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# Performance of a modified multi-stage bubble column reactor for lead(II) and biological oxygen demand removal from wastewater using activated rice husk

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ABSTRACT

The excessive release of wastewater into the environment is a major concern worldwide. Adsorption is the one of the most effective technique for treatment of wastewater. In this work activated carbon prepared from rice husk has been used as an adsorbent. In the present investigation a three phase modified multi-stage bubble column reactor (MMBCR) has been designed to remove lead and biochemical oxygen demand (BOD) from wastewater by means of its adsorption onto the surface of activated rice husk. The multi-staging has been achieved by hydrodynamically induced continuous bubble generation, breakup and regeneration. Under optimum conditions, maximum lead and BOD reduction achieved using activated rice husk was 77.15% and 19.05%, respectively. Results showed MMBCR offered appreciated potential benefits for lead removal from wastewater and BOD removal, even this extent of removal is encouraging and the MMBCR can be used a pretreatment unit before subjecting the wastewater to biological treatment.

## 1. Introduction

Environmental pollution due to development in technology is one of the most important contemporary problems. Industries have a large potential to cause lake, streams, sea and river pollution. It is very difficult to generalize the industrial wastes unlike the domestic sewage. The nature of pollution varies from industry to industry and also from plant to plant. The organic content of wastewater is traditionally measured using lumped parameters such as biochemical oxygen demand (BOD), chemical oxygen demand (COD) and total organic carbon (TOC).

These parameters, as such, do not indicate the specific chemical identities of the organic contaminants. Biochemical oxygen demand of wastewater is a measure of the oxygen required for the bio-degradation of the organic substrate in the wastewater. Due to high pollutant concentration, its disposal without treatment in water bodies has became undesirable because if done so, it will be very dangerous for the water bodies and human health. So, before its final disposal in water bodies, it needs a proper treatment.

Rapid industrialization has led to increased disposal of heavy metals into the environment. Lead is one of the potentially toxic heavy metals when adsorbed into the body. The presence of high levels of lead in the environment may cause long-term health risks to humans and ecosystems. It is therefore mandatory that their levels in drinking water, waste water and water used for agricultural and recreational purposes must be reduced to within the maximum allowable concentrations recommended by national and international health authorities such as World Health Organisation. Its removal from wastewater prior to discharge into environment is there fore necessary.

Various treatment technologies were utilized for organics and toxic inorganic metal removal from wastewater. The physicochemical techniques are widely used to treat wastewater in various industries. These techniques include adsorption, chemical reaction, filtration, ion-exchange, coagulation/flocculation reverse osmosis, electrodialysis and so on [1–5]. The choice of treatment depend upon effluent characteristics such as concentration of lead, pH, temperature, flow volume, biological oxygen demand, the economics involved and the social factor like standard set by government agencies.

Based on the level of treatment provided, wastewater treatment processes are frequently classified as preliminary, secondary or tertiary treatments. Voluminous literature is available on the applications of physicochemical techniques. Physicochemical processes have a number of advantages versus the biological and other treatment processes. Physicochemical treatment processes remain unaffected by the presence of toxic substances such as metals whereas biological systems fail to operate in case of wastes predominantly inorganic or non-biodegradable in nature. In India, there are ~7500 industries of considerable pollution significance

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**Nomenclature**

| | |
|---|---|
| $C_{ef}$ | concentration of effluent (g/l) |
| $C_{in}$ | concentration of influent (g/l) |
| $C_p$ | inlet activated rice husk loading (g/l) |
| $D$ | diameter of the bubble column (m) |
| $D_l$ | diffusivity (g/m$^2$ s) |
| $H$ | height of the bubble column (m) |
| $H_R$ | height to diameter ratio ($H/D$) |
| $Q_g$ | gas flow rate (m$^3$/s) |
| $Q_l$ | liquid flow rate (m$^3$/s) |
| $Re_g$ | superficial gas Reynolds number ($DV_g\rho_g/\mu_g$) |
| $Re_l$ | superficial liquid Reynolds number ($DV_l\rho_l/\mu_l$) |
| $Sc$ | Schmidt number based on activated rice husk loading ($\mu_l/D_lC_p$) |
| $V_g$ | gas velocity (m/s) |
| $V_l$ | liquid velocity (m/s) |

*Greek letters*

| | |
|---|---|
| $\eta$ | removal efficiency of pollutants experimental (%) |
| $\eta_{BOD}$ | removal efficiency of BOD theoretical (%) |
| $\eta_{Pb}$ | removal efficiency of lead theoretical (%) |
| $\eta_T$ | removal efficiency of pollutants theoretical (%) |
| $\mu_g$ | gas viscosity (g/m s) |
| $\mu_l$ | liquid viscosity (g/m s) |
| $\rho_g$ | gas density (g/m$^3$) |
| $\rho_l$ | liquid density (g/m$^3$) |

and ~4500 of them have put up effluent treatment plants [6]. There are several tens of thousands of other small industries, which contribute significantly to pollution load but escape attention. Considerable amounts of wastewater are also generated as human waste or sewage. Removal of these contaminants from wastewater to adequate levels is one of the fundamental goals in waste treatment using various available technologies. However, conventional treatment technologies implemented in the industrialized nations are expensive to build, operate and maintain in developing countries. Therefore, efforts are still going on to develop affordable treatment technologies for developing and underdeveloped countries. Various technologies to treat water/wastewater are very well documented but few studies are reported which use of low cost adsorbents to clean organic loads together with some toxic inorganic metal cations and anions from industrial wastewater/effluents.

The use of activated carbon is still very popular and different grades are available, but are quite expensive and the regeneration of the carbon is not always possible. Activated carbon has been chosen as an adsorptive media for removal of lead and BOD by many researchers [7,8]. Activated carbon is a black solid substance resembling granular or powder charcoal and are carbonaceous material that have highly developed porosity, internal surface area of more than 400 m$^2$ g$^{-1}$ and relatively high mechanical strength. They are widely used as adsorbents in wastewater and gas treatments as well as in catalysis. The increasing usage and competitiveness of activated carbon prices, has prompted, a considerable research work has been done in the search of inexpensive adsorbents especially developed from various agricultural waste materials i.e. the usage of agricultural by-products such as fruit stones, coconut shell, bagasse, nutshells, coirpith and rice husk as raw materials to prepare activated carbon [9]. These solid wastes are not only cheap and easily available but also are considered as wastes that contribute to the disposal problems. In this study, rice husk has chosen as an adsorptive media.

