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Empirical models for change in pH and temperature within gravity-based reactor columns

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ABSTRACT

Column reactor models of volume size 3,000 and 1,500 cm^3 are made using organic materials such as sawdust and immature (drumstick) Moringa oleifera and other natural materials such as gravels (6 mm size) and ball clay available locally at Jodhpur, India. Water is passed through these porous reactors under gravity at once. The experiments were aimed at finding low-cost solutions for wastewater or sewage disposal at point of use. The change in pH during water filtration experiments is measured and modelled as functions of X_1 (column height), X_2 (flow rate), X_3 (cumulative percolation time) and X_4 (change in electrical conductivity). The parameters X_1, X_2, X_3 and X_4 are found to be highly correlated to each other irrespective of materials used for making the bioreactors. There is a hyperbolic relationship between temperature gradient within the porous material column bed through which water is percolating and time taken during that process. The temperature distribution in the gravel or sawdust media reactors is not influenced by the inflow rate or height of the reactor column used for experimentation. Distinct temperature distribution exists at each depth of the heterogeneous reactors. The multi-parameter model developed and the hyperbolic relationships help to characterize the efficacy of bioreactors. The effect of the materials on the wastewater treatment can now be individually evaluated using the multi-parameter approach presented in this paper.

Keywords: Column reactor; Gravity; pH; Electrical conductivity; Correlated

1. Introduction

In India, toilets are flushed but the sewage goes untreated [1]. Indian cities discharge 15 billion L^3 of water daily [1]. This is equal to 80% of total water supplied that goes into sewage [2]. About 78% untreated sewage ends up in fresh water lakes, rivers and aquifers down below [1]. No quantitative figures or plans exist for sewage treatment [1]. Jawaharlal Nehru National Urban Renewal Mission started by India in 2005 looks into sanitation and waste management in cities as well as development of technologies to serve economically backward [2]. It aims at building carbon

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neutral, energy efficient smart cities but economically backward stay in rural India. More than 73% of major projects within this mission have not been completed on time and also villages have been neglected in these projects [2]. It represents neglect from the government as well as communities towards water infrastructure development in rural India [1,3]. Recently, an interesting research concentrating on water quality in Rajasthan's forest water bodies revealed shocking results [4]. Textile and steel industrial establishments in the state of Rajasthan dump chemical waste into rivers and their tributaries without proper treatment [4]. Further due to low loading capacity of Jodhpur wastewater treatment plant, polluted water is dumped in the forest wetlands which spreads over a score villages at Dhavadoli, Rajasthan [4]. The total dissolved solids in various wetlands in Dhavadoli ranged between 1,000 and 1,500 mg/L [4]. This figure is far above the WHO standard of 400 mg/L. Similarly, chemical oxygen demand (COD) of 1,320 mg/L was also recorded which beyond the safe limit of 250 mg/L as was recommended by the WHO [4].

These cases occur due to the very basic shortcomings of water infrastructure in India, which are poor planning in centralized supply, buildings, infrastructure and distribution, less research, negligible future planning and design, neglecting rural community and failure by public to adopt the service rules as well as inability to revise the rules laid down several decades ago [5].

Further to the above discussions, the premise derived is either to impose and enforce better water/waste water management laws for people to abide or the other way round is to device point of use technologies. This will help to find a pathway to help rural communities without much water infrastructure to dispose of their sewage at the source itself.

In the prior studies undertaken by Plappally and Lienhard in [6], recycle and reuse is much energy efficient and cost effective compared to regular water treatment [6,7]. Water effluent from residential places has varying pollutant concentrations, and variable frequency of effluent discharge depending upon the behaviour of household occupants [7]. Rural India is poor and hence, the aim is for low-cost wastewater treatment solutions.

Lowe [8] explained that soil is an opportunity in this regard for easy to use, cheap and extensively available treatment medium [8]. Soils which naturally exist in layers provide large surface area for sorption, aeration, ecosystem for micro-organism which breakdown waste materials and zones of nutrient transport [8]. According to Lowe [8], local soil properties, water addition and its interaction with soils, evolution of humic biomaterials with time, geometry and layering affect effluent infiltration. In [9], it was illustrated by Tomares et al. that bacterial evolution was abundant at top 15 mm of the infiltrative surface of the soils. This would mean that it is logical and may be fruitful to provide a top surface which can help microbes (which may help in impurity breakdown) to thrive.

For the soils to act as purifiers, it is important that they help in removal of the microbes polluting water. Gerba et al. [10] cited several studies in which there was a major reduction in coliform densities with depth of soils. Lowe [11] stated that microbial biomass will decrease with increase in soil depth. There will be high degree of diversity of the microbes in the infiltrative surface [11]. Slater and Mancl [12] expounded that a 4-feet-deep porous media will be required for an optimal treatment of the wastewater. Suspended solids can be removed by 1-foot-deep infiltration through unsaturated soils, ammonia, organic matter and microbes get removed at about a 2-feet depth [12]. Size and structural property of the media play a decisive role is wastewater treatment [12]. This would mean that depth may be a major parameter for design of biologically active soil columns or bioreactors which may be used in water purification.

Column bioreactors are known for decentralized wastewater treatment in rural areas far away from municipal sewage distribution systems of metropolitan cities [13]. Various media bioreactors were studied as economical methods for treatment in the Wet Weather Management Plan [13]. Bioreactors are used for single onsite sanitary discharge point treatment and they treat influent quickly [14]. They have the ability to produce effluent with low biological oxygen demand (BOD) and total suspended solids values and operate under varying hydraulic conditions [15]. Fixed media reactors are also readily accessible for monitoring and maintenance [16]. They have another important aspect that they can be reused and have stable effluent quality shortly after a long rest time without wastewater loading [12]. The other positive aspect of bioreactor is high treatment efficiency with relatively low maintenance [12].

Lance et al. [17] expounded that virus may get adsorbed to the soils surface. This may improve virus survival time [10]. Virus adsorption may decrease with soil becoming alkaline [10,17]. An acidic soil condition favours virus adsorption [10]. Isoelectric point or pH below it is found suitable for virus adsorption [10,17]. Soil particles with negative charge at this pH may also influence adsorption positively [10]. Similarly, increase in flow rate may results in proportional decrease in virus retention [17]. Therefore, it is important to study how the variation in pH, flow rate and electrical conductivity may influence wastewater treatment.

