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ORIGINAL PAPER

Oxygen transfer and hydrodynamic evaluation in a multistage flexible fibre biofilm reactor

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Abstract
In present work, the hydrodynamic studies and determination of oxygen mass transfer coefficients (K_La) were conducted in a multistage flexible fibre biofilm reactor developed for treating milk processing wastewater. In this regard, the residence time distributions in the MS-FFBR under various operating conditions as water flow rates, airflow rates, and hydraulic retention times were analysed using tracer experiments. The results revealed that the reactor's hydraulic regime is similar to a continuous stirred tank reactor. Furthermore, the multistage flexible fibre biofilm reactor exhibited a lower oxygen mass transfer coefficient (K_La of 11.955 1/h at AFR/WFR of 47) than that reported for continuous stirred tank reactor in the literature at similar WFRs and AFRs (K_La of 15 1/h at AFR/WFR of 40). From the results, dissolved oxygen transfer was hindered to some extent owing to the presence of the fibre packing.

Keywords Hydrodynamics · Multistage flexible fibre bioreactor · Oxygen mass transfer coefficient

Introduction

The management and treatment of industrial wastewaters containing high organic contents is a major environmental challenge. For example, milk processing wastewater (MPW) contains high amounts of organic matter, nutrients, solids, and detergents originated from sanitization and cleaning processes (Liu and Haynes 2010; Andrade et al. 2014; Rahimi et al. 2016). The release of such wastewaters without proper treatment into the receiving water sources causes deteriorative effects like eutrophication phenomenon, oxygen depletion, and ammonia toxicity (Buabeng-Baidoo et al. 2017). Therefore, the treatment of MPW is of great significance to reduce its adverse effects on human life and the environment. Various biological treatment technologies that were recently employed for the treatment of such a high strength wastewater (Rezaee et al. 2015; Asadi et al. 2016; Rahimi et al. 2016; Abdulgader et al. 2019, 2020a; b). Some of the high rate biological treatment technologies applied to treat the high strength wastewaters include up-flow anaerobic, anoxic and oxic (A2O) bioreactor; up-flow aerobic–anoxic flocculated sludge bioreactor (UAASB); up-flow aerobic/anoxic sludge bed (UAASB) bioreactor; and hybrid airlift bioreactor (HALBR) (Asadi et al. 2012; Amini et al. 2013; Abyar et al. 2018; Mirghorayshi et al. 2021).

Overall, aerobic biological treatment technology could be made more cost-effective by reducing the energy consumption in aeration processes (Longo et al. 2016). In this aspect, the oxygen mass transfer from the gas phase into the liquid phase as well as the flow hydrodynamics plays significant roles in the efficient performance of aerobic biological wastewater treatment systems (Chen et al. 2009). Due to the importance of these factors, much effort has been dedicated to the study of hydrodynamic and the determination of oxygen mass transfer