The process of adsorption has been carried out mostly in packed bed, fluidized bed and moving beds. However, operational complexity and the limitation of the efficiency of removal have led to search for new and efficient equipment which can give better removal efficiency without additional mechanical complications. Simple bubble columns [10,11] and airlift reactors are drawing increased attention as possible alternatives to these devices. Simple bubble column, in their various forms and manifestations belong to the category of buoyancy induced flow reactors in which the compressed air is used to simultaneously aerate and agitate the liquid with controlled recirculation. Thus, simultaneous gas–liquid (or gas–liquid–solid) mixing and liquid recirculation is achieved by using only compressed air.

It may further be appreciated that a simple bubble column operates in one stage only and cannot achieve high efficiency except for highly soluble gas in chemically reactive systems. In order to achieve high efficiency of mass transfer, bubble columns must be operated in series or in multiple stages. In commercially available bubble columns, multistage operation has been achieved by the use of perforated multi-orifice plates. Thus in such columns, high efficiencies can be achieved only with high energy dissipation and mechanical complications. In the present investigation a bubble column, operating in three stages has been designed—the staging effect being achieved through hydro dynamically induced bubble generation and breakup through bubble rupture and regeneration. The staging effect is produced using contraction and expansion elements a 2 mesh sieve acts as the contraction element and a 4 mesh sieve acts as the expansion elements. A multi-orifice antenna type sparger produces fairly uniform bubbles of 3–5 mm in the first stage of the column. Bubbles which are generated by the sparger in the first stage of the column, rupture and reforms at these sieves, hence starting a cycle of bubble breakup, coalescence and regeneration [12]. The continuous generation of new surface area coupled with high turbulence achieved due to bubble breakup was expected to lead to very high interphase mass transfer. The modified multistage bubble column reactor (MMBCR) can therefore, prove to be a very important contacting system for the liquid phase adsorption of trace pollutants using powdered activated carbons, because of their basic advantages like: a simple construction without moving parts, an excellent heat transfer capacity, a reasonable interphase mass transfer and good mixing properties at low energy consumption, as the gas phase serves the dual function of aeration and agitation.

The lead metal adsorption characteristics of activated carbon are quite well known. The interesting part of the investigation is how far the activated carbon treatment is successful in reducing BOD levels of the wastewater. Even a fractional of BOD means encouraging results because this comes over and above the lead metal abatement and the apparatus can be used as a pretreatment unit before subjecting the wastewater to biological remediation.

## 2. Experimental set-up and technique

### 2.1. Reagents

All the chemicals used in the study were from Merck (India) Ltd. and Qualigens Glaxo (India) Ltd. analytical grade.

### 2.2. Adsorbent

The rice husk collected from a nearby rice mill was washed with distilled water to remove the water-soluble impurities and surface adhered particles and then oven-dried at 60 °C to get rid of the moisture and other volatile impurities. Then, the dried rice husk was soaked in concentrated $H_2SO_4$ in an amount sufficient to cover

**Table 1**
Physico-chemical characteristics of the activated rice husk

| Parameters | Values |
|---|---|
| Moisture (%) | 4.12 |
| Ash (%) | 3.56 |
| Fixed carbon (%) | 36.7 |
| Bulk density (g/ml) | 0.832 |
| BET surface area ($m^2/g$) | 704 |
| Total pore volume ($cm^2/g$) | 0.529 |
| Mean pore radius (Å) | 24.3 |

the raw material completely at normal temperature and pressure, agitated at 120 rpm in an incubator shaker for 30 min and left for 2 h. After mixing, the slurry was subjected to vacuum drying at 100 °C for 24 h. Then this carbon was washed to get it acid free and its pH was checked. The carbonized adsorbents were dried and rewashed many times until its pH reaches to 4. After this the activated carbon was deacidified by use of water and ammonical solution in later stages. Deacidification was done in following manner. After 25–30 times washing carbon was treated with liquid aqueous ammonia solution in such a fashion that it does not affect the surface properties. Then carbon was dried to 60°°C. After this, carbon was crushed in a small ball mill with 50 small balls for 1 h. The powder from ball mill is collected and dried to remove the moisture. Then this powder carbon was kept in airtight packet for the experimental use. The various physico-chemical characteristics of the prepared activated carbon was given in Table 1.

The BET surface areas of the activated rice husk were measured in BET-Flowsorb-2300 analyzer on the basic principle of monolayer adsorption. Nitrogen and helium mixture nearly 30–35% was used to form the monolayer. In this method first sample quantity is optimized after several trial runs so that surface area falls with in 0.5–2.5 $m^2$. The sample is dried in an air oven at 105 °C and free from any gases or vapors for which 200–250 °C for 15 min is adequate. Surface area in Flowsorb-2300 is displayed in terms of quantity of sample contained in sample tube holder and the displayed number is converted to specific surface area by dividing the weight of the sample.

### 2.3. Wastewater collection

Wastewater samples were collected from the outlet of an industry located at Kolkata, West Bengal, India. Samples were collected as per standard methods, and transported immediately to the laboratory (Department of Chemical Engineering, IIT, Kharagpur, India) under standard conditions. Samples were processed and analyzed by standard methods. The wastewater characteristics, collected from the outlet of a chemical industry are given in Table 2.