The above review of literature presents insight on the interdependence of depth, flow rate, biomass content, electric conductivity and material characteristics while analysing the problems of wastewater treatment using soils or porous materials in general.

Tao [13] has compared the treatment of sanitary onsite discharge with fixed media bioreactors. There bioreactors used five different media compositions, namely, textiles, sand, felt, felt/sand and peat/sand. Similarly, Gaur et al. [16] had studied treatment of turkey fat-containing effluent water in coarse sand and gravel/coarse sand bioreactors. These media compositions are cost effective since they are locally available, considered waste and are natural materials. More heterogeneous flows occur through gravel compared to sand due to dual gravel porosities [18]. For flow through aggregates does not follow Darcy's law [19]. Similar stacked bioreactors with aerobic–anaerobic layer integration may help in removal of more than 90% COD from wastewater as well as conserve space [20]. Fixed film reactors have also been studied for organic fat removal from slaughterhouse effluents similar to effluent used by Gaur et al. [16,21,22].

Textile felt does meagrely effect on flow rate but helps improving homogenization of flow near to the felt region and colloidal retention [18]. This is one of the reasons why waste textile felt acquired from the local tailor shops is used as a material. This would help in remediating the solid waste from these small textile establishments.

Layering of media can increase the filtering capacity of soil by decreasing the colloidal pollutant transfer [18]. Kavanagh [23] illustrates the use of similar layering materials including peat moss, wood chips among other materials for use in point of use treatment using composting toilets. Kavanagh discusses both hard wired and portable composting toilets [23]. Evaporation or separation of the liquids and microbial decomposition are the principles on which these systems work [23]. Ecolet™ toilets uses peat moss, water and soil mix as the media with a regular rotation of the whole volume [23]. Clivus Multrum™ toilet compost system uses plant materials such as tree bark, wood chips and earth with mechanized aeration and evaporation system to enhance treatment efficiency [23]. Here, addition of plant materials is performed after defecation. Similarly, SAWI™ biocom also uses dried wood bark as the media [23]. In India, where only 10% of the rural households have toilet facility, composting toilets are a promising option to stop open defecation [21]. In India, the Defence Research and Development organization has a similar system with microbes collected from Antarctica for waste degradation and a structure to help immobilization of microbes [24].

The article tries to assess the behaviour of change in pH of water flowing through a single media as well as layered media. In order to provide homogenization of flow, fibrous waste media is used at the top inlet of layered media columns [18]. Also an effort has been made to establish a mathematical model to predict the change in pH of water flowing through a porous layered media depending upon parameters like column height, electrical conductivity, flow rate and time [19]. Another aspect dealt here is the characterization of reactors in terms of variation of temperature with respect to column height of a media. The motivation is also derived from the fact that drier soils have larger adsorption capacities in column bioreactors [17]. There is an increase in retention time of wastewater in unsaturated or dry media that brings constituents closer to the porous media surface that leads to improvement in mechanical straining, and they also are responsible for better aerobic conditions [17]. Therefore, importance is provided to the property variations in the transition period from unsaturated or dry media condition to wet or saturated media condition.

2. Materials and experimental methodology

Acrylic transparent sheets of 2 mm thickness were sourced from a local vendor (Mayur Plastic Ltd, Jodhpur, India). These sheets were glued (water seal) to form columns of 10 × 10 cm cross-section and distinct column height of 30 cm (approximately 1 foot) and 15 cm, respectively, for each media. Fig. 1 shows a gravel column reactor used in the experiments. A peristaltic pump (Ravel Hiteks Pvt. Ltd, Chennai, India) RH-P100VS-100-PC is used for dosing influent water. The inlet and exit pipes of the peristaltic pump as illustrated in Fig. 2 were of 3 mm internal diameter.

The peristaltic pump extracts the water from the source using the inlet pipe. Water thus extracted is dosed on to the column reactor where the water is intended to flow downwards under the effect of gravity and infiltrates through the media in the reactor column. A table stand for supporting the acrylic column reactors was made. These carried a wooden base as shown and a white cloth mesh was at the lowest part of the media layer to prevent media from flowing off the reactor columns.

For data analysis, specific influent dosage rates of 10 and 50 ml/min have been used. Sawdust, Moringa oleifera, gravel and clay were the four different media tested. Acacia sawdust is procured from the waste of

Fig. 1. Thirty centimetre acrylic column filled with gravels of average size 6 mm.

local carpenter shop in Jodhpur. The size of the sawdust was controlled using a 1 mm sieve. About 21.19% wood used in Jodhpur is Acacia [25]. Acacia is cheaper than other wood varieties and hence, its sawdust is available here in this part of Rajasthan, India [25]. Sawdust is utilized due to its viability as a denitrifier [26]. The idea is that when such sawdust (or plant material) reactor column is used for sewage treatment denitrifying bacteria may feed on the sustainable carbon in the sawdust and use the nitrate content within the reactor for respiration [26]. Similarly, Moringa oleifera was selected due to its known water treatment properties as well as nitrate content [27]. It is obtained from the local vegetable market, Ratanada Circle in Jodhpur. Before using it in the reactor, it was smashed into sheets and dried at sunlight (approximately 50˚C on the soil surface for 3 d) such that no moisture is left. Drying is performed to make the Moringa sheets dark and dry which may increase treatment efficiency [23]. Further, they are washed to remove organic carbon present due to burning off in the sun. These were again dried at room temperature (27˚C) and cut in 3–4 cm sheets. These three steps of processing of Moringa are enumerated in Figs. 3–5.

Fig. 1 depicts a gravel reactor. The gravels were washed and then dried before using them in the reactor so that dusts attached with them get removed and does not interfere with electrokinetic properties of the reactor effluent.

Another organic material used was cloth taken from the waste of a local tailor shop in Jodhpur. These may contain cotton and fibre clothes (Fig. 6).