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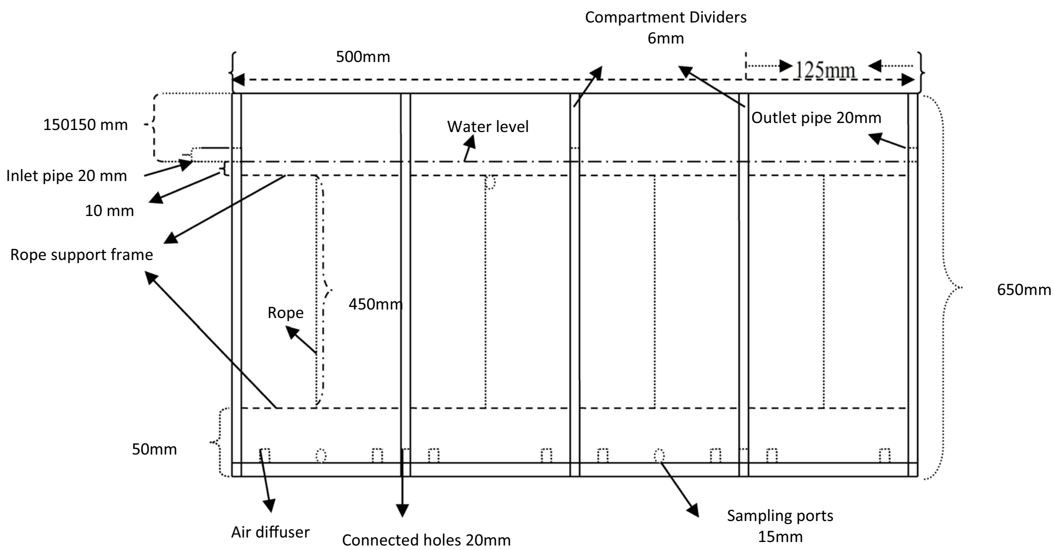
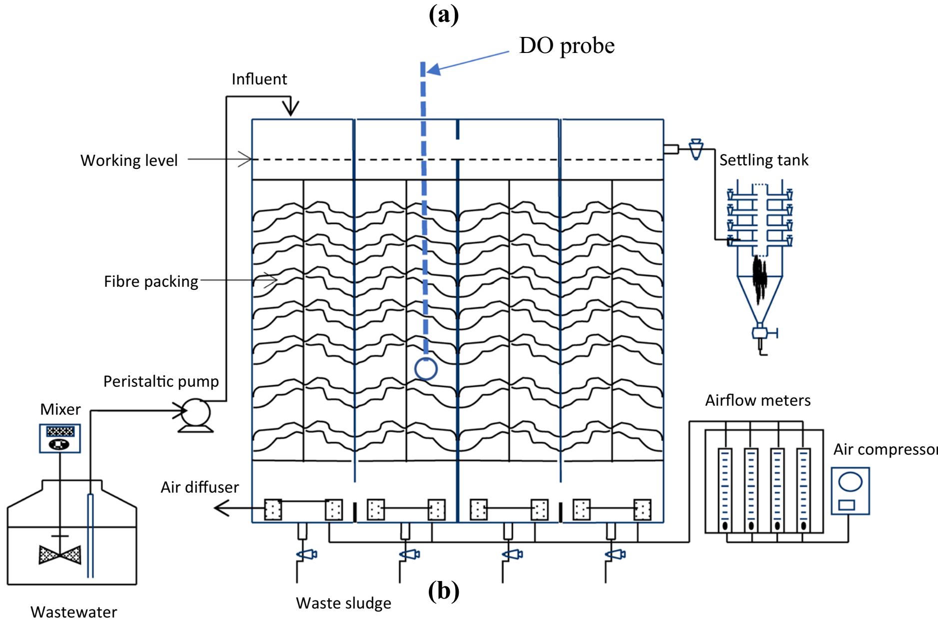
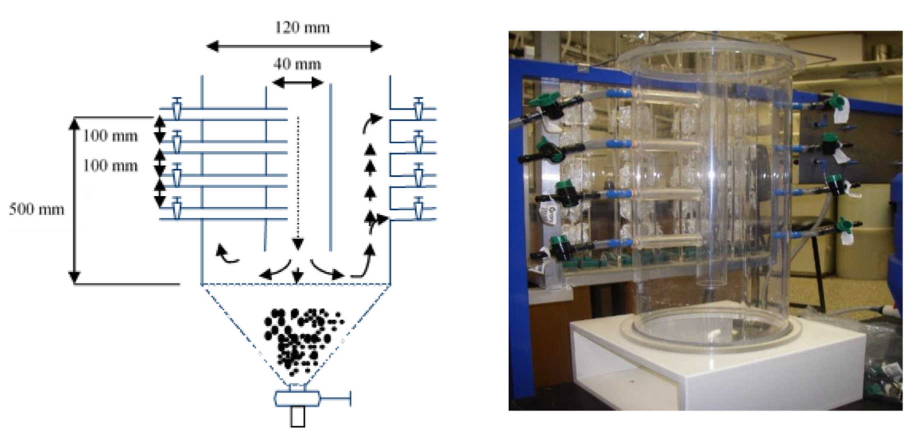