**Table 2**
Wastewater characteristics

| Parameters | Values |
|---|---|
| pH | 7.15 |
| Temperature (°C) | 25 |
| Electrical conductance (mho/cm) | $2.78 \times 10^{-3}$ |
| Turbidity (Nephalometer Turbidity Unit) | 127 |
| Total solid (g/l) | 1476 |
| Dissolved solid (g/l) | 854 |
| Suspended solid (g/l) | 582 |
| Chemical oxygen demand (g/l) | 1045 |
| Biochemical oxygen demand (g/l) | 608 |
| Lead (g/l) | 27.2 |
| Fluoride (g/l) | 0.253 |
| Chloride (g/l) | 78 |
| Zinc (g/l) | 8.25 |
| Chromium (g/l) | 3.57 |

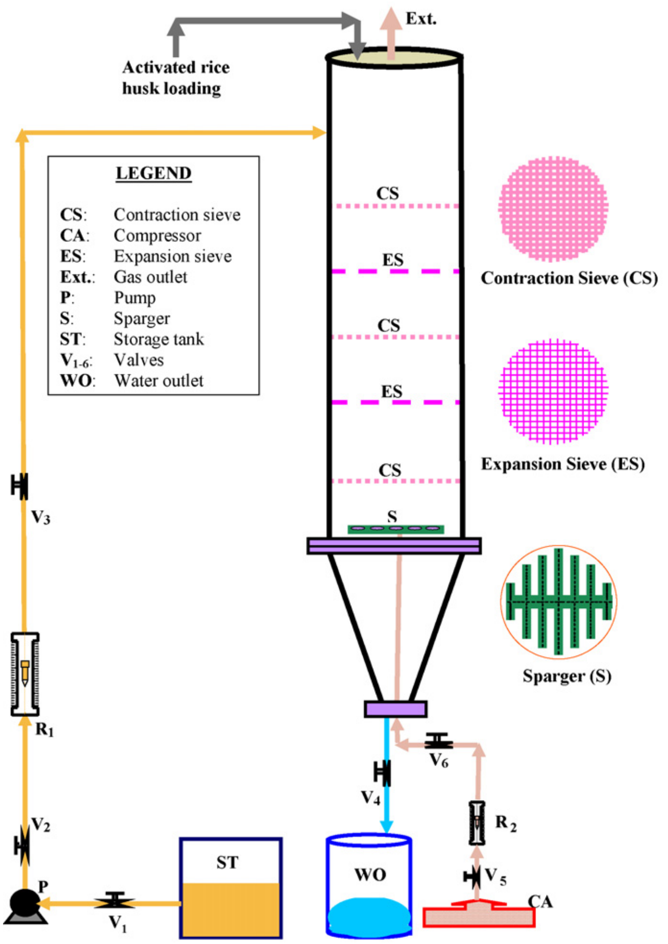

**Fig. 1.** Schematic of the experimental setup for removing lead and BOD in a MMBCR.

### 2.4. Method of experiment

The experimental set up shown in Fig. 1 has been used for studies on the performance of a MMBCR for removing of lead and BOD from wastewater using activated rice husk as adsorbent. The dimensions of the MMBCR have been presented in Table 3. The MMBCR consisting of a vertical cylindrical Perspex column, 0.46 m in diameter and 2.0 m long, fitted with a fructo-conical bottom of aluminum. The conical bottom has a divergence angle of 15° and a height of 0.4 m. The minimum diameter of the bottom is 0.24 m. The vertical cylindrical column is fitted with a total of five sieves termed as stages (three contraction sieves and two expansion sieves). The expansion

**Table 3**
Specification of MMBCR used for experimental purpose

| Parameters | Values |
|---|---|
| Diameter of bubble column (m) | 0.46 |
| Length of cylindrical portion of bubble column (m) | 2.0 |
| Length of conical portion of bubble column (m) | 0.4 |
| Diameter of bottom of conical portion (m) | 0.24 |
| Diameter of top of conical portion (m) | 0.42 |
| Apex angle (°) | 15 |
| Expansion sieve (mesh) | 2 |
| Contraction sieve (mesh) | 4 |
| Spacing between two consecutive sieves (m) | 0.26 |
| Diameter of wastewater feed inlet pipe (mm) | 12.7 |
| Diameter of water outlet pipe (mm) | 12.7 |
| Diameter of compressed air inlet pipe (mm) | 25.4 |

and contraction sieves had single opening on the screen 0.0111 and 0.00475 m, respectively.

The lowest part of the column, above the fructo-conical cone, a multi-orifice sparger was fitted an antenna type of sparger of 1.6 mm diameter and 144 holes for generating bubbles uniformly throughout the entire cross section of the column. It consists of a seven Perspex tubes of 12.7 mm diameter supported on another Perspex tube of 25.4 mm diameter in such a way as to form a circle. The seven thinner tubes are inserted in equidistant holes drilled in the shaft tube. The seven tubes form the chords of a circle which has the 0.42 m diameter tube as its diametrical element. A 25.4 mm hole was drilled in the shaft tube and threaded to enable fitting of the air supply pipe.

The first contraction sieve (known as first stage) of 4 mesh was placed at a height of 0.26 m above the sparger. The second sieve (second stage) of 2 mesh was fitted at a height of 0.52 m above the sparger and the third sieve (third stage) was fitted at a distance of 0.78 m above the sparger. The column is divided into three distinct sections. Section-I consists of sparger and first contraction sieve of 0.26 m height, Section-II consists of first contraction sieve, first expansion sieve and second contraction sieve of 0.78 m height and Section-III a height of 1.30 m. A 0.50 m clear space was provided above Section 3, for allowing time for gas–liquid separation to take place and also to accommodate bed expansion due to bubbly flow.

Experiments were conducted both with a constant liquid batch and continuous liquid down-flow. The wastewater was pumped by a pump (P) from storage tank (ST) and sprayed into the column from the top through a Perspex element drilled with holes at a height of 1.80 m. This wastewater was fed to the bottom of the reactor till a particular level was reached. At the bottom of the column a water outlet was provided as shown (WO). Compressed air from the compressor (CA) was forced through the antenna type sparger to produce bubbles at a controlled rate, so that a desired flow pattern was established in the column. A non-return valve ($V_6$) fixed in the air-supply line ensures that no water enters the air line or compressor. The bubbles generated rise vertically through the cylinder, break and are reformed producing the desired staging effect. The experiments were conducted at gas flow rates of $1.5–3 \times 10^{-4}$ m$^3$/s and wastewater flow rate $1.0–12.0 \times 10^{-4}$ m$^3$/s. The air flow was regulated by valves ($V_5$ and $V_6$) and was measured by a calibrated rotameter ($R_2$). The wastewater flow was regulated by valves ($V_2$ and $V_3$) and was measured by a calibrated rotameter ($R_1$). Known amounts of powdered activated rice husk were added to the wastewater in the riser from the top of the reactor. All the experiments were carried out at the room temperature of $20 \pm 2$ °C. The samples were collected in regular time intervals and stored for analysis for lead and BOD.