Another material tested is ball clay. It was procured from Ahmed & Co., a local vendor in Jodhpur, Rajasthan, India. The water after initial infiltration

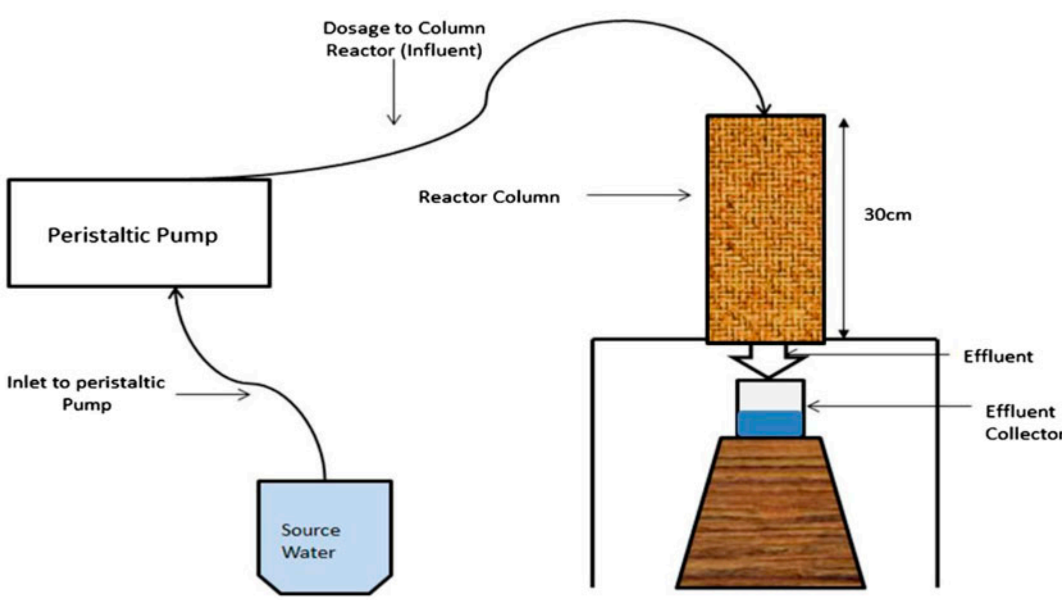

Fig. 2. The experimental set-up.

Fig. 3. Moringa oleifera or drumsticks sheets before drying.

Fig. 4. Moringa after drying.

through the dry clay column started to form effluent at 4.01 min. It took 2 h 35 min to saturate a clay column of 30 × 10 × 10 cm at a dosage rate of 10 ml/min when experiment was conducted as illustrated in Fig. 7. Clay acted as confining layer after saturation and negligible seepage took place through the column. Due to this, clay did not serve the purpose of a short residence time reactor column and hence will not be further discussed.

Therefore, sawdust, Moringa oleifera sheets, gravel and textile will be studied in this article. The reactor system is to be utilized for water purification. The mobility of ions determines conductivity. The degree of purification plays a major role in transport of ions. This means a pH change in influent and effluent water can help in study the transport of ions. The pH is measured using a pH meter pH700 (Eutech Instruments Inc.).

Fig. 5. Dark Moringa sheets in the reactor.

Fig. 6. Textile cloth pieces within the reactor.

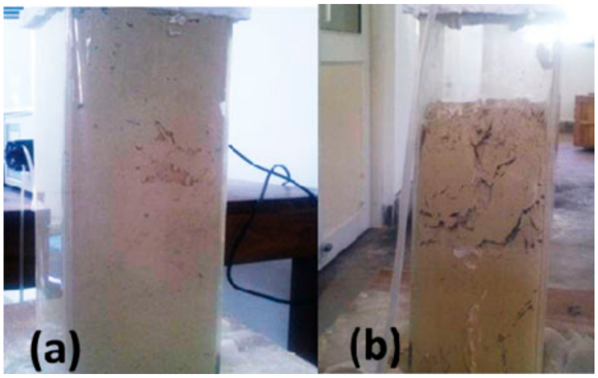

Fig. 7. Clay got saturated (a) and was transported downwards (b) (due to escape of air from the clay column).

Churaev [28] gave a linear relationship between molar fluxes as a function of pressure gradient and concentration. The material considered here show electrokinetic properties when they came in contact with water [28]. Molar fluxes are linear function of change in pressure gradient and change in electrical conductivity [29]. The irreversibility occurs due to ionic transport within a porous media occurring for a specified change of time [29]. This also means that a change in structure of the column due to a specific flow occurring for a specific time will change the transport of chemicals through material. The electrical conductivity change of the influent and effluent water with time will vary and is measured using CON700 (Eutech Instrument Inc.) probe. Further, for the analysis of COD, a thermoreactor Spectroquant TR 320 [Merck, Germany] has been used.

K-type thermocouples were used for the measurement of temperature. They were procured from Unitech Instrumentation, Mumbai. Real-time data of temperature are taken using NI Lab View 2011. Wireless Sensor Nodes 3212 and a Gateway (S. No. 1548d11 NI 9792) of NI for computer interface are used for the whole process of data acquisition. Fig. 8 illustrates how the thermocouples were inserted at different heights to measure the temperature gradient.

For any porous media, Darcy's Law states that flow rate (Q) is directly proportional to change in pressure head (ΔP), cross-section area of flow and inversely proportional to the length of the column [28]. This is valid as long as flow is laminar. Mathematically,

$$Q = -k\frac{\Delta PA}{L} \tag{1}$$

In this study, gravitational-layered flow reactor is considered. Therefore, the flow experiments conducted may basically illustrate irreversible nature. This also reiterates that the layered bioreactor will be deviating from the Darcy's relations [19].

Therefore, the main objective is to illustrate electrokinetic properties and temperature as a function of flow rate, length (here height of column) and also the time taken by water to make the dry or unsaturated columns wet or saturated.

2.1. Multi-parameter analysis

Water when percolating through the dry or unsaturated bioreactor undergoes random processes. For characterizing the random processes and variables, stochastic methods are incorporated [30]. The

Fig. 8. Thermocouples inserted in the multi-media-layered reactor.

bioreactor induces random changes in the properties of influent water percolating through the media within the acrylic columns of gravel, clay, sawdust and Moringa chips.

