Shahid Chamran University of Ahvaz

Irrigation Sciences and Engineering (JISE)
Vol. 45, No. 2, Summer 2022, p. 49-62

Original Paper

Journal homepage: https://jise.scu.ac.ir

The effect of the Geometric Shape of Bioreactors and Organic Matter on the Efficiency of Nitrate Removal from Drainage Water

H. Asgari[1], J. Azizi Mobaser[2*], A. Rasoulzadeh[3] and J. Ramazani Moghadam[4]

1- Graduate, MSc Irrigation and Drainage Engineering, Faculty of Agriculture and Natural Resources, University of Mohaghegh Ardabili, Ardabil, Iran.

2- Corresponding Author, Associate Professor. Department of Water Engineering, University of Mohaghegh Ardabili, Ardabil, Iran. (ja.mobaser22@gmail.com).*

3- Associate Professor. Department of Water Engineering, Faculty of Agriculture and Natural Resources, University of Mohaghegh Ardabili, Ardabil, Iran.

4- Assistant Professor. Department of Water Engineering, University of Mohaghegh Ardabili, Ardabil, Iran.

ARTICLE INFO

Artlcle history:
Received: 2 January 2022
Revised: 10 June 2022
Accepted: 11 June 2022

Keywords:
Denitrification, Water Reuse, Hydraulic Retention Time, Wood Chip.

TO CITE THIS ARTICLE:

Asgari, H., Azizi Mobaser, J., Rasoulzadeh, A., Ramezani Moghadam, J. (2022). 'The effect of the Geometric Shape of Bioreactors and Organic Matter on the Efficiency of Nitrate Removal from Drainage Water', Irrigation Sciences and Engineering, 45(2), pp. 49-62.

Abstract

Denitrification bioreactors for nitrate removal from agricultural water effluents have improved in recent years due to their low cost and ease of use. Scientific results and local experience are required for the optimal use of bioreactors. This study aimed to study nitrate removal efficiency and the effectiveness of each of these factors. Thus, 27 pilot bioreactors had the same volume and depth with different cross-sections in a randomized statistical design. Three geometric shapes of the trapezoid, rectangle, and triangle for the cross-section bioreactors and three organic matters including wood chips, corn stem chips, and wheat straw in 3 replications were used. Nitrate concentration at the inlet of the reactor and their outlet was measured at hydraulic retention times of 3, 6, 12, 16, and 24 hours. According to the average nitrate removal from the effluent, wood chips, wheat straw, and corn stem chips with 31.3, 28.6, and 27%, respectively, were prioritized during the 24-hour hydraulic retention time. Therefore, wood chips are the most suitable organic matter for nitrate removal from drainage water in actual biological reactors compared to other organic materials used in this study. The results demonstrated nitrate removal the 25.6, 30.1, and 35.3% for triangular, rectangular, and trapezoidal geometric shapes, respectively, for wood chips organic matters. Also, reactors with trapezoidal cross-sections have higher efficiency. In sum, this study showed that where there is a limit to the supply of wood chips, wheat straw and corn stalk chips can be used in bioreactors to remove nitrate.

Introduction

Artificial drainage implemented in agricultural lands has increased crop yield, optimized the timing operations, proper land use, and usability of saline and fertile lands in the world (Christianson et al., 2012). Complete construction of drainage networks located below groundwater level can increase agricultural production (Hoover et al., 2016). In addition to the positive effects of drainage networks, drainage in agricultural fields leads to the discharge of nitrate load to the surface water and groundwater (Christianson et al., 2010). Nitrate pollution in surface water and groundwater has become a serious problem