The pH and temperature of the wastewater samples were measured on collection site. Electrical conductance, turbidity, total solids, total suspended solids, total dissolved solids, BOD, lead and other metals were analyzed in laboratory. In this paper, we have studied the removal of lead and BOD only. The lead and BOD of the wastewater samples were measured in laboratory before and after its treatment with adsorbents. The removal efficiency of contaminates $\eta$, is defined as follows:

$$\eta = \left(\frac{1 - C_{\text{ef}}}{C_{\text{in}}}\right) \times 100 \tag{1}$$

where $C_{\text{ef}}$ and $C_{\text{in}}$ are the concentrations of effluent and influent, respectively. Two replicates per sample were done and the average results are presented.

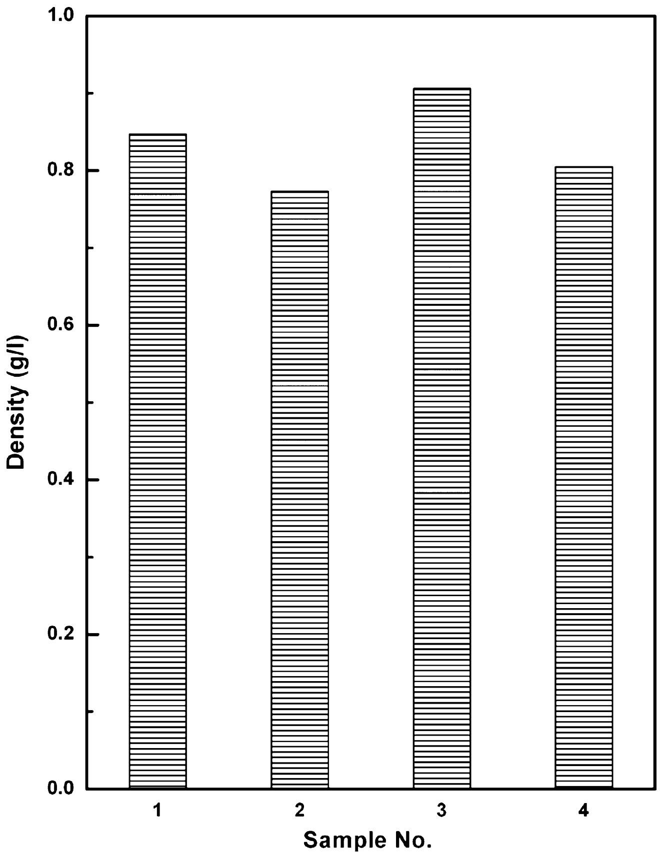

**Fig. 2.** Density of activated rice husk.

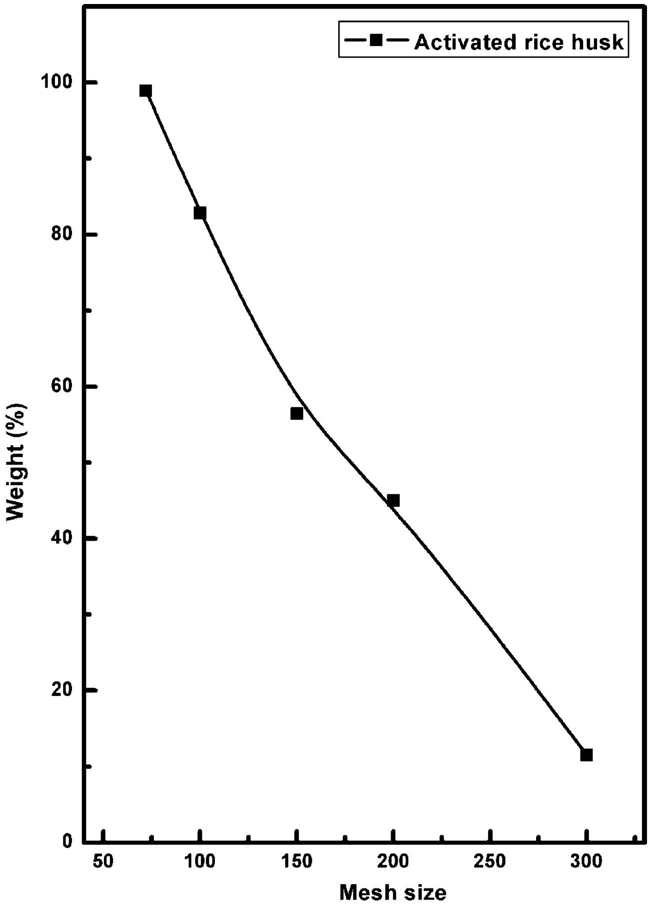

**Fig. 3.** Particle size analysis by sieves for activated rice husk.

## 3. Results and discussions

### 3.1. Physical and chemical characterization of the adsorbent

The smaller the particle sizes of a porous carbon, the greater the rate of diffusion and adsorption. Intraparticle diffusion is reduced as the particle size reduces, because of the shorter mass transfer zone, causing a faster rate of adsorption. Since we have prepared our carbon in a powdered form so it has a great efficiency of removal. Particle size distribution analysis was done manually. Initial sample of weight 145 g was taken for analysis. This sample was passed through different sieves and amount of fine and coarse were measured. For the mesh size 72, 100, 150, 200 and 300 data were obtained are shown in Fig. 2.

Density is particularly important in removal. If two carbons differing in bulk density are used at the same weight per liter, the carbon having higher bulk density will be able to remove more efficiently. Average bulk density can be calculated by water displacement method. In this method, volume of water displaced is observed by a particular amount of activated rice husk. The data were obtained for this experiment is shown in Fig. 3 we can see that average bulk density is 0.832 g/ml.