The electrokinetic properties of the water are given more importance since solute fluxes through a porous media depend on the pressure gradient, electrical conductivity change and ionic mobility. It is assumed that ionic mobility may be expressed in terms of pH change Y. Then [27,29,30],

$$Y = f(X_1, X_2, X_3, X_4) \tag{2}$$

where Y is parameter expressing change in pH of influent and effluent fluid and predictor variables, X_1 is parameter expressing column height, X_2 is the parameter expressing flow rate, X_3 is the parameter expressing cumulative time and X_4 is ΔEC that is parameter expressing change in electrical conductivity of influent and effluent fluid. It is observed that the units of each of these variables are different. Therefore, Y is again expressed as $\Delta pH/\Delta pH_{max}$, X_1 is h (cm)/h_{max} (cm), X_2 will be Q (ml/min)/Q_{max} (ml/min), X_3 is t/t_{max} and X_4 is $\Delta EC/\Delta EC_{max}$ [31].

$$\frac{\Delta pH}{\Delta pH_{max}} = \frac{h}{h_{max}} + \frac{Q}{Q_{max}} + \frac{t}{t_{max}} + \frac{\Delta EC}{\Delta EC_{max}} \quad (3)$$

Acrylic square base columns are filled with the selected media so that columns can act as a reactor. The column height is set. The experiments are performed with 10 ml/min and another one with 50 ml/min dosage rate of water, for individual columns of layered media [15]. All experiments were performed in a room maintained at a 32℃ temperature.

The effluent coming out is collected in the measuring beaker kept beneath as shown in Fig. 3. Samples of effluent are taken after every 50 ml initially and then 100 ml collection and time is also noted for each collection so that percolation rate can be measured. Approximately 30 readings of pH and conductivity are performed from the samples collected from time to time for each case studied here [15].

For the calculation of temperature gradient, thermocouples are inserted in the reactor and their real-time value is obtained using NI devices as shown in Fig. 9 [15]. The inlet water temperature was an average of 32℃ [17]. By changing the height and keeping the media same, water is dosed at two specific flow rates until the dry or unsaturated columns are wet or saturated by flowing water [15]. Similarly, same experiments are conducted for other media by changing height and flow rate [15].

3. Results and discussion

The improvement in for the 15-cm-deep cloth-only column is reported in Fig. 9 [15].

The fall in electrical conductivity is noted during the improvement of the pH of the effluent. This is observed from Fig. 10 [15].

A large gradient of pH was registered when water percolated through a 30 cm column compared to a 15 cm column. This is observed clearly from Figs. 9 and 11. The electrical conductivity of the reactor effluent dropped with time.

Similar behaviour as observed in Figs. 9 and 13 are observed for 15 cm cloth column and 50 and 10 ml/min dose of water, respectively. The variations do occur with the change in size of the column. These variations are tabulated and change in pH is predicted as a function of X_1, X_2, X_3 and X_4 in case of cloth-based bioreactor column are expressed as shown in Table 1 following Eq. (3).

Table 1 shows the step-by-step improvement in prediction with increasing predictor variables and decreasing error S of the model. This table may be used as a mathematical tool to show the improvement in R^2 values only with addition of multi-variables but not for the actual regression [24]. Therefore, the correlations between the multi-variables are removed by differentiating the correlation matrix to eigenvalue and eigenvector matrices [24]. This operation on the correlation matrix provides a new matrix with a diagonal unit matrix and uncorrelated multi-variables [27,28]. Regression is performed using these new uncorrelated variables and pH change is obtained as function of uncorrelated variables as:

$$Y = 0.609 - 0.116V_h + 0.205V_q + 0.160V_t - 0.350V_{\Delta EC} \quad (4)$$

where V_h, V_q, V_t and $V_{\Delta EC}$ are uncorrelated variables representing parameters of reactor column height, flow rate, cumulative time and change in electrical conductivity. The prediction model in Eq. (4) has a coefficient of determination of R^2 = 82.9 and error in prediction to be around 0.161. This procedure will be repeated in this article as when the need for regression arises and will be applied to find the new independent variable V_i from the X_i variables [27,29].

Similar analysis performed with cloth column is performed for columns with Moringa chips. The Moringa column had a prominent influence on the alkalinity of the effluent water. It is to be noted that organic molecules from the Moringa mix with water to produce acidity in the effluent, which is the reason for the pH of the range observed in Figs. 14 and 15. The electrical conductivity is seen to decrease with time in both the cases enumerated here.

The experimental data enumerated in Figs. 14 and 15 are tabulated according to the required statistical design for performing the variance analysis and regression. Table 2 enumerated the improvement of coefficient of determination while predicting the change in pH between the influent and effluents while water was passed through Moringa chip columns.

Regression is performed using these new uncorrelated variables and pH change in Moringa chip columns is obtained as function of uncorrelated variables as:

$$Y = \Delta pH = 2.79 - 0.0363V_h - 0.232V_q + 0.243V_t + 0.536V_{\Delta EC} \quad (5)$$

Eq. (5) models the change in pH with a modelling error of S = 0.0863858 *and its coefficient of determination is* R^2 94.3%. Here, V_h, V_q, V_t and $V_{\Delta EC}$ are uncorrelated variables representing parameters of reactor col-

Table 1
The summary of constants a, b_1, b_2, b_3 and b_4, coefficient determination R^2 and error S of the model for clothes using correlated parameters [15]

Predictor variables	a	b_1	b_2	b_3	b_4	R^2	S
X_1	−0.079	0.0344				42.6	0.28
X_2	−0.485	0.0359	0.0192			73.1	0.1984
X_3	−0.309	0.0327	0.0180	−0.00236		75.1	0.1924
X_4	−1.12	0.504	0.0168	0.00326	−0.188	82.9	0.1611

Table 2
The summary of constants a, b_1, b_2, b_3 and b_4, coefficient determination R^2 and error S of the model for Moringa column reactors [15]

Predictor variables	a	b_1	b_2	b_3	b_4	R^2	S
X_1	1.80	0.0427				90.4	0.1068
X_2	1.75	0.0416	0.00116			92.3	0.0971
X_3	1.84	0.0405	0.00349	−0.00223		92.6	0.0966
X_4	1.83	0.0682	0.00457	−0.00512	0.0137	94.3	0.0863

umn height, flow rate, cumulative time and change in electrical conductivity, respectively.

