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ORIGINAL PAPER

Performance evaluation of fixed bed anaerobic baffled reactor and its upgrading by integrated electrocoagulation process for municipal wastewater treatment

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ABSTRACT

Anaerobic baffled reactor is efficient for wastewater treatment, while it lacks efficient nutrient removal and must be upgraded. The present study aimed to evaluate performance of fixed-bed media anaerobic baffled reactor (FABR) for municipal wastewater treatment. The performance of the integrated electrocoagulation process in the FABR (E-FABR) was also investigated. The large bench-scale five of sectional FABR reactor was assessed continually to the hydraulic retention times (HRTs) of 40, 30, and 20 hours, respectively to meet the effluent disposal standards using the HDPE-2H media in the FABR. After determining the optimum HRT, EP was integrated in 4^{th} section of the FABR to improve the performance. At the E-FABR, the steel-steel and aluminum electrode pair (Al-Al) was evaluated at the current densities of 0.05-0.5 mA/cm^2 (HRT=20 hours). The performance of FABR decreased with reduced HRT from 40 to 30 and 20 hours. At the optimum HRT (30 hours), the reactor met the TSS, COD, and BOD effluent discharge standards. The mean steady-state removal of TSS, COD, BOD_5, total nitrogen, and total phosphorus was 93±0.5%, 91±0.8%, 93.4±1%, 16±1%, and 28±0.7%, respectively. The E-FABR with the steel and aluminum electrodes at the current densities of 0.3 and 0.1 mA/cm^2 and HRT of 20 hours decreased the TSS, COD, BOD, SO_4, and TP concentrations to the effluent discharge standard limits. Therefore, the FABR is an efficient system for municipal wastewater treatment, and E-FABR with aluminum electrodes and extremely low current density could easily treat wastewater to the effluent discharge standards.

Keywords: Municipal Wastewater Treatment, Anaerobic Baffled Reactor, Electrocoagulation Process

Introduction

Anaerobic treatment of wastewater is a major concern of environmental engineers and researchers owing to the advantages of the anaerobic process over conventional aerobic methods. Such advantages include no energy requirement, simple operation, and extremely low excess sludge production, which reduces sludge management and disposal costs. These features have rendered the anaerobic process particularly effectual (especially high-rate anaerobic reactors) to be used frequently for municipal wastewater treatment (MWT). Among high-rate anaerobic reactors, anaerobic baffled reactor (ABR) has high potential for the treatment of various types of wastewater.[1]

ABR is a system with numerous advantages over other anaerobic reactors, including longer biomass retention time, high resilience to organic and hydraulic shocks, ability to separate the phases of anaerobic catabolism, and lower construction and operation costs. These benefits have justified the use of ABR for sanitary wastewater treatment, especially in small colonies and developing countries.[2] However, ABR has lower quality effluent in comparison to other similar methods, and the removal of

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nitrogen and phosphorus is difficult using this system. Therefore, adequate research and development regarding ABR is essential to the enhancement of the efficiency and the effluent qualification.

Several studies have focused on the optimization of ABR performance using new technologies. A major alteration suggested in this regard is the integration of fixed-bed media anaerobic baffled reactor (FABR) into ABR.[3] Moreover, a novel approach to the performance improvement of anaerobic reactors as FABR might involve its integration with electrochemical processes, such as electrocoagulation. This process produces *in-situ* coagulants that result in the occurrence of in-line electrocoagulation process (EP), thereby increasing the removal rate of contaminants. In addition, EP provides the batter reduction conditions for methanogen activity.[4,5]

In 2019, ABR with submerged membrane was used for the treatment of municipal sewage as a 105-liter pilot with 12 hours of residence time, and the process resulted in the complete removal of total suspended solids (TSS), with 94% removal rate of organic matters and 54% removal of nitrogen.[6] In another study, the electrolysis process was reported to affect the upgrading of ABR for MWT at the batch laboratory scale. Within two hours of contact time at the voltage of 8V with an aluminum (Al) electrode pair, the system efficiency increased to 10% in proportion to ABR.[7] The results of the ABR operation indicated that at the hydraulic retention time (HRT) of 24 hours, the mean removal of biochemical oxygen demand (BOD), chemical oxygen demand (COD), TSS, total nitrogen (TN), total phosphorous (TP), and log reduction value of the coliforms were reported to be 71%, 75%, 79%, 23%, 30.3%, and 5.8 log, respectively. With the reduction of HRT from 24 hours to 18 and 14 hours, the removal efficiency of all the parameters decreased as well. [7,8]

The present study aimed to evaluate the optimum HRT for FABR to meet the effluent disposal standards and integrate EP into the FABR in order to enhance its performance in MWT. The innovation of this study was the use of microbial media to enhance the ABR performance, as well as the employment of integrated EP to the FABR to improve its efficiency.