Compartment Dividers
6mm
500mm
125mm
150150 mm
Water level
Outlet pipe 20mm
Inlet pipe 20 mm
10 mm
Rope support frame
Rope
450mm
650mm
50mm
Air diffuser
Connected holes 20mm
Sampling ports
15mm

(a)


DO probe
Influent
Working level
Settling tank
Fibre packing
Peristaltic pump
Mixer
Airflow meters
Air compressor
Air diffuser
Wastewater
Waste sludge

(b)


120 mm
40 mm
100 mm
100 mm
500 mm

(c)

◂**Fig. 1** **a** Construction details of MS-FFBR; **b** schematic diagram of MS-FFBR experimental setup; and **c** schematic diagram (left) and experimental setup (right) of settling tank designed in this study

coefficients in various biological systems (Chen et al. 2009; Luo et al. 2011; Lei and Ni 2014; Dias et al. 2018).

Biofilm reactors or attached growth systems are known as cost-effective systems and hence are increasingly used in industrial wastewater treatment processes. For instance, submerged aerated filters, moving bed biofilm reactors, integrated fixed-film activated sludge and flexible fibre biofilm reactors are some of the biofilm reactors utilized in wastewater treatment (Rusten et al. 1992; Malovanyy et al. 2015; Abdulgader et al. 2020a). Biofilm reactors support and allow microorganisms to grow on carrier media, thereby, promote high biomass retention, prevent washout, and enhance the development of slow-growing bacteria. Furthermore, attached growth systems maximize the loading capacity and treatment efficiency when compared to the activated sludge process (ASP) at decreased footprints (McQuarrie and Boltz 2011).

Compared to other biofilm reactors, flexible fibre biofilm reactor (FFBR) has further advantages such as lower capital costs, higher resistance towards organic loading shocks and biofilm clogging, and easier control of effluent quality (Chen et al. 2009). Therefore, the FFBR has been employed extensively to treat high strength food processing wastewaters (Yu et al. 2003; Abdulgader et al. 2009, 2020a, b). Recently, we investigated the functionality of the FFBR in various configurations as single-stage flexible fibre biofilm reactor (SS-FFBR), sequencing batch flexible fibre biofilm reactor (SB-FFBR), multistage flexible fibre biofilm reactor (MS-FFBR) for treating the milk processing wastewater under different operating and process conditions (Abdulgader et al. 2019, 2020a, 2021; b).

The evaluation of hydrodynamics and determination of oxygen mass transfer coefficient in a single-stage FFBR has been carried out (Chen et al. 2009). In this research, hydrodynamic behaviour was studied to determine oxygen mass transfer coefficient in a multistage flexible fibre biofilm reactor (MS-FFBR). The effects of three operating parameters, hydraulic retention time (HRT), airflow rate (AFR, Q_G) and water flow rate (WFR, Q_L) were studied to investigate the hydrodynamics and oxygen transfer efficiency. Tracer experiments were also carried out to determine mean residence time distribution in the MS-FFBR. This study was conducted in January 2010 at Griffith University, Australia.

Materials and methods

Bioreactor description

In this research, a laboratory-scale multistage flexible fibre biofilm reactor was made of acrylic (Perspex) with thickness and dimensions of 6 mm and 500 * 125 * 650 mm, respectively, for the treatment of the actual milk processing wastewater. The characteristics of the wastewater used are given in our previously published paper (Abdulgader et al. 2020a). The reactor was divided into four compartments (stages) with equal sizes by means of baffles. The total and working volumes of the reactor were 40.6 and 32 L, respectively. The oxygen was introduced into the reactor using two identical air diffusers for the supply of required dissolved oxygen (DO) levels and adequate mixing. The airflow rate (AFR) was monitored in situ with airflow meters. The reactor was followed by a cylindrical-shaped settling tank in order to settle suspended solids (SS) washed out from the reactor and get a clear effluent. The total volume of the settling tank was 12.5 L. A schematic diagram of the experimental apparatus is delineated in Fig. 1. A seven-flexible fibre bundle was placed in all four compartments of the reactor. Details regarding the characteristics of the flexible fibre used in this research can be found elsewhere (Abdulgader et al. 2019).