The variation of pH and electrical conductivity with time through different gravel reactor columns is illustrated from Figs. 16 to 21. The regression analysis for the prediction of change in pH as a function of flow rate, change in electrical conductivity, size of the reactor columns and time with gravels as a reactor media is shown in Table 3 and Eq. (6). The coefficient of prediction in case a gravel-based column reactor is low. Column height, inflow rate, time and electrical conductivity do not influence the development of change in pH of water passing through the gravel column. This also reiterates the fact that gravels will not be following Darcy's law [19]. Gravels treat the effluent water as a point source and may divert the flow through a specific path. This phenomenon will allow wetting of a portion of the gravel column; thus, preventing homogenous interactions of water and the overall volume of the gravel reactor. This is also observed from the Fig. 1 which shows specific surface wetting by the water percolating through the gravel column.

$$\begin{aligned} Y = \Delta \mathrm{pH} \\ &= -0.0878 - 0.0262V_{\mathrm{h}} - 0.122V_{\mathrm{q}} - 0.0830V_{\mathrm{t}} \\ &\quad - 0.179V_{\Delta \mathrm{EC}} \end{aligned} \tag{6}$$

Eq. (6) predicts with an error of S = 0.1386 and coefficient of determination R^2 = 57.6%. Here, V_{h}, V_{q}, V_{t} and $V_{\Delta \mathrm{EC}}$ are uncorrelated variables representing parameters of reactor column height, flow rate, cumulative time and change in electrical conductivity, respectively. The formalization of the models derived in the Eqs. (4–6) can be performed. From the data available from Figs. 9 to 21, the influence of Moringa, cloth and gravel on the percolation can be individually assessed. In order to bring this influence into effect an extension of the models in Tables 1–3 is sought. The new expression will be derived as:

$$Y = \Delta \mathrm{pH} = a + b_1X_{\mathrm{h}} + b_2X_{\mathrm{q}} + b_3X_{\mathrm{t}} + b_4X_{\Delta \mathrm{EC}} + b_5X_{\mathrm{QC}} \tag{7}$$

Table 3
The summary of constants a, b_1, b_2, b_3 and b_4, coefficient determination R^2 and error S of the model for gravel [15]

Predictor variables	a	b_1	b_2	b_3	b_4	R^2	S
X_1, X_2, X_3, X_4	0.570	−0.0168	−0.00494	−0.00363	−0.0114	57.6	0.13856

where X_{QC} = constant (a in Table 1, a in Table 2 and a in Table 3) × X_q [32]. The other variables are column height (X_h), flow rate (X_q), cumulative time (X_t) and change in electrical conductivity (X_{EC}). This procedure of espousing new parameter for enumerating material effect was illustrated by Soboyejo et al. [32]. This framework is helpful in the design and selection of newer materials irrespective of the materials presented in this article for manufacture of bioreactor [32]. Following the same theory as stated in Eqs. (2) and (3), the change in pH is modelled as a function of $X_{1,}$ column height (X_h), X_2 flow rate (X_q), X_3 cumulative time (X_t) and X_4 change in electrical conductivity (X_{EC}) and X_5 is X_{QC}/X_{QCmax} in Table 4. The prediction is having a coefficient of determination of 89.8% and an error of 0.353.

Eq. (8) is a new multi-parameter multivariate stochastic equation which can be used for characterizing the electrokinetic behaviour of any bioreactor irrespective of the material. This equation also represents the prediction of the variation in pH as a function of independent process parameters of bioreactor column height, flow rate, cumulative time, electrical conductivity and a parameter presenting the material effect.

$$Y = \Delta\text{pH} = 0.7578 + 0.63V_h - 0.366V_q + 0.18V_t - 0.53V_{\Delta EC} - 0.21V_{QC} \quad (8)$$

Eq. (8) has an error of the model, S = 0.353 and coefficient of determination R^2 = 89.8%. Here, V_h, V_q, V_t $V_{\Delta EC}$ and V_{QC} are uncorrelated variables representing parameters of reactor column height, flow rate, cumulative time and change in electrical conductivity, respectively. The coefficient of determination is found to be good enough to provide accurate results with a very small error of the model S.

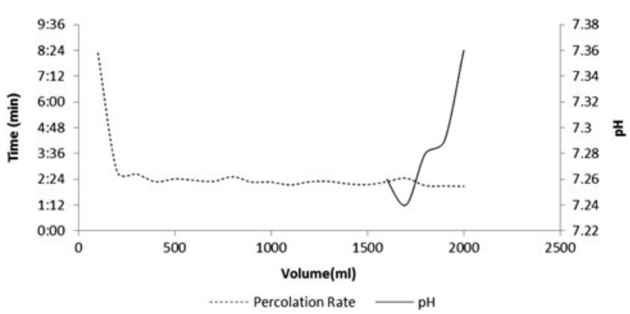

Fig. 9. The change in pH of the effluent with time in the 15 cm cloth column when water is dosed at 50 ml/min [15].

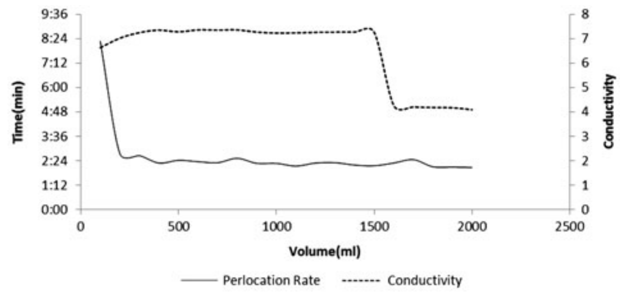

Fig. 10. The change in electrical conductivity of the effluent with time in the 15 cm cloth column when water is dosed at 50 ml/min [15].

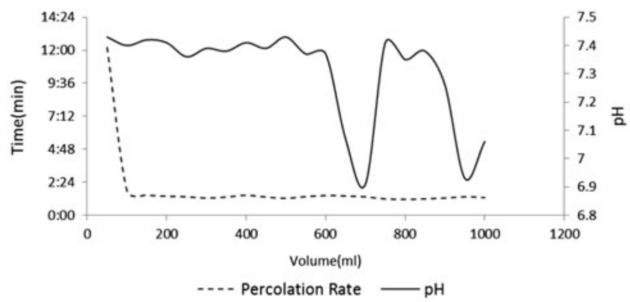

Fig. 11. The change in pH of the effluent with time in the 30 cm cloth column when water is dosed at 50 ml/min [15].

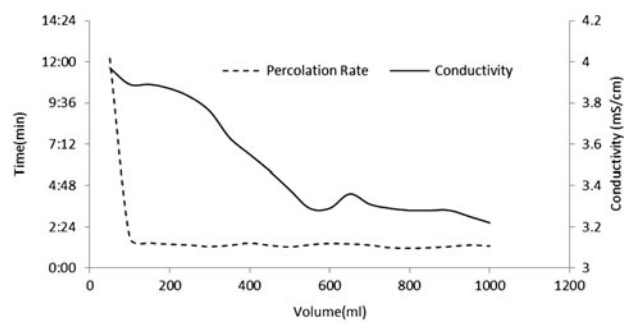

Fig. 12. The change in electrical conductivity of the effluent with time in the 30 cm cloth column when water us dosed at 50 ml/min [15].