Materials and Methods

Setup of the reactor

A bench-scale FABR setup was fabricated from Plexiglas sheets and installed in the wastewater treatment plant in Khoy city, Iran. The schematic of the setup is depicted in Fig. 1. The FABR had L×W×H dimension of 60×25×30 centimeters, consisting of five chambers with equal size and total net volume of 37 liters. Each chamber had the volume of 6.15 liters, and the volume ratio of the up-comer to the down-comer of each compartment was 3:1. The top of the reactor was covered, and a valve was installed to vent the biogas. The used microbial media was HDPE-2H with the specific surface of 535 m^2/m^3 and net volume of 11 liters (30% of the reactor net volume). The reactor was fed with the municipal wastewater using a peristaltic pump, and the effluent was collected in a tank and discharged daily.

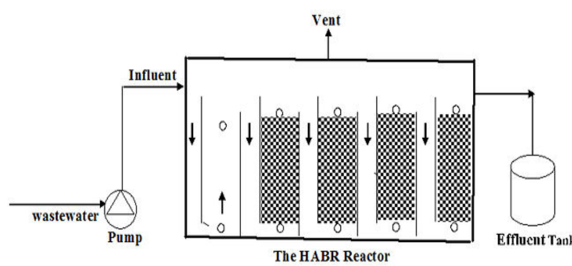

Fig. 1. The FABR and the E-FABR schematic

In order to improve the performance of the FABR, it was integrated into an EP system known as E-FABR, which was composed of a pair of similar materials (steel/aluminum) interlaced plate-type electrodes with the width, length, and thickness of 2.5 and 25 centimeters and two millimeters and powered by a DC power supply (model: MPS3010L, Matrix, China). The electrodes were inserted at the distance of one centimeter from each other in the down-comer of the 4th chamber of the FABR, and the submerged height of the electrodes was 15 centimeters. The DC electricity was applied between the anode and cathode electrodes through the wires that were connected to the power supply instrument, and the electrodes were cleaned three times a day.

Reactor startup and experiment

The FABR setup was inoculated with the active bio sludge at the volatile suspended solid (VSS) concentration of 8.5 g/l and pH of 7.7, which was obtained from a local anaerobic treatment plant as the initial seed. The municipal wastewater was continuously collected from the downstream channel of the screening unit at the target treatment plant in order to feed the reactor. The mean characteristics of the wastewater are shown in Table 1.

Upon seeding, the FABR was started up using a calibrated variable speed Etatron peristaltic pump (made in Italy) at the HRT of 48 hours. When the removal of COD and TSS remained below 2% for seven consecutive days, the startup was considered complete. At the end of the startup, the oxidation reduction potential (ORP) of the reactor compartments was measured.

Table 1. The av3erage main characteristic of the unicipal wastewater used in this study

Parameter	Value (mean ± SD)[b]
TSS	267 ± 14
BOD	352 ± 26
Total COD	564 ± 41
Soluble COD	277 ± 22
pH	7.4-7.6
Total phosphate	23 ± 2
Total nitrogen	66 ± 8.4
Ammonia nitrogen	57 ± 11
Nitrate	2.4 ± 0.3
Sulfate	76 ± 9
Alkalinity($CaCO_3$)	513 ± 20

[a] All unit expressed as mg/ L except for pH
[b] Total number of samples = 270

Upon startup, the steady-state performance of the FABR was evaluated at the HRTs of 40, 30, and 20 hours. In addition, the HRT of the reactor net volume and setup was calculated through the peristaltic pomp course. The steady-state performance was defined as the changes in the COD removal efficiency, remaining below 5% during seven days of operation. On day 260 of the operation, the FABR integrated was with the EP, and the process was operated with a pair steel-steel and aluminum (Al)-Al electrodes at the HRT of 20 hours. The electrical current densities were within the range of 0.05-0.2 mA/cm^2 in the Al electrodes and 0.1-0.5 mA/cm^2 in the steel electrodes. The reactor was operated for 15 days for each experimental condition, and the target parameters were analyzed in the effluent on a daily basis.