Residence time distribution

The residence time distribution was determined using tracer tests. The tracer test is commonly conducted to investigate the hydraulic performance of bioreactors. This test is usually done by pulse input or C-curve and F-curve inputs.

In the C-curve test, to evaluate and understand the hydraulic characteristics of multiple reactors in series, a tracer was instantaneously introduced in the first stage of the reactor. The experiment was conducted at hydraulic retention times (HRTs) of 2, 4 and 8 h, corresponding to water flow rates (WFRs, Q_L) of 271, 135, and 68 mL/min, respectively. In addition, the airflow rate (AFR, Q_G) was controlled at 564, 270, and 135 mL/min at HRTs of 2, 4, and 8 h, respectively. Based on predetermined values of AFRs and HRTs, the ratio of the airflow rate to water flow rate (AFR/WFR) was kept 2 in all experiments. A solution of food dyes was pulsed into the influent stream as a tracer. For a completely mixed reactor in series, the theoretical mean residence time was calculated using the following equation (Levenspiel 1999; Metcalf 2003):

$$E(t) = \frac{t^{n-1}}{(n-1)\tau_{i\cdot}^{n}} e^{-\theta_i} \tag{1}$$

where $E(t)$ is the residence time distribution in one reactor, $\theta_i = \frac{t}{Nt_i}$ is mean residence time in the N reactor, τ is theoretical hydraulic residence time, and N is the number of reactors.

In the F-curve test, a dye solution as tracer with initial concentration of C_0 was continuously injected to the reactor. This test was conducted at constant AFR of 807 mL/min and HRTs of 4 and 8 h corresponding to the AFR/WFR ratios of 6 and 11.8, respectively. The tracer response curve is determined as C/C_0. It should be noted that the theoretical mean residence time can be obtained from the F-curve by integrating Eq. 1.

The reactor was free of any suspended materials such as microorganisms during tracer experiments. The dye concentration of effluent samples was measured by using an absorbance of UV–Vis spectrophotometer at a wavelength of 629 µm (Shimadzu Corporation, UV 1601).

Determination of oxygen mass transfer coefficient

To estimate the capability of dissolved oxygen mass transfer into the bulk water phase in the MS-FFBR, the oxygen mass transfer coefficient ($K_L a$) was measured by using clean tap water. The oxygen transfer rate was determined by direct measurement of the rate of the increase in the dissolved oxygen (DO) concentration in the reactor. Then, the DO concentration was decreased by passing pure nitrogen gas into a mixer equipped wastewater tank to nearly zero. The reactor was aerated through the air sparger mounted at the bottom of the reactor. Simultaneously, water was introduced into the reactor by a peristaltic pump at water flow rate (WFR, Q_L) of 1.0178 L/h and HRT of 8 h. The experiments were conducted at airflow rates (AFRs, Q_G) of 15, 48.2, 94.5, 142.4, 190, and 239.8 L/h, which corresponded to the AFR/WFR ratios of 15, 47, 93, 140, 187, and 235, respectively. The dissolved oxygen (DO) concentration in the reactor was recorded with a DO meter at intervals of every 20 s. The oxygen mass transfer coefficient was quantified by the equation below (Amaral et al. 2008).

$$\text{In}\frac{C_s - C_0}{C_s - C} = \left(\frac{Q_L}{V} + K_L a\right)\left(t - t_0\right) \tag{2}$$

where $K_L a$ is the overall mass transfer coefficient (1/h), C_s is dissolved oxygen saturation concentration at the test temperature (20 °C) and pressure (1.01325×10^5 Pa) (mg/L), C is DO concentration at time t (mg/L), t_0 is initial time (h), t is time (h), and Q_L and V are the water flow rate (m^3/h) and the volume of the reactor (m^3), respectively.