4. Temperature analysis

Kang et al. [33] demonstrated the treatment of turkey fat effluent using sand bioreactor which included a pea gravel layer supporting coarse sand and fine sand layers stacked one over the other. They also proposed low loading rates to optimize treatment [33]. The treatment by the sand bioreactor columns was reported to be highest within a week [33]. More than

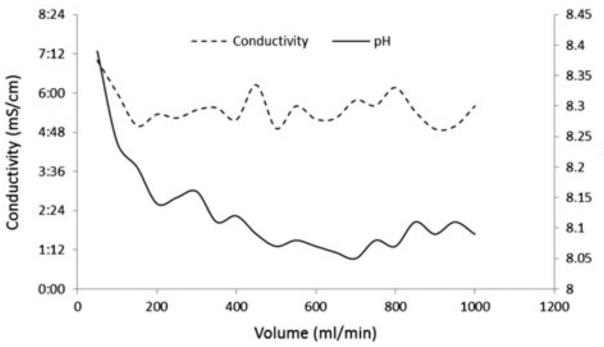

Fig. 13. The change in electrical conductivity of the effluent with time in a 15 cm cloth column when water is dozed at 10 ml/min [15].

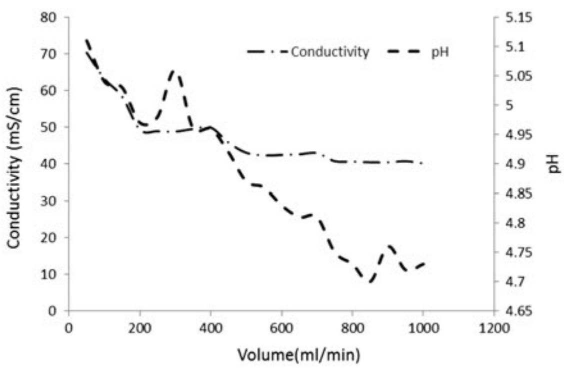

Fig. 14. The variation of pH and electrical conductivity in the effluent from the Moringa column of 50 cm when the dosage rate of water is 10 ml/min.

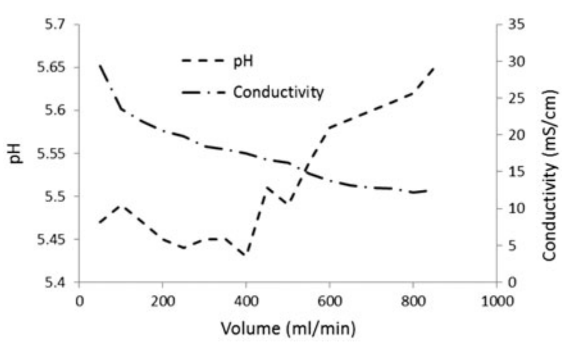

Fig. 15. The variation in pH and electrical conductivity through a 15 cm Moringa column dosed with water at 10 ml/min.

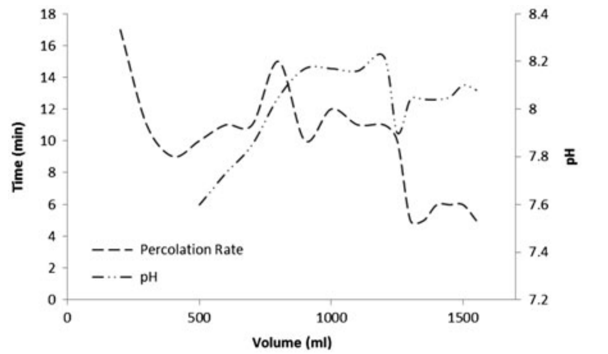

Fig. 16. The change in pH of the effluent with time in the 30 cm gravel column when water is dosed at 10 ml/min [15].

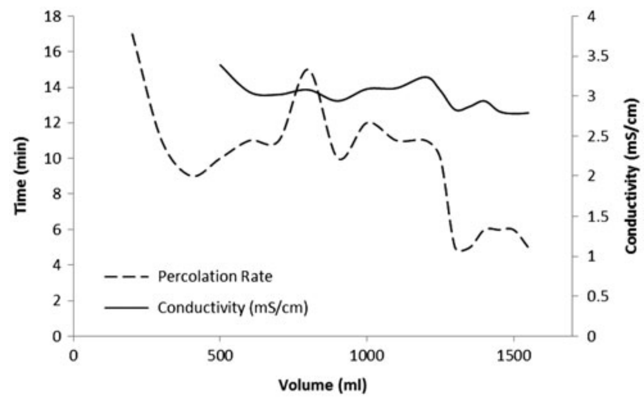

Fig. 17. The change in electrical conductivity of the effluent with time in the 30 cm gravel column when water is dosed at 10 ml/min [15].

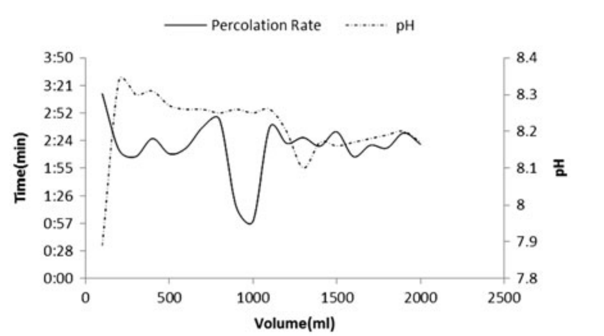

Fig. 18. The change in pH of the effluent with time in the 15 cm gravel column when water is dosed at 50 ml/min [15].

90% removal rate of total organic carbon and BOD was reported throughout two and a half month period of operation of the sand bioreactors [33].

Porous media with water in contact is characterized by thermo-osmosis [25,26]. This is movement of ions due to change in thermal energy or temperature

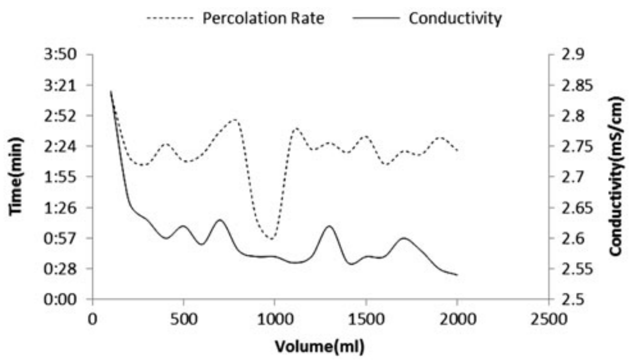

Fig. 19. The change in electrical conductivity of the effluent with time in the 15 cm gravel column when water is dosed at 50 ml/min [15].