 DOI: 10.22055/JISE.2022.39610.2010

worldwide. The increase is mainly due to excessive use of nitrate fertilizers, industrial and domestic effluents discharge, and deep percolate from septic wells (Ashoori et al., 2019; Mardani et al., 2020). Denitrification is a nitrate or nitrite decrease in nitrogen gases, such as N_2O, NO, or N_2. This process occurs biologically and chemically, and about 99% of denitrification is done biologically (Hashemi et al., 2011). Because of carbon restriction in subsurface soils, biological denitrification occurs in surface soils more than in subsurface soils (Feyereisen et al., 2016). Therefore, the removal of nitrate from water resources is essential, and one of the appropriate solutions for nitrate removal is the use of an organic denitrification process, for which a biological reactor can be used (Asgari et al., 2020; Christianson et al., 2010; Cameron and Schipper, 2012). Bioreactors are an alternative that has shown potential in the United States as a technology to remove nutrients from wastewater (Hassanpour et al., 2017). Bioreactors are created with the wood core as a carbon source in the drainage path and are prepared by excavating a trench and filling it with wood chips. Denitrification bioreactors for nitrate removal have been investigated in Ontario, Canada, Northern Iceland, and New Zealand countries and have accelerated in recent years in the United States (Asgari et al., 2020; Hassanpour et al., 2017). Although denitrification bioreactors have recommended reducing nitrate loads, their efficiency needs to be assessed for each site by the climate and facilities available (Christianson et al., 2010; Hassanpour et al., 2017). Furthermore, utilizing denitrification bioreactors in agricultural drainage is a new technology. There is not much information about their design and maintenance, so it is necessary to research hydraulics and their internal processes (Christianson et al., 2013). In different parts of the world, many kinds of research done on denitrification bioreactors for nitrate removal. The efficiency of nitrate removal from agricultural water using a bioreactor (with woodchip core) was investigated. The results showed that although biological reactors are effective for nitrate removal, other factors such as design, implementation, input nitrate concentration, and carbon content are important (Aalto et al., 2020). The woodchip bioreactor efficiency for nitrate removal, metals, and organic matter from municipal runoff, was evaluated. The results showed that contaminants from runoff for decades were removed by controlling the inlet flow to bioreactors (Ashoori et al., 2019). Besides reducing the contamination exchanging phosphorus filters and bioreactors, was conducted. The results showed that if the bioreactor before the phosphorus filter is installed, it will have good efficacy in removing contaminants (Christianson et al., 2017). Denitrification woodchip bioreactors were evaluated for managing non-point nitrate sources in the residential zone. The results showed that although reactors reduce nitrate pollution, it is necessary to optimize the long-term study method (Lopez-Ponnada et al., 2017). Mardani et al. (2020) investigated the effect of woodchip bioreactor on microbial concentration in groundwater drainage. They found that laboratory and field research could guarantee the expected elimination of the microbial population in agricultural drainage. According to Maxwell et al. (2020), the temperature sensitivity of nitrate removal in woodchips bioreactors is related to short and long-term changes in carbon quality or availability. Sharrer et al. (2016) assessed modeling and phosphorus reduction released from aquaculture effluent using a bioreactor in another study. These researchers found that regardless of water quality conditions, the most phosphorus released occurred in the first 24 hours, and the most appropriate model for phosphorus is the Elovitch model. Soupir et al. (2018) found that woodchip bioreactor implementation to nitrate removal has a secondary advantage through the nitrate removal of input bacteria. The adsorption efficiency of sugarcane bagasse in nitrate removal from agricultural wastewater was investigated by Hashemi et al. (2017). The results showed that bagasse particles with a diameter of 210 μm had maximum nitrate removal. Kaetzl et al. (2018) investigated the inexpensive anaerobic treatment of effluent using biochar and woodchip filter. The results showed that due to indicators such as TOC, COD, and turbidity, the use of biochar had a better performance than woodchip filters and sand filters. Yao et al. (2020) declared that aerobic fungi increase nitrate removal in the bioreactor. The efficiency of bioreactors is affected by factors such as type of carbon source, water, and ambient temperature, water acidity, and nitrate input load (Corbett et al., 2019; Christianson et al., 2017; Aalto et al., 2020; Mardani et al., 2020; Martin et al., 2019). According to this research, one of the most suitable carbon sources for bioreactors is woodchips, which can be effective for up to 15 years. It is cheaper than other carbon sources and does not require advanced technology to produce it (Asgari et al., 2020; Christianson et al., 2017). Also, many studies about the efficiency of the bioreactor at relatively high air temperatures (≥ 25° C) were conducted. Due to the dependence of nitrate removal in biological methods on air temperature, these results cannot be generalized to other regions with lower temperatures (Aalto et al., 2020). Hashemi et al. (2011) examined the effect of biological filters in groundwater drainage on nitrate removal and found that these filters had an acceptable efficiency in removing nitrate from the drain. Tangier et al. (2017) found that sugarcane bagasse has a good performance for nitrate removal under anaerobic conditions.

The results showed that denitrification bioreactors for nitrate removal from agricultural and wastewater effluents are a practical solution for sustainable agricultural water management. Because the core of these reactors is made of organic materials such as wood, and most parts of Iran cannot provide the required amount of wood, there are restrictions on its use. Also, the construction and maintenance of a bioreactor require cost and experience. If the volume of bioreactors is larger, their building costs will be higher. On the other hand, the bioreactor volume is directly related to the retention time. Therefore, it is necessary to determine accuracy. Is the efficiency of organic matter used in the bioreactor according to different hydraulic retention times? Are various organic matters significantly different in terms of nitrate removal efficiency? Which organic matter has the best performance to remove nitrate from agricultural effluent? Which retention time is most effective? The effect of a cross-sectional shape of bioreactors on nitrate removal performance?

This study was directed to find possible solutions and answer the questions. Due to the high efficiency of woodchips (according to previous research) and the availability of wheat straw and corn cob at the research site, this study aimed to evaluate biological reactors with cores of wood chips, wheat straw, and corn steamship.

Materials and Methods

Study site

The study was conducted at the Moghan Faculty of Agriculture farm, University of Mohaghegh Ardabili (UMA) in Pars Abad town. It is located in the north of Ardabil province (Iran), in 39º 20´ to 39º 42´ east longitude and 47º 30´ to 48º 10´ north latitude (Fig. 1). The mean rainfall in the studied area was 275 mm per year. Also, the minimum and maximum temperature in the region was -15 and 41 Celsius, respectively. The average altitude of the area was 45 meters above sea level with a humid and warm climate. Moghan plain irrigation and drainage network to irrigate 70,000 hectares of agricultural lands. Its drainage network is subsurface drainage and discharges an average of about 220 million cubic meters of drainage from the network annually (Abdi Aghdam et al., 2018).

Bioreactor design and operation

The bioreactors were triangular, rectangular, and trapezoidal cross-sections (Fig. 2). To prevent water infiltration, the bioreactors were lined with ethylene-propylene on the bottom and sides (Rivas et al., 2020). The reactor's depth was 75cm (organic matter (woodchips, corn steamship, and wheat straw) 60cm, and the remaining depth was 15cm with soil). An ethylene-propylene layer was used to prevent the mixing organic matter and soil (Fig. 3).