This experiment was conducted at a water flow rate (WFR, Q_L) of 1.0178 L/h and a reactor volume of 8 L. Hence, the value of Q_L/V was 0.127, which was much less than $K_L a$. Therefore, Eq. 2 can be simplified to the following equation:

$$\text{In}\frac{C_s - C_0}{C_s - C} = K_L a\left(t - t_0\right) \tag{3}$$

Plot of $t - t_0$ versus ln $(C_s - C_0)/(C_s - C)$ was drawn for the FFBR to obtain an overall oxygen mass transfer coefficient, $K_L a$, at different ratios of AFR/WFR. To determine the relationship between AFR/WFR ratio and the value of $K_L a$, a correction coefficient was considered.

Results and discussion

Distribution of hydraulic retention time in the MS-FFBR

In the C-curve method, a tracer was instantaneously added into the first stage of the reactor and the tracer concentration in the effluent was measured as a function of time. All the experimental results and theoretical data obtained from C-curve test are shown in Tables S1-3 (Supporting information). Figure 2 illustrates the experimental and theoretical results for the MS-FFBR (the whole bioreactor) as a function of time at HRT of 2, 4, and 8 h, respectively. The data showed almost complete tracer recovery at all conditions studied. The experimental data obtained at various HRTs are in close agreement with those achieved for completely mixed flow reactors. In addition, the data of the distribution of hydraulic retention time in the MS-FFBR were similar at various HRTs. Hence, HRT was not affected by the flexible fibre packing in the MS-FFBR, and in practice, the concerned reactor can be considered as a continuous stirred tank reactor (CSTR). The results of this work are in agreement with those reported by Yu et al. (2003), while Dias et al. (2018) in their study concluded the presence of packing media indicated a positive impact on the reactor effective volume.

The experimental data or calculated theoretical data achieved from F-curve are listed in Tables S4-6 (Supporting information). Moreover, Fig. 3 displays F-curve experimental and computed data at HRTs of 2, 4 and 8 h for the whole reactor. As can be seen from Fig. 3, the actual and theoretical data reported at HRT of 2 h are in close agreement. In contrast, the results at HRTs of 4 and 8 h exhibited some deviations. This was attributed to the insufficient sparging energy resulting from the airflow rate applied, so that the portions of the reactor contents may be unmixed with the incoming water with dead zones being developed inside