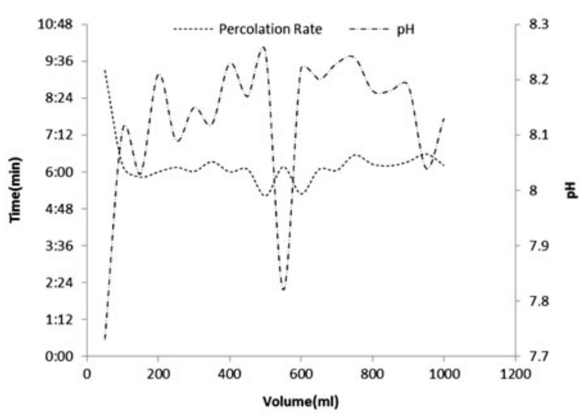

Fig. 20. The change in pH of the effluent with time in the 15 cm gravel column when water is dosed at 10 ml/min [15].

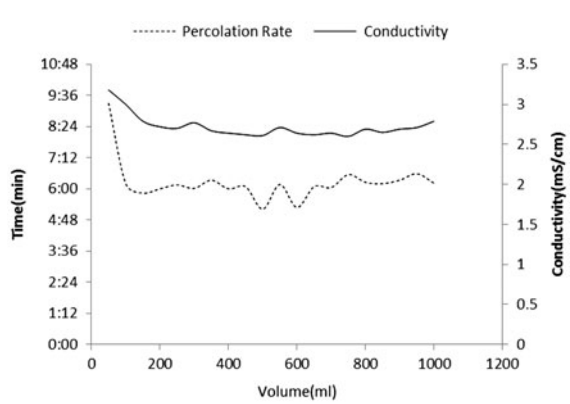

Fig. 21. The change in electrical conductivity of the effluent with time in the 15 cm gravel column when water is dosed at 10 ml/min [15].

of the environment [25]. Fig. 22 provides the variation of temperature measure from top to bottom of the gravel reactor using thermocouples TC0, TC1, TC2, TC3, 2TC0, 2TC1, 2TC2, 3TC0, 3TC1, 3TC2 and 3TC3 within the reactor at different heights 2, 4.5, 6, 8, 12, 14, 18, 20, 24, 26 and 28 cm, respectively. Fig. 22 shows a decrease in temperature moving down the gravel reactor with time.

The trend followed by gravel bioreactors for temperature change is assumed to be very similar to the overall behaviour of the temperature distribution characteristics which other bioreactors may follow.

Fig. 23 illustrates a temperature variation as a function of height for a fully wet gravel reactor of 30 cm height. It can be easily observed that gravel temperature at a specific height follow a distinctly different family of temperature distribution curves characteristic to the properties of the material at the location. This would also means that temperature change within a specific heterogeneous media column like gravel or soil may not have much influence on the temperature change at a different location within the same column when water transport occurs through it. This phenomenon may also be observed in larger systems such as the layers in the Earth’s crust.

This nonlinear relationship for phenomena observed as shown in Figs. 22 and 23 can be expressed as [27,34–36]:

$$Y_i = \frac{X_i}{(a_i + b_i X_i)} \tag{9}$$

Here, Y_i represents the temperature within in the bioreactor recorded at distinct heights. The heights are 2, 4.5, 6, 8, 12, 14, 18, 20, 24, 26 and 28 cm, respectively, for gravel or any porous media. In this case, X_i represents the variable of time t_i. Using, the present scenario Eq. (9) is rewritten as:

$$T_i = \frac{t_i}{(a_i + b_i t_i)} \tag{10}$$

where T_i = Temperature in ℃, t_i = time in s. Eq. (10) can also be rephrased as:

$$Z = \frac{t_i}{T_i} = (a_i + b_i t_i) \tag{11}$$

According to Eq. (11) the following data (from Figs. 22 and 23) analysis of the gravel bioreactor helps in the development of the model as illustrated in Eq. (11) for

Table 4
The summary of constants a, b_1, b_2, b_3, b_4 and b_5 coefficient determination R^2 and error S of the general model for any treatment media

Predictor variables	a	b_1	b_2	b_3	b_4	b_5	R^2	S
X_1	−0.102	0.0415					7.2	1.051
X_2	−0.252	0.0315	0.0035				29.3	0.922
X_3	−0.9	0.430	0.0029	0.0079			39.9	0.853
X_4	0.13	−0.004	0.0023	0.0011	−0.060		85.0	0.419
X_5	0.41	−0.0085	0.0033	−0.0023	−0.049	0.0014	89.8	0.353

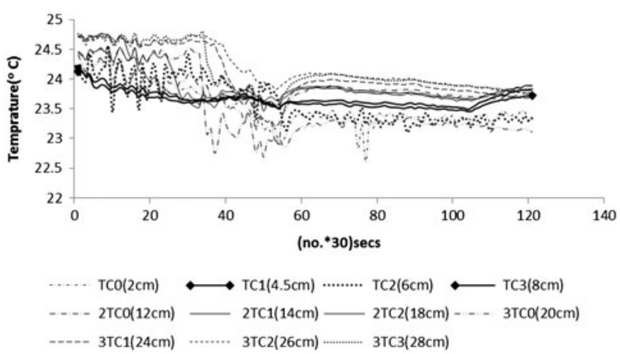

Fig. 22. A decreasing trend in temperatures within the 30 cm gravel reactors with time in the 50 ml/min rate of flow.

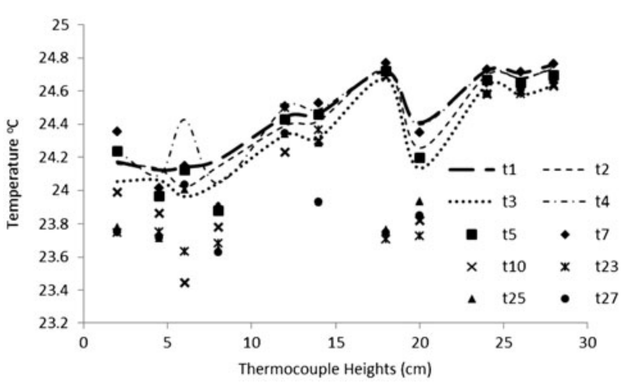

Fig. 23. Reactor temperature distribution as a function of time in a 30 cm gravel column when dosed with water at a rate of 50 ml/min.