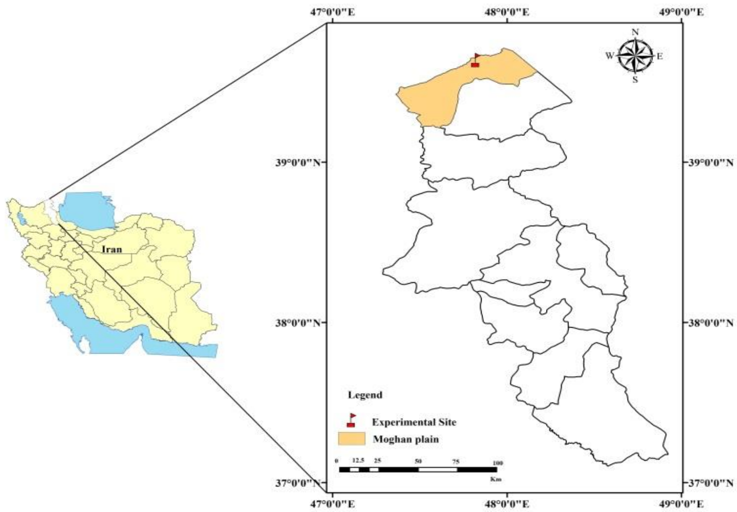

Fig.1- Map of Iran showing the location of theexperimental site

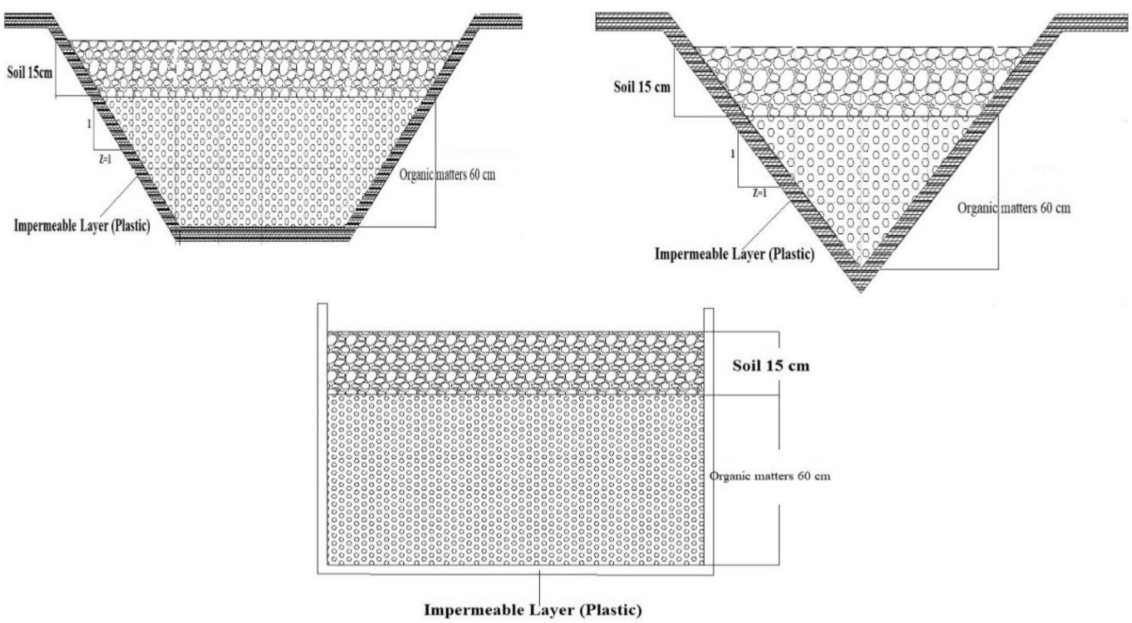

Fig.2- The shape of the bioreactor cross-section

In rectangular and trapezoidal bioreactor cross-sections, the slope of their walls was 1: 1 (Christianson et al., 2011). The layer of woodchips in the pilot reactors was covered with a lightweight fabric and approximately 15 cm of topsoil and water drainage effluent as the inlet flowed to the reactors. Wood chips, corn steamship, and wheat straw choose because these are available in Iran easily. The particle diameter of the woodchips and corn steamship (70% of the cumulative distribution) varied from 1.2 cm to 2.3 cm, and the particle diameter of wheat straw was less than 7mm (90% of the cumulative distribution). The organic matter porosity in the bioreactor was determined using the porosity determination procedure as described by Christianson et al. (2010). The analysis showed that the woodchip porosity was 60%, and the corn cob and wheat straw porosity were 52% and 44%, respectively. Influent and effluent samples were collected every 3, 6, 12, 16, and 24 hours

(Povilaitis and Matikiene, 2020). To determine the concentration of nitrate, 50ml of each treatment was first sampled. Colored samples passed through filter paper. Then one ml of HCl was added to it. A UV spectrophotometer at a wavelength range of 220 nm to 270 nm measured the absorbance. The following equation calculates nitrate removal efficiency for each sample:

$$\left(1-\frac{C}{C_0}\right)\times 100 \quad (1)$$

where C is the effluent concentration and C_0 is the influent concentration (Asgari et al., 2020).

Statistical Analysis

A randomized block design was used to analyze the data of all the sampling campaigns in the study. ANOVA was conducted using SPSS 16.0 software, and the mean comparison was performed by Duncan's multiple range test at the appropriate probability level. A significance level of p = 0.01 was used for all statistical tests. When a significant difference was observed between treatments in the ANOVA procedure, multiple comparisons were made using the least significant difference (LSD) test for differences between means.