Sampling and analysis

The influent and effluent of the reactor were sampled three times per week. Due to the influent and effluent qualitative fluctuations, sampling of the compound was carried out daily. In order to determine the performance of each chamber, all the compartments were sampled through the sampling port and installed at the top of the compartments. This was accomplished when the FABR reached the steady state under each set of the experimental conditions (end of all HRTs). The target parameters included TSS, VSS, COD, BOD_5, TP, NO_3^-, TN, SO_4^-, temperature, and total alkalinity, which were analyzed in accordance with standard methods,[9] and pH and temperature were measured using the Metrohm pH meter. Moreover, the OxiDirect BOD meter and COD reactor (Aqualytic, Germany) were used for the measurements. The concentration of the mentioned parameters was measured using the DR6000 Hach spectrophotometer. Data analysis was performed in Microsoft excel software.

Results and Discussion

Startup of the FABR

After the initial fluctuations in the effluent quality, the FABR approached steady-state efficiency (fixed COD removal) on days 100-107 of the startup operation. At this point, the startup was considered to be successfully completed. The mean steady-state removal rate of TSS, soluble COD (SCOD), and COD was calculated to be 92±0.4%, 81±1%, and 88±1%, respectively. At the end of the startup, the ORP of the reactor parts was -280 up to -310 mV in the first up to the final part. Therefore, it could be concluded that the anaerobic biomass was established in the reactor.[10]

Considering the long time of the startup and high SCOD removal, alkalinity and pH increased at the effluent ratio to the inflow (ORP>-300mv), so that the system showed distinctive signs of the anaerobic steady-state biodegradation of the organic matters. On the other hand, the local climate and wastewater type and quality have been associated with various startup times (50-120 days) for the anaerobic reactors in similar studies[11]. In the present study, this duration was slightly longer due to the influent quality fluctuations and local cold climate.

Effect of HRT on the FABR performance

According to the startup results, the HRT of 40 hours was set and maintained in order to achieve the steady-state performance. Following that, the HRT was switched to 30 and 20 hours. At each HRT, the FABR was operated to attain sustainable performance. Fig. 2 shows the profile of the FABR proficiency. After each reduction in the HRT, the removal efficiency of the target parameters reduced, while it relatively improved over time to the steady-state level. However, the FABR efficiency dropped when the HRT was switched from 40 to 30 hours although it almost recovered to the previous steady-state condition by continuing the operation at the HRT of 30 hours.

The reduction of HRT to 20 hours resulted in the significant depletion of the proficiency, especially in the COD removal. Furthermore, continuing the operation for 10 days at the HRT of 20 hours resulted in another stable performance despite the inability to achieve the previous level. Fig. 3 depicts the mean steady-state removal rate of TSS, COD, and BOD_5 at all the HRTs. As can be seen, the mean steady-state removal rate of TSS, COD, and BOD_5 at the HRT of 40 hours was 94.5%, 93%, and 94.8%, respectively. It is also notable that the TSS removal was not significantly affected by the reduction of the HRT from 40 to 30 hours (<1%). However, the performance decreased when the HRT reduced to 20 hours, and the mean steady-state removal rate of TSS, COD, and BOD at the HRT of 30 hours was estimated at 93.7%, 91%, and 93%, while at the HRT of 20 hours, the rate was calculated to be 92.8%, 86%, and 89%, respectively.

