a harmonious relationship between the real and estimated values of quadratic, quadratic zero, cubic, restricted exponential, logistic, and Von Bertalanffy models according to the data from the HF_p reactor.

Table 7
Coefficients of the model for the HF_p reactor

Model	a	b	c	d
Proportional	0.994			
Linear	29.097	0.574		
Quadratic	–0.007	1.284	17.539	
Quadratic zero	–0.012	1.975		
Parabola	0.005	41.158		
Cubic	4.08E-05	–0.013	1.524	15.746
Exponential	35.701	0.009		
Restricted exponential	86.059	70.599	0.023	
Logistic	18.823	77.341	0.059	
Von Bertalanffy	0.452	0.104	48.332	
Gompertz	–7.39E+10	0.222	0.043	–8.33E-10
Richards	7.145	7.129	9.021	6.004

Figs. 8 and 9 show graphical representations of the predicted values of the regression models that were created using data sets from the HF_p and VF_p reactors, respectively. Examining the graphs, we found a harmonious relationship between the actual and the predicted values for the linear,

Table 8
Coefficients of the model for the VF_p reactor

Model	a	b	c	d
Proportional	0.889			
Linear	26.173	0.511		
Quadratic	–0.006	1.091	16.730	
Quadratic zero	–0.011	1.750		
Parabola	0.004	36.797		
Cubic	5.27E-05	–0.014	1.401	14.417
Exponential	31.903	0.009		
Restricted exponential	77.597	62.949	0.022	
Logistic	18.206	69.851	0.054	
Von Bertalanffy	0.412	0.099	54.938	
Gompertz	0.113	0.405	0.908	463.409
Richards	3.564	9.057	9.936	9.449

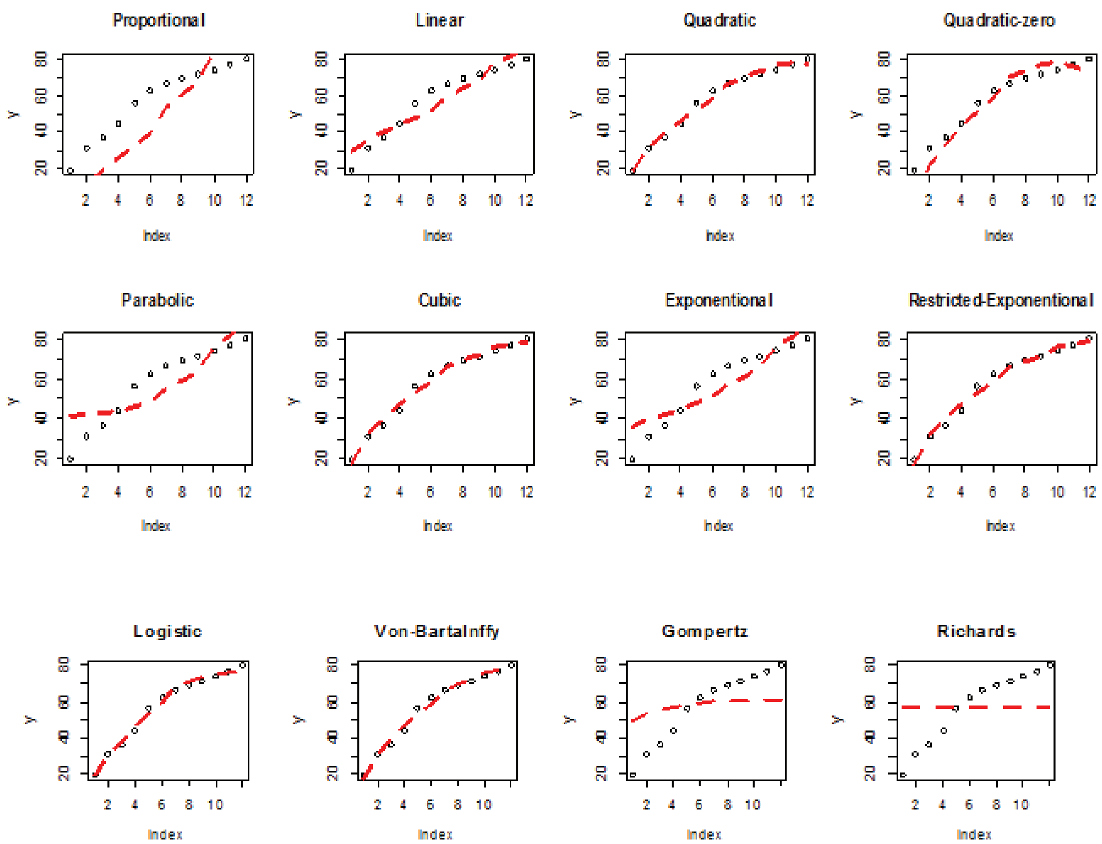

Fig. 9. Graphs of estimates for the HF_p reactor.