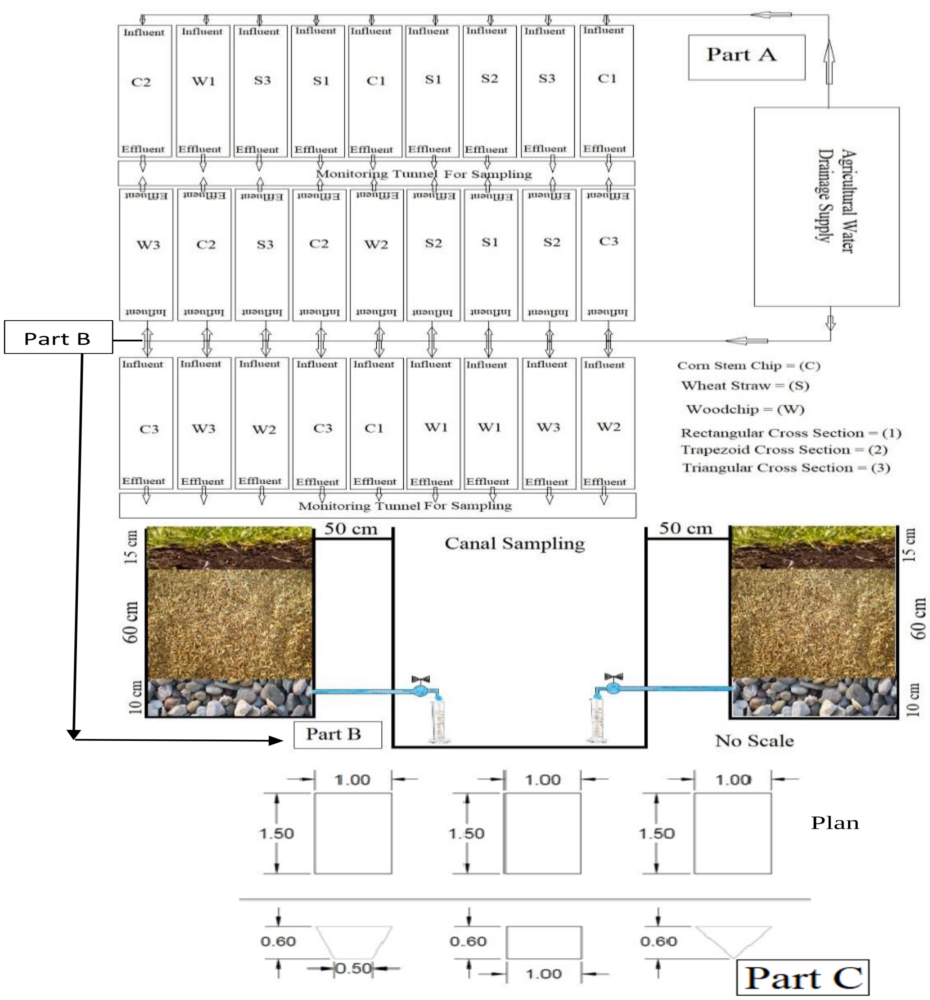

Fig. 3- Performance of statistical plan (Part A), cross-section and method of sampling (Part B), and plan of biological reactors (Part C)

Results and discussion

The analysis of variance showed that, at one percent probability, the main treatments of the experiment had a significant effect on the removal of nitrate. In other words, the organic material, the hydraulic retention time, and the cross-section shape of the bioreactors change the percentage of nitrate removal from agricultural effluent. Considering that the efficiency of bioreactors in nitrate removal is defined as the ratio of the difference between the input and output nitrate concentrations of the reactor to the input nitrate concentration, it can be said that changing the input nitrate charge concentration affects the nitrate removal performance by bioreactors. In addition, the effect of retention time of interactions of treatments on the performance of bioreactors significantly affected nitrate removal from the effluent at the level of one percent (Tab.1).

In general, treatment analysis variance showed that the nitrate removal efficiency in the trapezoidal section was better than in other cross-sections. Also, rectangular and triangular cross-sectional nitrate removal efficiency were prioritized. Also, results show that the percentage of nitrate removal increases in all treatments with increasing hydraulic retention time. The nitrate removal with high efficiency was obtained during the 24-hour hydraulic retention time for wood chips. Furthermore, the lowest nitrate removal performance for the corn stem chip was measured during the hydraulic retention time of 3 hours (Fig. 4).

Design Geometric

The geometric sections used in this study were effective in removing nitrate. Bioreactors with the trapezoidal cross-section with average removal (35.3 ± 9.1%) had the highest removal efficiency

Table 1- Analysis of variance related to the effect of variables on nitrate removal from agricultural effluent

Source	Sum of Squares	df	Mean Square	F	Sig.
Time	1051.417	4	525.708	18.407	0.000
section	1010.409	2	505.204	17.689	0.000
organic	406.798	2	203.399	7.122	0.002
Time * section	402.326	8	100.582	3.522	0.013
Time * organic	658.633	8	164.658	5.765	0.001
section * organic	43.425	4	10.856	0.38	0.822
Time * section * organic	969.97	16	121.246	4.245	0.001
Treatment	14.578	2	7.289	0.255	0.776
Total	6042.67	134			