Activated carbon pH may influence the removal efficiency. Distinctly acidic activated carbon may react with the material to be removed and may hamper the surface properties of the activated carbon. For our experiment the pH of carbon was 6.5. Ash content of the activated carbon is the residue that remains when the carbonaceous portion is burned off. The ash consists mainly of minerals such as silica, aluminum, iron, magnesium and calcium. Ash in activated carbon is not required and considered to be an impurity. As the ash content is 4.56% it resembles good adsorbent.

The BET surface area of activated rice husk was measured and it was found 704 $m^2$/g. The average pore diameter was found 24.3 Å and total pore volume was found 0.529 $cm^2$/g. This shows that activated rice husk is reasonably good for adsorption.

### 3.2. Effect of gas flow rate on percentage removal of lead and BOD

The percentage removal of lead from a wastewater sample increases very slightly with the increase in gas flow rate for constant liquid flow rates and constant loading of activated rice husk. These experiments were carried out for a liquid flow rate of 0.001 $m^3$/s and adsorbent dose of 5 g/l. The percentages removal of lead observed varied from 72.75% to 76.95% as increase gas flow rate at constant values of loading of activated rice husk and liquid flow rates. This increase results from the increased turbulence in the gas phase and higher relative velocity of the gas liquid interface. It is interesting to note that after a certain value of gas flow rate the percentage removal of lead remains almost constant. This phenomenon is depicted in Fig. 4, as the curve flattens out and becomes parallel to the abscissa after increasing the gas flow rate after a certain limit.

The percentages removal of BOD observed varied from 5.27% to 20.12% as increase gas flow rate at constant values of adsorbent dose 5 g/l and liquid flow rate 0.001 $m^3$/s. The percentage removal

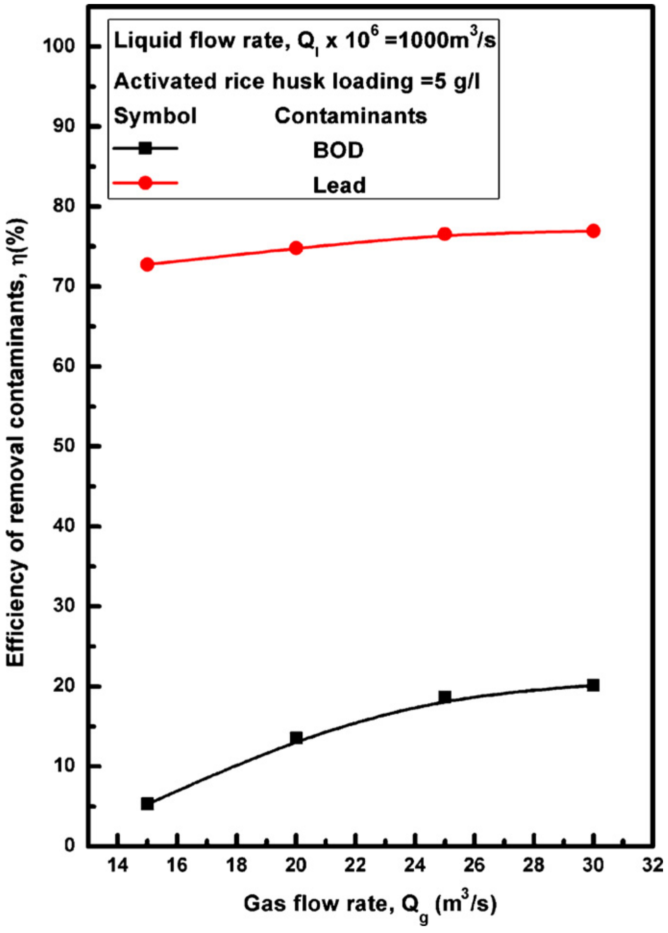

**Fig. 4.** Effect of gas flow rate on efficiency of removal contaminants.

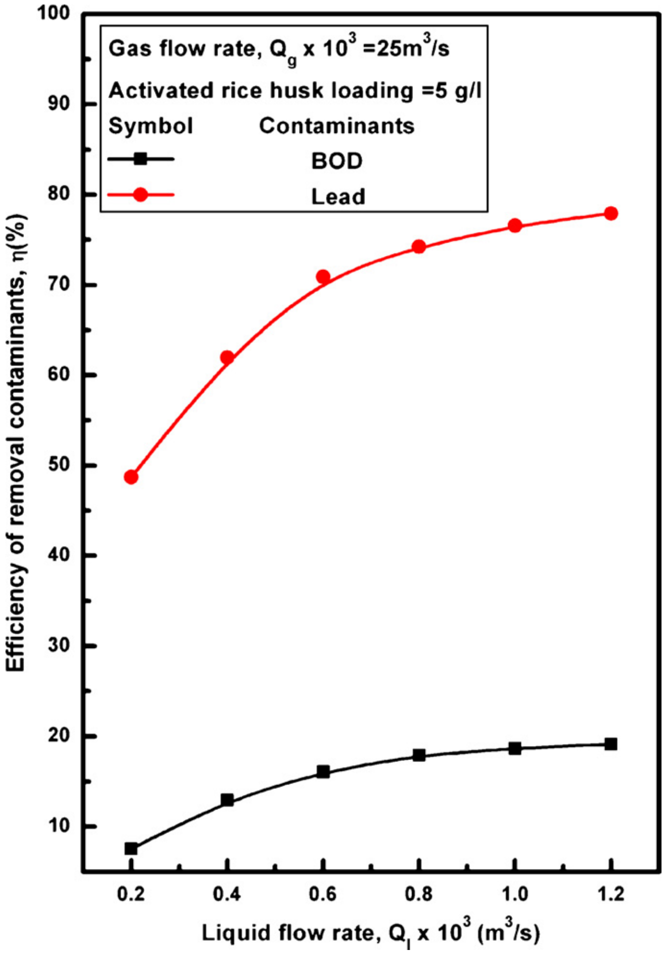

**Fig. 5.** Effect of liquid flow rate on efficiency of removal contaminants.

of BOD increases markedly with the increase in gas flow rate for constant liquid flow rates and constant loading of activated rice husk. This is a marked deviation from the observations made in the case of lead adsorption, where there is only a slight increase in the percentage removal on increasing gas flow rate. This may be attributed to the fact that increased gas flow rates means increased aeration, which helps the microorganisms inherently present in the wastewater to stabilize the BOD biologically. This is over and above the increased removal due to higher turbulence in the gas phase and higher relative velocity of the gas liquid interface. Fig. 4 depicts the observation.