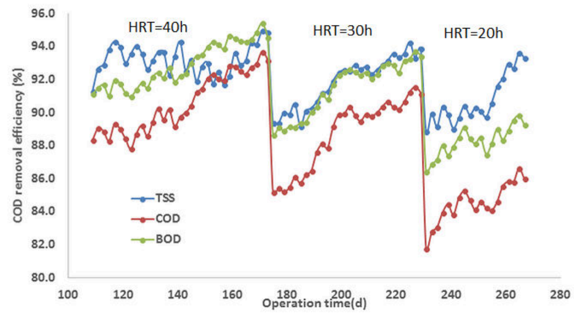

Fig. 2. The profile of TSS, BOD, and COD removals in the FABR at various HRTs

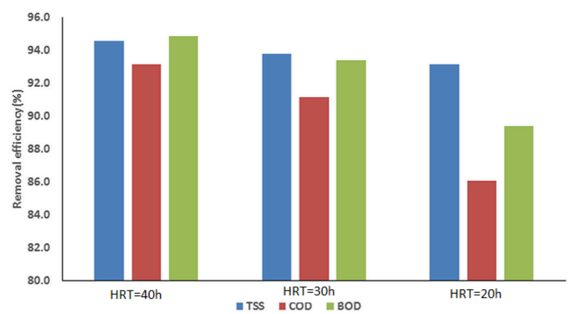

Fig. 3. The average steady-state performance of the FABR at various HRTs

The concentration of SO_4^- and NO_3^- was measured in order to determine the COD removal mechanism. According to the obtained results, the highest COD removal efficiency was associated with the highest SO_4^- and NO_3^- removal at the HRT of 40 hours, and the reduction mostly occurred at the initiation of the reactor. In total, 65% of SO_4 and 43% of NO_3 were removed on average. Table 2 shows the comparison of the FABR effluent quality in stable conditions based on the effluent discharge standards in Iran, which met the effluent standard of TSS at all the HRTs, while meeting the COD and BOD_5 standards only at the HRTs of 40 and 30 hours, respectively. It is also notable that TN and TP were above the standard limit at all the HRTs, while all the parameters at all the HRTs were below the standard limit for agriculture effluent uses.

Table 2. The effluent quality of the FABR operated under steady-state conditions

HRT	TSS (±SD) mg/L		COD (±SD) mg/L		BOD (±SD) mg/L		TN (±SD) mg-N/L		TP (±SD) $mgPO_4/L$	
	Influent	Effluent	In	Ef	In	Ef	In	Ef	In	Ef
40 h	258 ± 11	19 ± 1	588 ± 28	43 ± 3	376 ± 10	21 ± 5	72 ± 3	57 ± 2	23 ± 2	16 ± 1
30 h	276 ± 10	21 ± 2	595 ± 12	54 ± 4	370 ± 7	26 ± 6	66 ± 2	55 ± 3	23 ± 1	16.6 ± 1
20h	270 ± 18	24 ± 2	582 ± 17	84 ± 6	375 ± 11	40 ± 10	60 ± 6	51 ± 2	23 ± 1	17 ± 1.5
Standard[a]	-	30	-	60	-	30	-	-	-	6

[a] Discharge standards to the surface water bodies based on the Iran Environment Protection Organization

According to the findings of the current research, the optimum HRT was 30 hours as the FABR performed well at the HRTs of ≥30 hours, while lower HRTs led to the depletion of the performance, especially in the COD removal. The failure of the FABR performance at the HRT of 20 hours could be associated with the increased organic loading rate, which in turn affected the microbial metabolism.[12] On the other hand, the HRT reduction diminished the required time for methanogens bacteria to metabolize the soluble products that were developed by acidogenesis bacteria.[13]

The reduction of the SCOD/COD ratio in the effluent of 0.82 at the HRT of 40 hours to 0.93 at the HRT of 20 hours was observed in the present study. Another reason for the performance decline might be the reduction of the effective volume in each chamber due to the accumulation of the solids and toxic waste microbial products over the operation course. The previous studies in this regard have denoted a direct correlation between pollutant removal and HRT, and HRT has been reported to be the most important influential factor in the efficiency of this type of reactor.[14,15]

The main mechanism of TSS removal might be the settlement of solid particles in the reactor (especially in the first chamber), as well as the enmeshment of the particles in the sludge blanket.[16] Therefore, it could be inferred that the main mechanisms that contributed to COD removal were the methanogenesis activity (particularly in the reactor end), sulfate and nitrate reduction by anoxic bacteria, and physical capture of the particulate organic materials. In other words, a consortium of microorganisms act in an anaerobic multistage reactor, including sulfate- and nitrate-reducing bacteria, acid- and methane-forming bacteria, and other such microorganisms.[17]

According to the findings of the current research, the BOD/COD ratio reached 0.29 in the effluent from 0.62 in the inflow, which indicated the proficiency of the reactor. Comparison of the FABR performance with the previous studies that have reported the COD removal rate to be 68-80% in ABR,[8, 2,18] the COD removal efficiency in the present study was relatively higher. This discrepancy could be due to the successful long-term startup and high microbial density on media (1.2 mg VSS/cm^2) based on the biomass concentration measurement in all the compartments of the reactor.