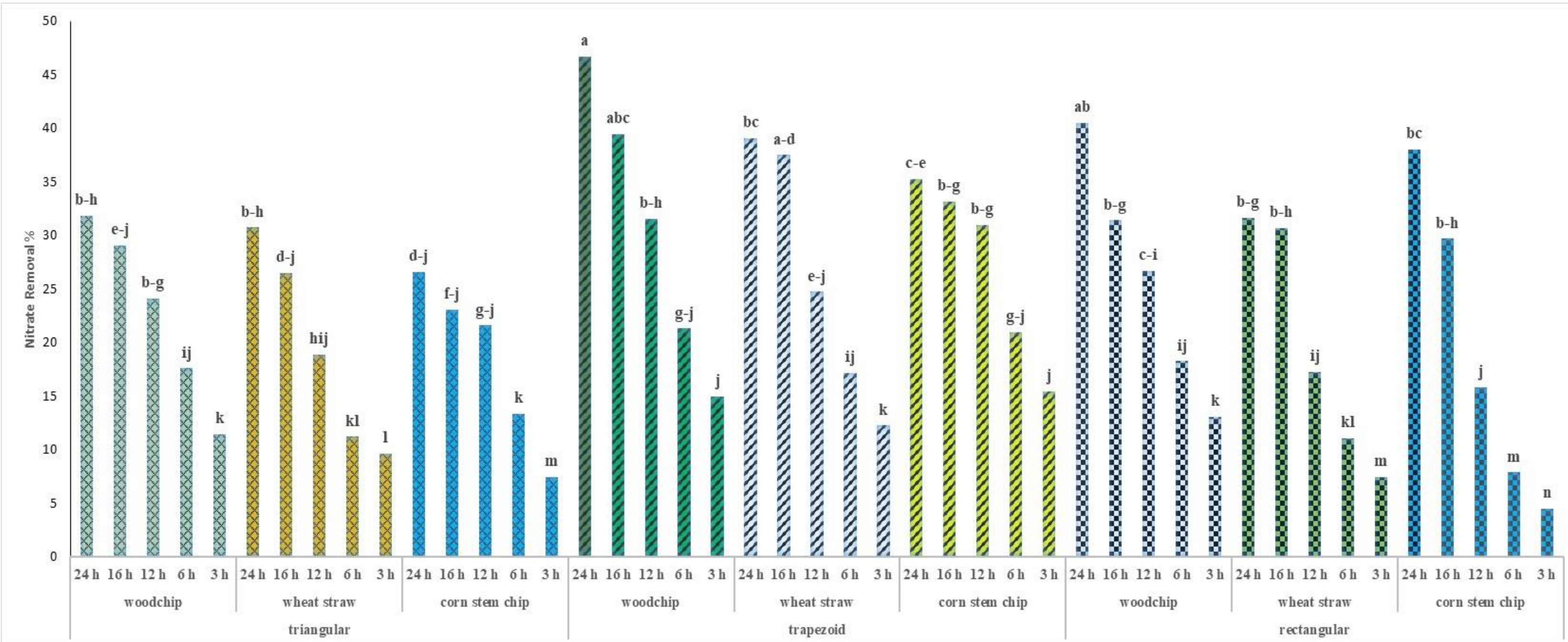

Fig. 4- Result of analysis of variance of treatments

 DOI: 10.22055/JISE.2022.39610.2010

During the test period. Because at the same level (not the same cross-section), the trapezoidal section holds more water than the triangular section. Therefore, it removes more nitrate at the same time. The depth is the same in trapezoidal and rectangular sections, but the volume and upper surface of the trapezoid are larger. The larger the surface, the more heat it receives, which increases efficiency. The lowest removal rate was 17.4%, and the highest removal efficiency was 50%. Rectangular section biological reactors with average removal (30.1 ± 8.6%) were in the next rank. At this cross-section, the lowest removal rate was 16.7%, and the highest removal efficiency was 47.9%. Finally, reactors with a triangular cross-section with an average removal (25.6 ± 5.5%) percent, 17.5 to 36 percent, had the lowest removal efficiency (Fig. 2). The geometric design of bioreactors affects the area required for their construction (Asgari et al., 2020; Jalali et al., 2021; Christianson et al., 2010). A comparison of the efficiency of bioreactors for nitrate removal, affected by the geometric design, showed the definite retention time of the trapezoidal, rectangular, and triangular cross-sections with average nitrate removal of 35.3%, 30.1%, and 25.6% removal, respectively (Fig. 5). Christianson et al. (2010) reported that the shapes of different cross-sections (trapezoidal, rectangular, and channel) differ in nitrate removal efficiency. They also showed that rectangular cross-sections are more efficient using the hydrograph test and Definitive retention. Trapezoidal cross-section performance is higher.

Hydraulic retention time

All bioreactors reduced the nitrate concentration from the output stream compared to the inlet stream during the available hydraulic retention times. The mean nitrate removal (10.8 ± 4.5%) was 3% during a hydraulic retention time of 3 hours. In the hydraulic retention time of 6 hours, compared to the nitrate concentration of the inlet biological reactors removed (16.5 ± 5.1%) nitrate on average. At 12 hours of hydraulic retention, the mean nitrate removal was (24.8 ± 6.9%). At 16 hours of hydraulic retention time, the mean nitrate removal was (30.9 ± 5.9%). Finally, the mean nitrate removal (24.2 34 34.6%) was 24% (Fig. 3). Determining the optimal hydraulic retention time is one of the objectives of this study and similar studies because good performance may not be achieved at low hydraulic retention times. If a long hydraulic retention time was considered, it could cause ammonium accumulation (Martin et al., 2019; Feyereisen et al., 2016). Given that increasing the time provides ample opportunity for better reactor performance, increasing the hydraulic retention time is expected to improve the reactors' nitrate removal performance. The results of Figure (6) show that increasing the residence time from 3 hours to 24 hours causes, on average, the removal performance of the reactors to increase by about 24%. Rivas et al., 2020; Jin et al., 2019 reported that the percentage of nitrate removal by bioreactors increases due to an increase in residence time. The mean values and amplitude of changes in nitrate removal percentage in proportion to the increase in residence time can be seen in Figure (6). This increase is upward quiet. In other words, the deletion increases with increasing time, which is similar to the results by Asgari et al. (2020), Feyereisen et al. (2016), Abdi et al. (2020), Mardani et al. (2020), Christianson et al. (2011), and Martin et al. (2019).

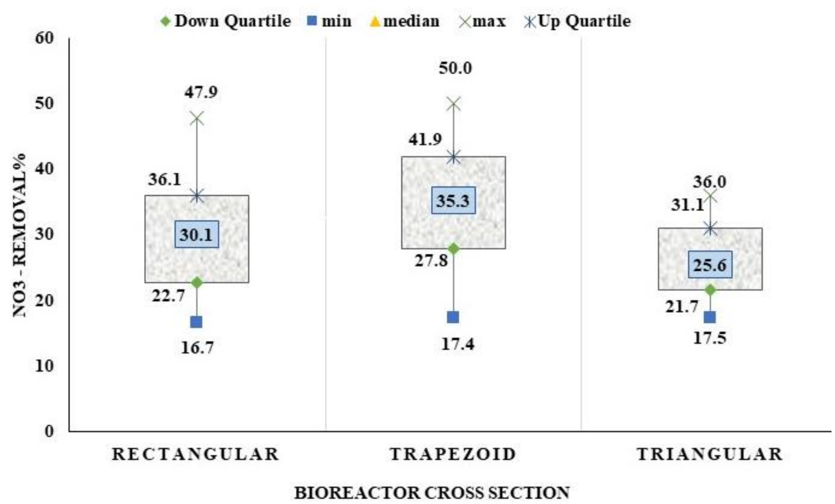

Fig. 5 - The effect of the cross-sectional shape of bioreactors on nitrate removal from agricultural effluents