30 cm gravel column dosed with 10 ml/min of influent water. This formulation is presented in Table 5.

In order to test the reproducibility of the model in Eq. (11) and analysed in Table 5, another test of water percolation through a 30 cm Acacia sawdust porous column is carried out. The temperature variation is again measured using thermocouples at different

Table 5
The summary of constants a, b_1, coefficient of determination R^2 and error S of the fit for Eq. (11) for gravels at an experimental dosage rate of 50 ml/min

Predictor variables	a	b_1	R^2	S
t_i	−0.245	0.0420	99.9	0.5149

heights 2, 4.5, 6, 8, 12, 14, 18, 20, 24, 26 and 28 cm, respectively.

The variation in the temperature during percolation through this sawdust column is illustrated in Fig. 24.

Table 6 illustrates Eq. (11) fit for 30 cm saw dust column dosed with influent water at 50 ml/min. Table 6 also enumerates a good prediction of the change in temperature within the column. This enumerates that the model in Eq. (11) can be used for a general heterogeneous porous media column used in treatment of wastewater.

A similar equally spaced layered stacked combination of the materials used in the manufacture of the layered reactor is elaborated in Fig. 8. From the above discussion, the Moringa is found to be the dark

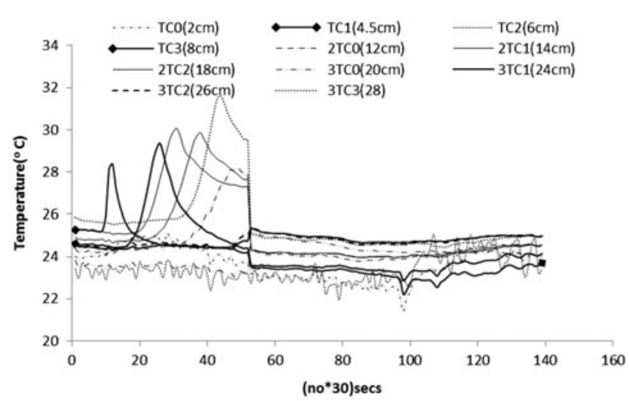

Fig. 24. Temperature variation through the 30 cm sawdust column dosed with water at 50 ml/min.

Table 6
The summary of constants a, b_1, coefficient of determination R^2 and error S of the general model for sawdust at an experimental dosage rate of 50 ml/min

Predictor variables	a	b_1	R^2	S
t_i	0.489	0.390	98.2	1.85

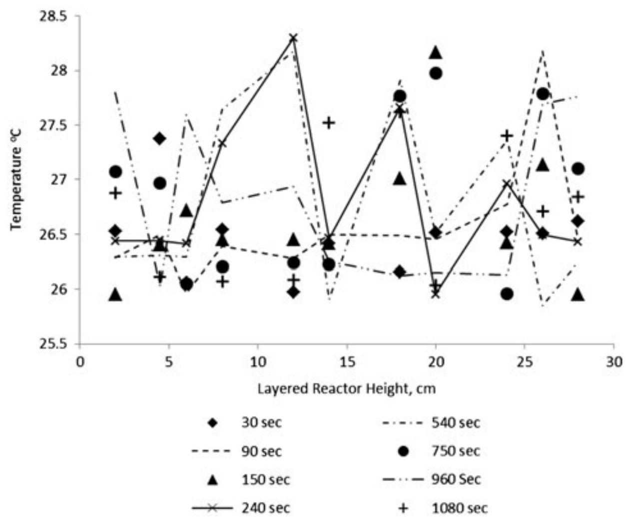

Fig. 25. The variation in temperature with time at different heights during a saturated flow event (50 ml/min) through the bioreactor.

organic material which would help in providing the zone of breakdown and location for microbial development. Cloths are stacked below the Moringa and are good enough to prevent or resist the mobility of microbes. This is because cloths or textile materials can help filter microbes [37]. This will help in the containing the growth of microbes at the top most layer where probable deposition of organic waste materials is conceived. The gravel is used as a support as well as a media forming the base of the column. Gravel column is structured with the same dimensions as Moringa and cloth columns. This would mean that 10 cm of Moringa is placed over a 10 cm layer of cloth which is again supported by a 10 cm gravel layer. Thermocouple-based temperature measurement at different heights of this layered reactor shown in Fig. 8 is illustrated in Fig. 25. A repeated crest and trough

Table 7
The summary of constants a, b_1, coefficient of determination R^2 and error S for Eq. (11) fit for the temperature variations within the layered media enumerated in Fig. 25

Predictor variables	a	b_1	R^2	S
t_i	−0.0855	0.0375	99.7	0.6503

pattern of variation of temperature is observed within each 10 cm of the bioreactor column.

Eq. (11) is again put into use to model the flow occurring within this layered bioreactor. The value of the coefficient of determination and low error in the model illustrated in Table 7 suggest better predictability and accuracy for the model. This also provides a better framework to characterize and model the heterogeneous bioreactor manufactured with different layers of materials. This framework also provides a single equation to characterize bioreactor column behaviour as a function of time.

5. Conclusion

The electrokinetic characteristics of water passing through different material reactor columns are experimentally studied. Size effects of the bioreactor columns were also studied. A new relationship has been derived to predict the change in pH of water flowing through a porous media. From Eq. (4), it is found that textile or cloth fabric helped in the reduction of electrical conductivity and pH in the effluent water. Dark Moringa sheets helped provide an acidic environment within the reactor. This was reiterated by the fact that the increasing height of the Moringa column had a negative influence on the development of change in pH within the column. From Eq. (6), it was observed that water chemistry did not vary much during its transport through a media of gravels. An additional new multi-parameter model Eq. (8) was developed which helped to include the effect of any specific porous material treatment bioreactor on the prediction of the final chemistry of the effluent-treated water.

Temperature variation within reactors can be predicted with good accuracy as a function of time. This new relationship will provide new pathways to theoretically and empirically characterize reactors and also bioreactors used in wastewater treatment.

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