According to the information in Table 2, there was a negligible reduction in the TN and TP concentrations in the effluent due to the less requirement of the anaerobic biomass to the nutrients and its low metabolism.[19] Moreover, the TN and TP concentrations at the inflow were higher than the normal level, and the mean removal rate of TP (28%) was higher compared to TN (18%) at the HRT of 30 hours despite the COD:N:P=300:10:1 ratio required for the anaerobic bacteria. It is also notable that the removal of TN was influenced by the HRT, while the TP concentration did not vary with the changes in the HRT.

Adsorption and cellular synthesis are two major paths for TP removal, and biomass absorption is higher than cellular synthesis [16] due to the anaerobic conditions of the effluent nitrogen (95%) in the form of NH_4. Therefore, it could be inferred that small amounts of NH_4 was absorbed by the biomass, and NH_4, mainly exits of reactor without change. and its major exited without change. In addition, the TP removal was higher compared to the TN removal. Similar studies have also demonstrated lower rates of

NP removal (19% and 30%) in ABR in sanitary wastewater treatment. On the other hand, the slightly higher phosphorus removal to N could be attributed to its removal through sludge adsorption and its sedimentation in the form of calcium, magnesium or organic phosphate compounds.[20]

COD removal at various compartments

The removal of COD in all the compartments at the end of all the HRTs was evaluated, and the results are depicted in Fig. 4. In addition, the partial COD removal was assessed in order to determine the partition and anaerobic decomposition phases and their effects on the reactor performance. As can be seen in Fig. 4, the COD removal portion of the first section was approximately 0.45 at all the HRTs, which could be attributed to its main TSS removal. With the reduction of HRT, the primary section portion of COD removal decreased, and the end section quote increased.

According to the findings of the current research, the COD removal at the HRT of 40, 30, and 20 hours was 0.08, 0.14 and 0.18, respectively. Therefore, it could be concluded that methanogens activity increased in the reactor end parts with decreased HRT. Moreover, the reduction of HRT caused the organic load of the end parts of the reactor to increase, thereby resulting in biomass metabolism promotion.[13]

As is depicted in Fig. 4, use of the FABR at the HRT of ≥20 hours were mostly independent of its baffling features, and the separation of acid and methanogen phases occurred partially. In other words, COD removal mostly occurred at the reactor early parts where the activity of the biomass was highest. Therefore, it could be inferred that the operation of the FABR was better at the HRT of <20 hours for MWT. This finding has also been reported regarding ABR in the litterateur.[21]

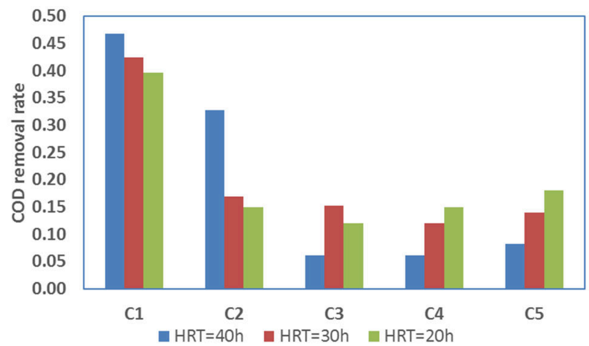

Fig. 4. The profile of COD removal at different compartments of the FABR

Effect of EP integrated with the FABR

As is shown in Fig. 4, the forth part of the reactor might be an appropriate place to incorporate the EP. Therefore, this compartment was converted into the electrocoagulation cell through inserting a pair of steel or aluminum electrodes and applying various densities of DC electrical current. Table 3 shows the comparison of the effluent quality of the FABR with the E-FABR.