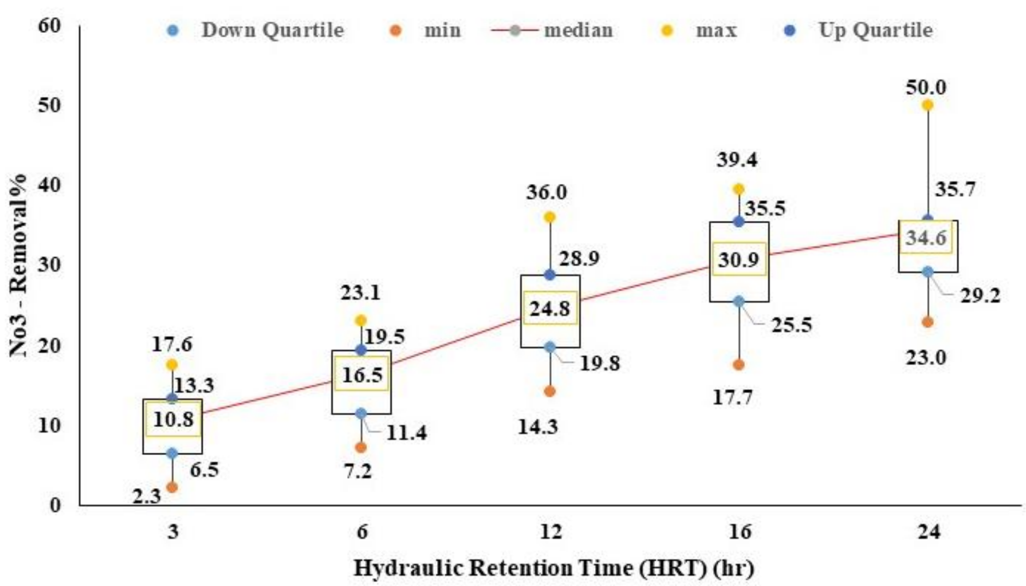

Fig. 6- Nitrate removal efficiency at hydraulic retention times

Increased nitrate removal with increasing retention time was expected since increasing retention time allowed the bacterial population to degrade the organic substrate, leading to high nitrate removal efficiencies. Increasing retention time also gives microbes more contact time for activity (Feyereisen et al., 2016; Zhao et al., 2020). Also, longer reaction times provide a carbon source to reduce nitrate and nitrate accumulation in the effluent (Abdi et al., 2020).

Another factor that increases the performance of bioreactors at longer residence times, especially when the temperature is not reactive under optimal conditions (< 25°C), is that the water temperature in the reactors increases and its efficiency in nitrate removal increases as well (Lepine et al., 2016). Because carbon and temperate are more influential than any other factors, in general, it can be said that during longer residence times (up to several days), the amount of available carbon and the temperature inside bioreactors with wood chip core increased, and the number of removal increases (Martin et al., 2019). In addition to the hydraulic retention time, temperature, and nitrate inlet concentration, the core material is essential in the bioreactor. Because in addition to adsorption by providing carbon as a source of energy for bacteria, it affects the amount of nitrate removal (Lepine et al., 2016; Martin et al., 2019).

Organic Matter

The results showed that the average nitrate removal for corn stem chips was (27 ± 8.4%). Also, wheat straw and wood chips with values of (28.6 ± 9.2%) and (31.3 ± 7.9%) of the percent removed nitrate from the effluent, respectively (Fig. 7). Although wood chips in denitrification bioreactors are more efficient at nitrate removal than corn straw and wheat straw, in general, the organic materials used in this study were effective in removing nitrate from the effluent. These results are consistent with Jalali et al. (2021), which indicate the high performance of wood chips in nitrate removal. In another study, results showed the best performance in treatments for bioreactors with walnut wood chips and residence time of 12 hours with an efficiency of about 50% reduction of water nitrate (Nordstrom and Herbert, 2017). The woodchip is better than other organic matters because of the higher amount of total organic carbon (TOC) at 12 hours. The importance of this factor for biological nitrate removal has been emphasized by Corbett et al. (2019). The increase in organic carbon in the early hours for woodchips in a short time is due to its high contact surface relative to wheat straw and corn stem chips, adjusted to increasing time (Zhao et al., 2020). In organic matter treatments, nitrate removal percentage is directly related to retention time. In other words, with increasing retention time, nitrate removal efficiency also increases in these treatments. It is similar to the results of Christianson et al. (2012) and Greenan et al. (2009). The researchers concluded that it takes from a few hours to a few days to remove nitrate by 10% to 100%, respectively.

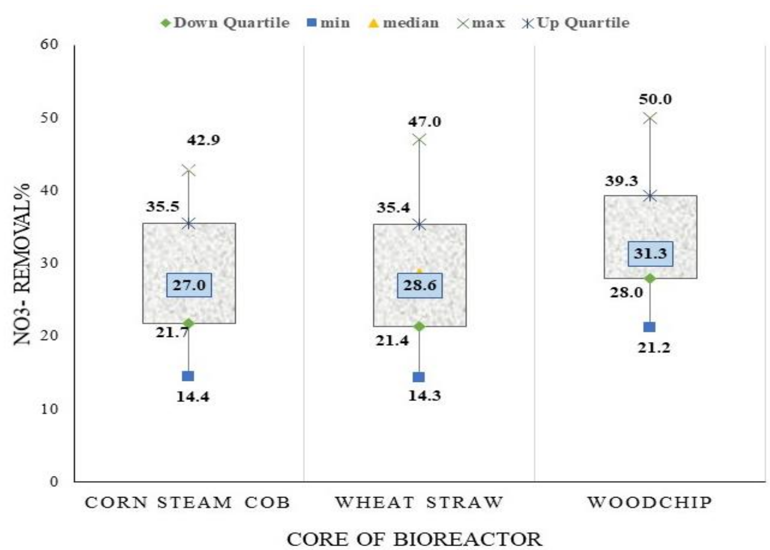

Fig. 7- The effect of organic matter used in bioreactors on the removal of nitrate from agricultural effluents