### 3.3. *Effect of liquid flow rate on percentage removal of lead and BOD*

Liquid circulation flow rate is one of the most important parameters that affect the MMBCR characteristics. The effect of liquid flow rate on the percentage removal of the two contaminants, at constant gas flow rates and constant loading of activated rice husk, has been depicted in Fig. 5. These experiments were carried out for a gas flow rate of 0.025 $m^3$/s and adsorbent dose of 5 g/l. The percentages removal of lead observed varied from 48.72% to 77.92% as increase liquid flow rate at constant values of loading of activated rice husk and gas flow rate. The percentages removal of BOD observed varied from 7.54% to 19.13% as increase liquid flow rate at constant values of loading of activated rice husk and gas flow rate. It can be seen from the figure that the percentage removal of the contaminants increases markedly as the liquid flow rate is increased. In the present investigation, as the liquid flow rate is increased the bubble-water interfacial contact area increases. As a result of this, percentage removal increases with increased liquid flow rates. Actually the increased flow rates does not increase the number of bubbles formed, but affects positively the efficiencies of the individual bubbles, as long as sufficient area is available in the system.

### 3.4. *Effect of the adsorbent dose on the percentage removal of lead and BOD*

Fig. 6 shows the effect of adsorbent dose on the percentage removal of lead and BOD from contaminated wastewater in a MMBCR for a liquid flow rate of 0.025 $m^3$/s and a gas flow rate of 0.001 $m^3$/s. The percentages removal of lead observed varied from 46.13% to 77.15% as increase loading of activated rice husk at constant values of gas and liquid flow rates. The percentages removal of BOD observed varied from 5.23% to 19.05% as increase loading of activated rice husk at constant values of gas and liquid flow rates. It was observed that maximum removal occur at the dose of 5 g/l, after that the equilibrium was set up by further addition of adsorbent dose. The efficiencies increase steeply at first, with increased amounts of adsorbent used. Slowly the rate of increase decreases till a stage comes when the percentage removal no longer increases with increased amounts of adsorbent used. This means that the saturation point for adsorption has been reached and no further removal is possible by using increased amounts of adsorbent. This increase is attributed to the increase in the number of sites with higher dose. At lower doses, the significantly small adsorption is

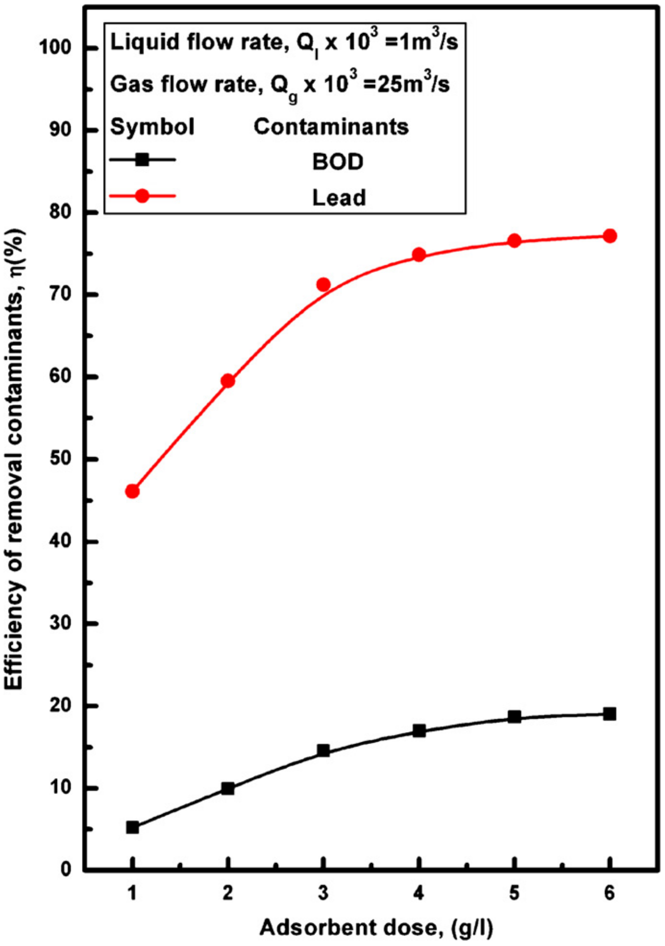

**Fig. 6.** Effect of adsorbent dose on efficiency of removal contaminants.

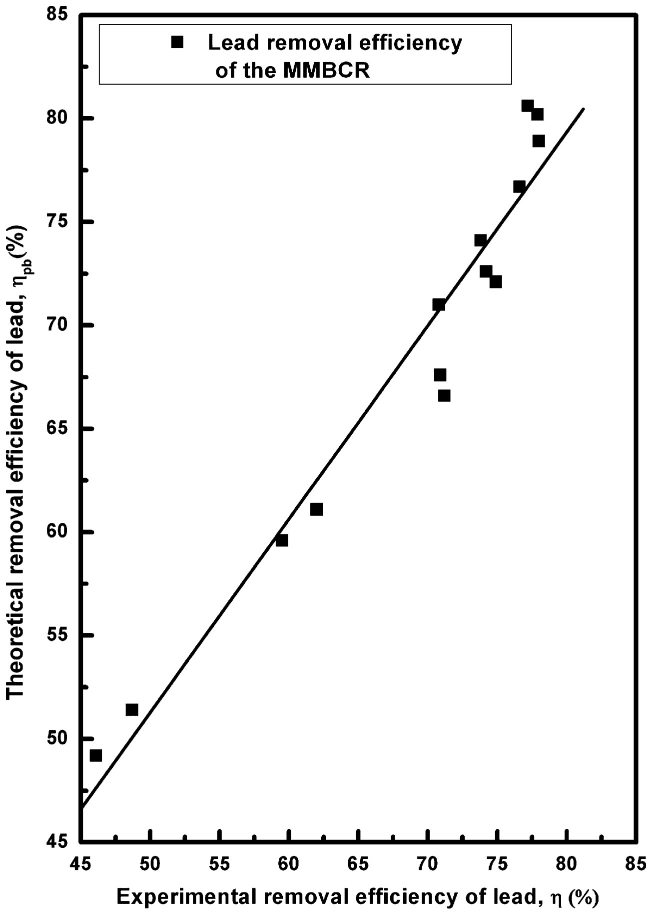

**Fig. 7.** Comparison of theoretical and experimental values of lead removal efficiency.

possibly due to the saturation of surface active sites with the adsorbate molecules.