Table 3. The comparison of the effluent q.uality of FABR with E-FABR

Parameter	pH	TSS mg/ L	COD mg /L	BOD_5 mg/L	SO_4^- mg/L	TN mg N/L	TP mg PO_4^-/L
Inlet	7.6	267	564	352	76	60	23
FABR outlet (HRT20h)	7.5	24	84	40	28	51	17
E-FABR outlet [a]							
0.05 mA/cm^2	7.9	19	73	35	22	47	1.9
0.075	7.9	20	64	31	18	48	1.5
0.1	8	16	52	23	15	45	0.8
0.2	8.1	14	39	20	14	47	0.4
E-FABR outlet [b]							
0.2 mA/cm^2	7.7	22	65	28	9.2	54	1.8
0.3	8.3	18	51	23	5.9	50	1.4
0.4	8.4	20	47	20	6.8	52	2.1
0.5	7.9	17	32	18	8.1	49	1.7
Standard [c]	6.5-8.5	30	60	30	400	-	6

[c] discharge standards (monthly average) to the surface water bodies based on the Iran Environment Protection Organization-
a: with Al electrodes, b: with steel electrodes

According to the information in Table 3, the removal of TSS, COD, BOD, TP, TN, and SO_4^- that was obtained in the E-FABR with low current density was comparable with those attained in chemical sedimentation and UASB. Furthermore, in the EP that was used with the aluminum electrode for MWT, the removal of COD, TN, and TP was determined to be 68%, 13%, and 93%. The main features of the E-FABR compared to chemical wastewater treatment are no need for external chemical addition and daily solid waste.[22, 23]

Another batch scale study in this regard was conducted at the initial pH of 7, current density of 20 mA/cm^{-2}, and electrolysis time of six minutes on the urban wastewater with the COD concentrations of 1,000 mg/l, and COD removal was reported to be 84% and 80% using aluminum and iron electrodes, respectively. Therefore, it could be concluded that the cost of aluminum electrode is lower compared to iron electrodes,[24] and the E-FABR could be an efficient and economic technique for the upgrade of the FABR to replace post-aerobic treatment in anaerobic reactors.

In the current research, the improvement of the FABR effluent quality upon integration with the EP could be mainly attributed to the formation of hydroxyl-metal precipitates due to anode scarification, which in turn resulted in the coprecipitation of contaminants at the sludge bed with the generated flocks. According to the obtained results, 100% of TP was removed at the optimum current density in the aluminum electrode, which could be ascribed to the adsorption of soluble phosphorus by the generated coagulants, as well as the precipitation of phosphate ions into $AlPO_4(s)$ and $Al_6(OH_{15})PO_4(s)$.[25]

There is the possibility of °OH radical formation in the EP that oxidizes organic matters. Moreover, EP helps improve reduction conditions and methane production through decreasing oxygen and hydrogen in the cathode.[26] In addition, the reactor sludge blanket completely filters the tinny flocks that have resulted from EP. Therefore, the E-FABR efficiency was observed to be superior to the FABR, and higher current density enhanced the quality of the E-FABR effluent. The E-FABR performance enhanced with the increased current density, which could be due to the fact that higher electrical current accelerates anodic scarification and increases the generation of Fe^{3+} and Al^{3+} ions, thereby improving the electrocoagulation reaction.[27] Considering the lower scarification of the aluminum electrode (weight<1%) and extremely low current density (0.1 mA/cm^2), the E-FABR with the aluminum electrodes is a cost-effective option for the efficient post-treatment of wastewater. Moreover, the performance of the aluminum electrode was remarkably better compared to the steel electrode, which could be due to the fact that aluminum produces more flocks with larger sizes and more viscosity compared to iron.[28]

Conclusion

According to the results, the FABR could meet the TSS, BOD_5, and COD discharge effluent standards at the optimum HRT of 30 hours. Furthermore, the E-FABR with the aluminum electrode was more efficient compared to the steel electrodes, which could treat wastewater at the current density of 0.1 mA/cm^2 and HRT of 20 hours to the discharge standard limits of TSS, COD, BOD, SO_4^-, and PO_4^-. As a result, the integrated EP reduced the required HRT of the FABR by 33%, and the integration of the EP with the low current density in the FABR could be used as an appropriate technique for the improvement of FABR performance.

Acknowledgments

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Ethical considerations

All the data collected during the research process have been expressed in the manuscript, and none will be published elsewhere separately.

Authors' Contributions

All the authors equally contributed to data collection, analysis, and interpretation. In addition, all the authors reviewed, revised, and approved the final manuscript.

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