Also, the results showed that in terms of bioreactor performance for nitrate removal, woodchips, and wheat straw, corn steamships were determined, respectively. As Lepin et al. (2016) reported, nitrate removal increased with an increasing hydraulic retention time that the factor was warmer water inside the reactor and a better reaction for nitrate removal. Besides, the results showed that the woodchip had a remarkable ability to remove nitrate, similar to that of Abdi et al. (2020). The results showed that the bioreactor with the woodchip, under the conditions in which the study was performed and within 72 hours, could nitrate removal about 99%. In general, according to the results of this study, hydraulic retention time in 24 hours, nitrate removal efficiency is more than 40%. One of the reasons for this is the presence of more carbon in the reaction conditions, with increasing retention time. Cameron and Schipper (2001) and Martin et al. (2019) also stated that to remove more nitrate than any other factor, temperature and the amount of organic matter. The reason why wood is better could be the higher total organic carbon (TOC) content at hydraulic retention time in 24 hours. The importance of this factor for the biological removal of nitrate has been emphasized by Corbett et al. (2019). The increase in organic carbon in the early hours for wood chips in a short time is due to its high contact surface relative to wheat straw and corn stem chips, adjusted to increasing time (Zhao et al., 2020). Also, the statistical comparison of the means showed that for the organic matter of woodchips, wheat straw, and corn stem chips, the time factor is an influential factor in nitrate removal. Reduces contact level reducing the contact surface of organic matter with water in less carbon released into the substrate, as noted by Feyereisen et al. (2016) and Greenan et al. (2006).

Conclusion

In a completely randomized experimental design, this study used the effect of different organic matter and geometric shapes of bioreactors 3, 6, 12, 16, and 24 hours in hydraulic retention times. Then, was investigated nitrate removal from agricultural effluent. The results showed that although the organic matter was effective in removing nitrate, the wood chip was better than wheat straw and corn stem chips. Since (1) access to wood chips is limited at the research site, (2) the nitrate removal efficiency of wheat straw and corn stem chips is also acceptable. So instead of wood chips, can be used this two organic materials.

The results also showed that the geometric shape of bioreactors is effective in their performance in nitrate removal. The trapezoidal, rectangular, and triangular cross-sections were prioritized compared to nitrate removal. According to the performance comfort and the drainage collector's cross-section that is trapezoidal, the trapezoidal reactors were selected as the optimal cross-section.

Acknowledgment

The cost of performing this project was provided by the Vice-Chancellor for Research and Technology of Mohaghegh Ardabili University, for their support, we are grateful.

References

1- Aalto, S.L., Suurnäkki, S., von Ahnen, M., Siljanen, H.M., Pedersen, P.B. and Tiirola, M. (2020). Nitrate removal microbiology in woodchip bioreactors: A case study with full-scale bioreactors treating aquaculture effluents. Science of the Total Environment, 723, p.138093.

2- Abdi Aghdam, F., Rasoulzadeh, A., Ghavidel, A., and Torabi Giglou, M., (2018). The effect of water drainage on soil properties and yield of tomato in Moghan plain. M.Sc. dissertation, University of Mohaghegh Ardabili, Ardabil.

3- Abdi, D.E., Owen Jr, J.S., Brindley, J.C., Birnbaum, A.C., Wilson, P.C., Hinz, F.O., Reguera, G., Lee, J.Y., Cregg, B.M., Kort, D.R. and Fernandez, R.T. (2020). Nutrient and pesticide remediation using a two-stage bioreactor-adsorptive system under two hydraulic retention times. Water Research, 170, p.115311.

4- Asgari, H., Azizi Mobaser, J., Rasoulzadeh, A., Ramezani Moghaddam, J. (2020). 'Evaluating the Efficiency of Bioreactor with Triangular Cross Section to Remove Nitrate from Agricultural Wastewater', Iranian Journal of Soil and Water Research, 51(5), pp. 1105-1113.

5- Ashoori, N., Teixido, M., Spahr, S., Lefebvre, G.H., Sedlak, D.L. and Luthy, R.G. (2019). Evaluation of pilot-scale biochar-amended woodchip bioreactors to remove nitrate, and metals, and trace organic contaminants from urban stormwater runoff. Water Research, 154, pp.1-11.

6- Cameron, S G. and Schipper, L. A. (2012). Hydraulic properties, hydraulic efficiency, and nitrate removal of organic carbon media for use in denitrification beds. Journal of Ecological Engineering, 41, 1-7.

7- Christianson, L., Castelló, A., Christianson, R., Helmers, M. and Bhandari, A. (2010). Hydraulic property determination of denitrifying bioreactor fills media. Journal of Applied Engineering in Agriculture, 26(5), 849-854.

8- Christianson, L., Christianson, R., Helmers, M., Pederson, C., and Bhandari, A. (2013). Modeling and calibration of drainage denitrification bioreactor design criteria. Journal of Irrigation and Drainage Engineering, 139(9), 699-709.

9- Christianson, L.E., Bhandari, A. and Helmers, M.J. (2012). A practice-oriented review of woodchip bioreactors for subsurface agricultural drainage. Journal of Applied engineering in agriculture, 28(6), 861-874.

10- Christianson, L.E., Bhandari, A. and Helmers, M.J., 2011. Pilot-scale evaluation of denitrification drainage bioreactors: Reactor geometry and performance. Journal of Environmental Engineering, 137(4), pp.213-220.

11- Christianson, L.E., Lepine, C., Sibrell, P.L., Penn, C. and Summerfelt, S.T. (2017). Denitrifying woodchip bioreactor and phosphorus filter pairing to minimize pollution swapping. Water Research, 121, pp.129-139.

12- Corbett, T.D., Dougherty, H., Maxwell, B., Hartland, A., Henderson, W., Rys, G.J. and Schipper, L.A., (2019). Utility of Diffusive Gradients in Thin-Films' for the measurement of nitrate removal performance of denitrifying bioreactors. Science of the Total Environment, p.135-267.

13- Feyereisen G W., Moorman T B., Christianson L E., Venterea R T., Coulter J A., and Tschirner U W. (2016). Performance of Agricultural Residue Media in Laboratory Denitrifying Bioreactors at Low Temperatures. Journal of environmental quality, 45 (3), 779-787.

14- Greenan, C M., T. B. Moorman, T B. Parkin, T C. Kaspar, and D B. Jaynes. (2009). Denitrification in wood chip bioreactors at different water flows. Journal of environmental quality, 38(4), 1664-1671.