### 3.5. Development of empirical correlation

In the light of inadequacy of the existing literature, and the complex characteristics of the modified multi-stage bubble column reactor an attempt has been made to develop a correlation to predict the percentage removal of lead and BOD from the directly measurable parameters. Conceivable variables on which the efficiency of removal of lead and BOD in the MMBCR may depend are: geometrical parameters namely, diameter of the column ($D$), height of the column ($H$); flow parameters, namely gas velocity ($V_g$), liquid velocity ($V_l$); physical properties, namely, gas density ($\rho_g$), liquid density ($\rho_l$), gas viscosity ($\mu_g$), liquid viscosity ($\mu_l$), inlet activated rice husk loading ($C_p$), and diffusivity ($D_l$). The removal of pollutants efficiency thus becomes a function of 10 parameters. The large numbers of possible variables on which the efficiency of pollutants removal depend have been reduced to a pertinent few, since many of these variables are interrelated or are maintained constant. A theoretical relation exists between the efficiency of contaminates removal $\eta_T$, and the physical characteristic, and the fluid variable of the system. Then $\eta_T$ may be written in the following form:

$$\eta_T = f(D, H, V_g, V_l, \rho_g, \rho_l, \mu_g, \mu_l, C_p, D_l) \tag{2}$$

The variables in the above equation can be grouped into dimensionless groupings by employing the Buckingham's π-Theorem, and the equation can be reduced to

$$\eta_T = f_2\left(\frac{DV_g\rho_g}{\mu_g}\right)^a \left(\frac{DV_l\rho_l}{\mu_l}\right)^b \left(\frac{\mu_l}{C_P D_l}\right)^c \left(\frac{H}{D}\right)^d \tag{3}$$

The form of equation can be rearranged to:

$$\eta_T = f_2(Re_g)^a(Re_l)^b(Sc)^c(H_R)^d. \tag{4}$$

#### 3.5.1. Removal efficiency of lead

In order to establish the fundamental relationship between the removal of lead efficiency $\eta_{Pb}$ and the various dimensionless groupings, the dimensionless analysis presented earlier indicates that the percentage of contaminates removal efficiency MMBCR presented in Eq. (4), may be simplified to

$$\eta_{Pb} = S(Re_g)^a(Re_l)^b(Sc)^c(H_R)^d \tag{5}$$

A multiple linear regression analysis has been carried out to evaluate the constant and coefficients of the equation. The optimum equation which yield's minimum percentage of error and minimum standard deviation, gives the best possible correlation of fractional efficiency as

$$\eta_{Pb} = 0.373(Re_g)^{0.152}(Re_l)^{0.248}(Sc)^{-0.275}(H_R)^{0.262} \tag{6}$$

The values of percentage removal of lead, $\eta_{Pb}$ predicted by Eq. (6) have been plotted against the experimental values of percentage removal of lead, $\eta$ in Fig. 7. The percentage deviation between the experimental data and those of predicted by Eq. (6) has been plotted in Fig. 8. It is seen from this figure that the percentage deviation is quite low (within ±22%).