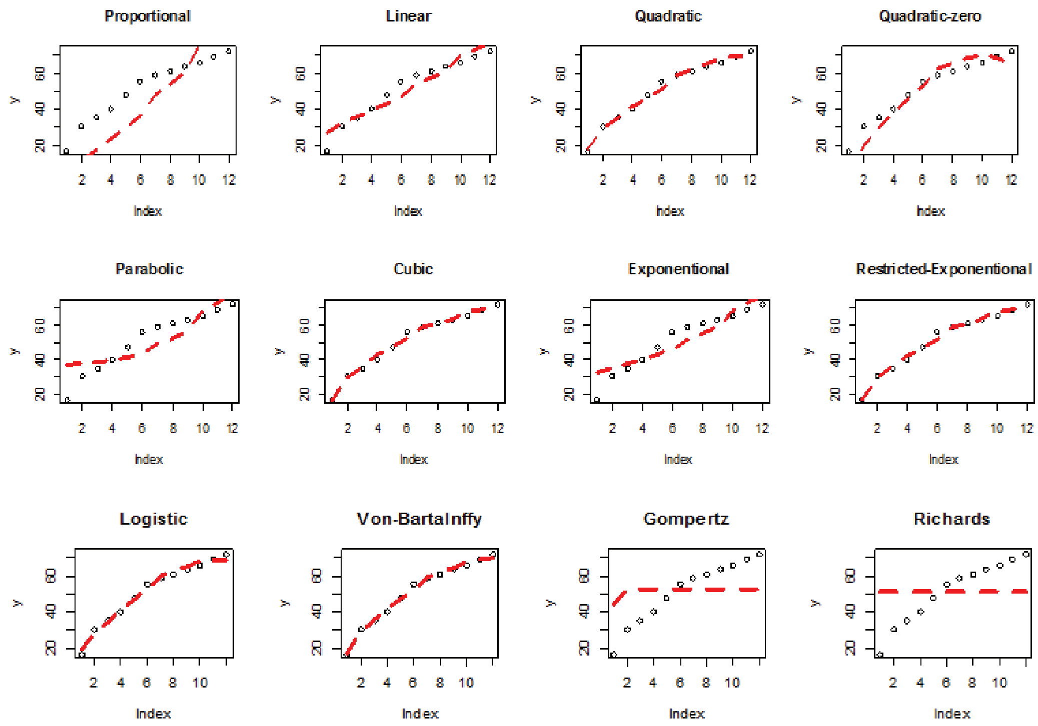

Fig. 10. Graphs of estimates for the VF_p reactor.

quadratic, quadratic zero, cubic, restricted exponential, logistic, and Von Bertalanffy models according to the data set from the VF_p reactor; whereas, there is a harmonious relationship between the real and estimated values of quadratic, quadratic zero, cubic, restricted exponential, logistic, and Von Bertalanffy models according to the data from the HF_p reactor.

Growth modeling was applied in various other studies. For example; Yildizbakan [44] studied the growth model of the eucalyptus tree and found that the Gompertz model was the most suitable. Yılmaz et al. [45] studied the growth model of the *Eucalyptus grandis* W. Hill ex Maiden and found that the Von Bertalanffy model was the most suitable.

4. Conclusion

Hybrid CWs containing VF and HF reactors in series are implementable alternatives for the treatment of wastewater from food processing plants when organics, ammonia, and phosphates are the targets for removal. This study revealed that the 6-d HRT hybrid CWs were very efficient in removing nutrients from the potato processing wastewater.

The study kept a record of the mean values for removal efficiencies (87.67%, 54.10%, 88.49%, 83.70%, and 82.50%) for COD, SS, TN, NH_4-N, and PO_4-P using HS_P. Also, the removal efficiency means of 77.03%, 46.08%, 79.35%, 77.6%, and 73.83% were recorded for COD, SS, TN, NH_4-N, and PO_4-P, respectively, using HS_{UP}.

We found *C. alternifolius* to be an effective plant in the efficient treatment of wastewater from potato processing plants. Plant height growth in the HF_p and VF_p reactors using the HS_p system was found to be most consistent with the logistic and Von Bertalanffy models, respectively.

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