15- Hashemi SE, Heidarpour, M., and Mostafazade Fard, B. 2011. Investigation of nitrate removal in two forms of biofilter position in subsurface drainage systems. Journal of Irrigation science and engineering, 34(2), 71 - 81. (In Farsi)

16- Hashemi, M., Naseri, A., Takdastan, A. (2017). 'Investigation of the Sugarcane Bagasse Adsorbent Efficiency For Nitrate Removal from Agricultural Outflow Drainage', *Irrigation Sciences and Engineering*, 40(3), pp. 1-10

17- Hashemi, S., Heidarpour, M., Mostafazadeh-Fard, B. (2011). 'Investigation of Nitrate Removal in Two Forms of Biofilter Position in Subsurface drainage systems', *Irrigation Sciences and Engineering*, 34(2), pp. 71-82.

18- Hassanpour, B., Giri, S., Pluer, W T., Steenhuis, T S. and Geohring, L.D. (2017). Seasonal performance of denitrifying bioreactors in the Northeastern United States: Field trials. Journal of environmental management, 202, 242-253.

19- Hoover, Natasha L Bhandari, A., Soupir, M L, and Moorman T B. (2016). Woodchip Denitrification Bioreactors: Impact of Temperature and Hydraulic Retention Time on Nitrate Removal. Journal of environmental quality 45 (3), 803-812.

20- Jalali, R., azizi mobaser, J., ghavidel, A., Rasoulzadeh, A., ramezani moghaddam, J. (2021). Investigation of woodchip bioreactor for nitrate removal from wastewater, Iranian Journal of Soil and Water Research, 52(4), 887-898.

21- Jin, S., Feng, C., Tong, S., Chen, N., Liu, H., & Zhao, J. (2019). Effect of sawdust dosage and hydraulic retention time (HRT) on nitrate removal in sawdust/pyrite mixotrophic denitrification (SPMD) systems. Environmental Science: Water Research & Technology, 5(2), 346-357.

22- Kaetzl, K., Lübken, M., Gehring, T. and Wichern, M., (2018). Efficient low-cost anaerobic treatment of wastewater using biochar and woodchip filters. Water, 10(7), p.818.

23- Lepine, C., Christianson, L., Sharrer, K. and Summerfelt, S. (2016). Optimizing hydraulic retention times in denitrifying woodchip bioreactors treating recirculating aquaculture system wastewater. Journal of environmental quality, 45(3), 813-821.

24- Lopez-Ponnada, E.V., Lynn, T.J., Peterson, M., Ergas, S.J. and Mihelcic, J.R. (2017. Application of denitrifying wood chip bioreactors for management of residential non-point sources of nitrogen. Journal of biological engineering, 11(1), p.16.

25- Mardani, S., McDaniel, R., Bleakley, B.H., Hamilton, T.L., Salam, S., and Amegbletor, L. (2020). The effect of woodchip bioreactors on microbial concentration in subsurface drainage water and the associated risk of antibiotic resistance dissemination. Ecological Engineering: X, p.100017.

26- Martin E A., Davis M P., Moorman T B., Isenhart T M., Soupir M L. (2019). Impact of hydraulic residence time on nitrate removal in pilot-scale woodchip bioreactors. Journal of Environmental Management, 237, 424-432.

27- Maxwell, B.M., Díaz-García, C., Martinez-Sánchez, J.J., Brigand, F. and Álvarez-Rogel, J. (2020). Temperature sensitivity of nitrate removal in woodchip bioreactors increases with woodchip age and following drying–rewetting cycles. Environmental Science: Water Research & Technology, 6(10), pp.2752-2765.

28- Nordstrom, A. and Herbert, R. (2017). Field-scale denitrifying woodchip bioreactor treating high nitrate mine water at low temperatures. In 13th International Mine Water Association Congress-Mine Water & Circular Economy. Lappeenranta University of Technology, Finland.

29- Povilaitis, A. and Matikienė, J., 2020. Nitrate removal from tile drainage water: The performance of denitrifying woodchip bioreactors amended with activated carbon and flaxseed cake. *Agricultural Water Management*, *229*, p.105937.

30- Rivas, A., Barkle, G., Stenger, R., Moorhead, B. and Clague, J., 2020. Nitrate removal and secondary effects of a woodchip bioreactor for the treatment of subsurface drainage with dynamic flows under pastoral agriculture. Ecological Engineering, 148, p.105786.

31- Schipper, L.A., and Vojvodic-Vukovic, M. 2001. Five years of nitrate removal, denitrification, and carbon dynamics in a denitrification wall. Water Research, 35(14), 3473-3477.

32- Sharrer, K.L., Christianson, L.E., Lepine, C. and Summerfelt, S.T. (2016). Modeling and mitigation of denitrification 'woodchip' bioreactor phosphorus releases during treatment of aquaculture wastewater. Ecological Engineering, 93, 135-143.

33- Soupir, M.L., Hoover, N.L., Moorman, T.B., Law, J.Y. and Bearson, B.L. (2018). Impact of temperature and hydraulic retention time on pathogen and nutrient removal in woodchip bioreactors. Ecological Engineering, 112, 153-157.

34- Tangier, S., Naseri, A., Moazed, H., Hashemi Garm Dareh, S., Boroomand nasab, S. (2017). 'Evaluate the Performance of Sugarcane Bagasse as a Carbonic Source Required in the Design of Denitrification Substrates', *Irrigation Sciences* and Engineering, 40(2), pp. 39-57.

35- Yao, Z., Yang, L., Wang, F., Tian, L., Song, N. and Jiang, H. (2020). Enhanced nitrate removal from surface water in a denitrifying woodchip bioreactor with a heterotrophic nitrifying and aerobic denitrifying fungus. BBioresourceTechnology, 303, p.122948.

36- Zhao, J., He, Q., Chen, N., Peng, T., and Feng, C. (2020). Denitrification behavior in a woodchip-packed bioreactor with gradient filling for nitrate contaminated water treatment. Biochemical Engineering Journal, 154, p.107454.