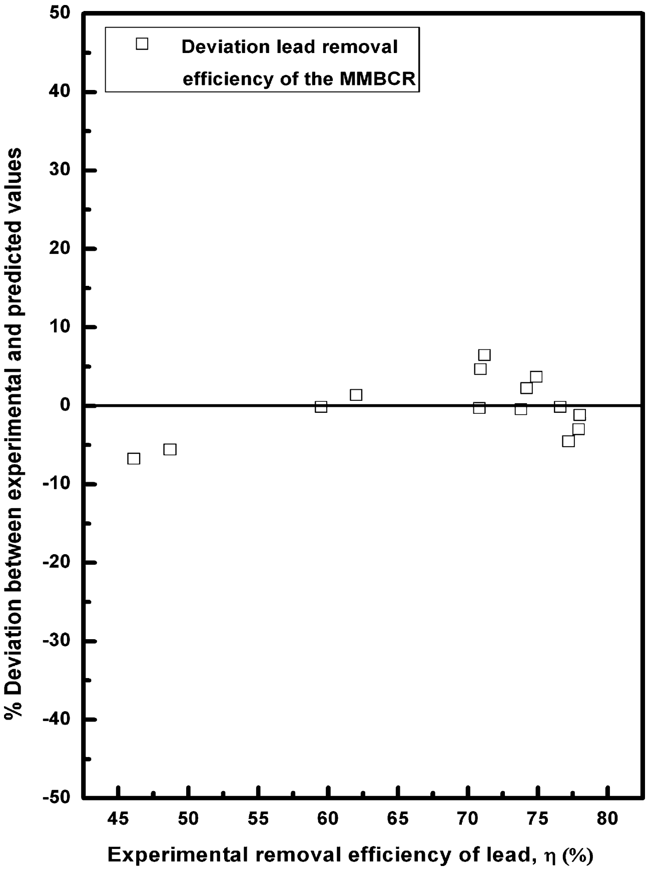

**Fig. 8.** Deviation between experimental and predicted values of lead removal efficiency.

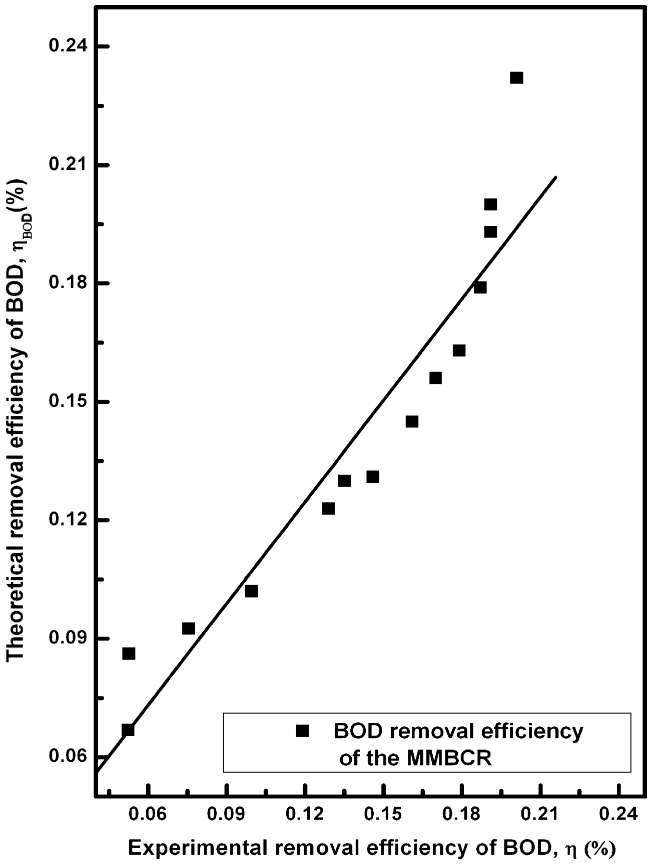

**Fig. 9.** Comparison of theoretical and experimental values of BOD removal efficiency.

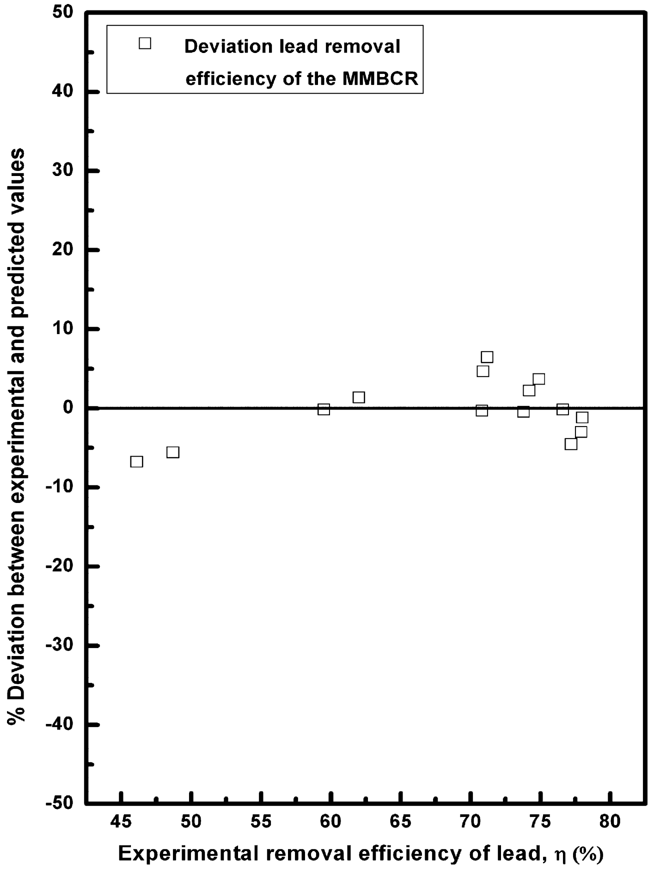

**Fig. 10.** Deviation between experimental and predicted values of BOD removal efficiency.

### 3.5.2. *Removal efficiency of BOD*

In order to establish the fundamental relationship between the removal of BOD efficiency $\eta_{\mathrm{BOD}}$ and the various dimensionless groupings, the dimensionless analysis presented earlier indicates that the percentage of contaminates removal efficiency MMBCR presented in Eq. (4), may be simplified to

$$\eta_{\mathrm{BOD}} = Z(Re_{\mathrm{g}})^{a}(Re_{\mathrm{l}})^{b}(\mathrm{Sc})^{c}(H_{\mathrm{R}})^{d} \tag{7}$$

A multiple linear regression analysis has been carried out to evaluate the constant and coefficients of the equation. The optimum equation which yield's minimum percentage of error and minimum standard deviation, gives the best possible correlation of fractional efficiency as

$$\eta_{\mathrm{BOD}} = 0.017(Re_{\mathrm{g}})^{1.42}(Re_{\mathrm{l}})^{0.41}(Sc)^{-0.61}(H_{\mathrm{R}})^{0.19} \tag{8}$$

The values of percentage removal of BOD, $\eta_{\mathrm{BOD}}$ predicted by Eq. (8) have been plotted against the experimental values of percentage removal of BOD, $\eta$ in Fig. 9. The percentage deviation between the experimental data and those of predicted by Eq. (8) has been plotted in Fig. 10. It is seen from this figure that the percentage deviation is quite low (within ±7%).

## 4. Conclusions

In this investigation detailed results were presented for adsorption of lead and BOD by using activated rice husk in a three phase modified multi-stage bubble column reactor with continuous mode. The major findings are summarized as follows:

- Characterization has shown a clear demarcation in the physicochemical properties of the adsorbent.
- The performance of the MMBCR was evaluated for lead removal; it shows that percentage removal of lead increase very slightly with the increase in gas flow rate for constant liquid flow rates and constant loading of activated rice husk. But the percentage removal of lead increases markedly as the liquid flow rate is increased for constant gas flow rate and constant loading of activated rice husk. The percentages removal of lead observed varied from 46.13% to 77.15% as increase loading of activated rice husk at constant values of gas and liquid flow rates.
- The performance of the MMBCR was evaluated for BOD removal; it shows that percentage removal of BOD increases markedly with the increase in gas flow rate for constant liquid flow rates and constant loading of activated rice husk. Also its removal of BOD increases markedly as the liquid flow rate is increased for constant gas flow rate and constant loading of activated rice husk. The percentages removal of BOD observed varied from 5.23% to 19.05% as increase loading of activated rice husk at constant values of gas and liquid flow rates. Even this extent of removal is encouraging and the apparatus can be used a pretreatment unit before subjecting the wastewater to biological treatment.
- The experimental values were compared with the values obtained by empirical and it shows close agreement between the experimental points and empirical curves.

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