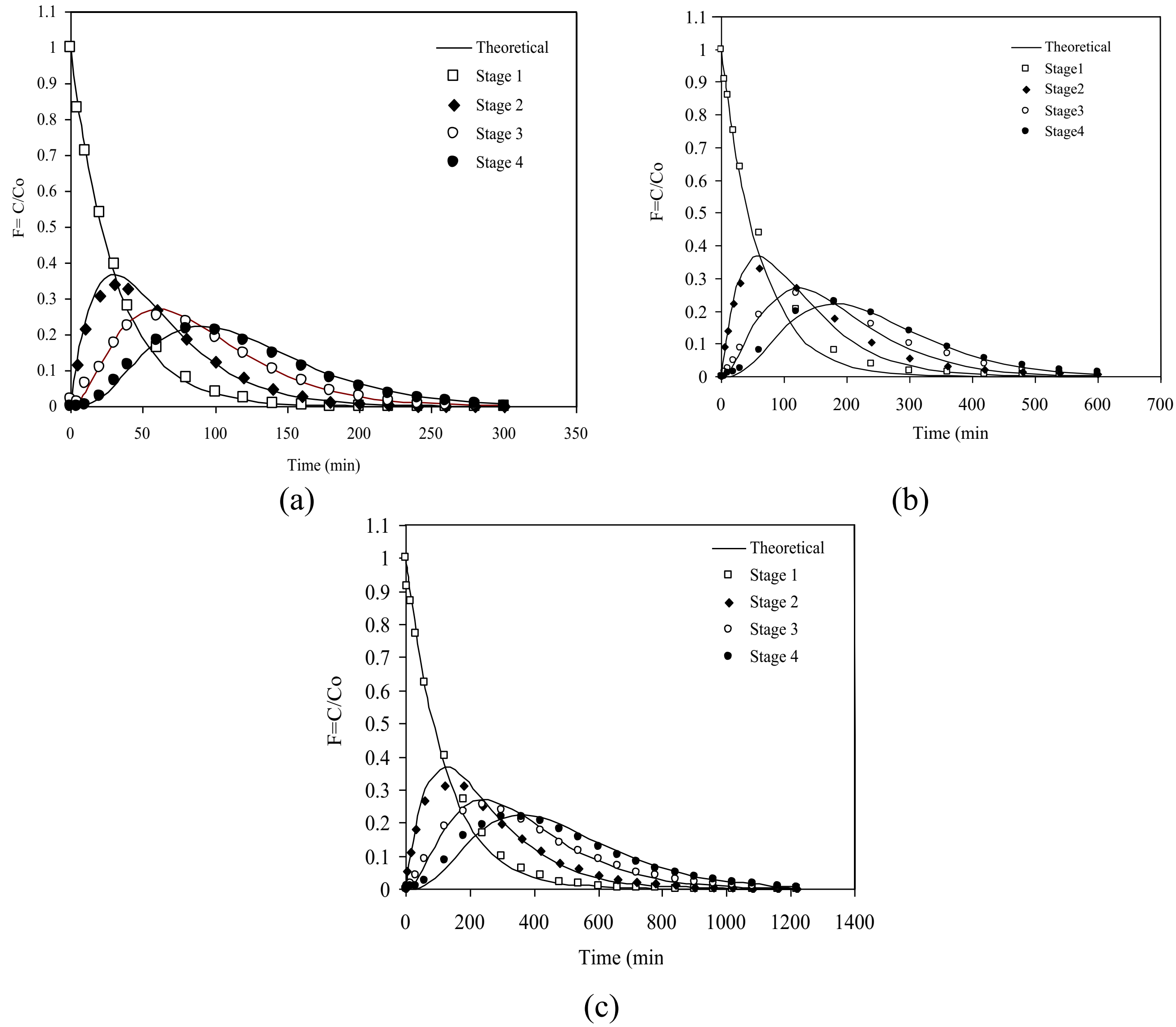


Fig. 2 Residence time distribution of C-curve for four compartments in series at various HRTs of **a** 2 h; **b** 4 h; and **c** 8 h

the reactor (Levenspiel 1999; Metcalf 2003). Therefore, the HRT slightly affected the residence time distribution of the bioreactor. However, the flexible fibre packing media located in the centre of the individual reactor stages had no impact on the regime and the reactor can be consider to act as a completely mixed reactor. The results of this study are in agreement with literature data (Plascencia-Jatomea et al. 2015). The calibration curve for the tracer experiments is shown in Figure S1 (Supporting information).

Oxygen mass transfer coefficient

The oxygen mass transfer coefficient (K_La) is one of the most important parameters in aerobic bioreactors. It depends on various factors such as geometrical and operational characteristics of the reactor, media composition, and microorganisms present (Amaral et al. 2008). The data obtained from this experiment and the calculated data for the estimated mass transfer coefficients are given in Tables S6-11 (Supporting information). Figure 4 shows the regression plots used to determine dissolved oxygen mass transfer coefficients.

The K_La values of MS-FFBR at various AFR/WFR ratios are given and graphically presented in Table 1 and Fig. 5, respectively. The results clearly show that the K_La notably increased with increasing the AFR/WFR ratio. The correlation equation acquired for the MS-FFBR is as follows:

$$K_La = K_La = 0.1533 \text{ AFR/WFR} + 3.77$$

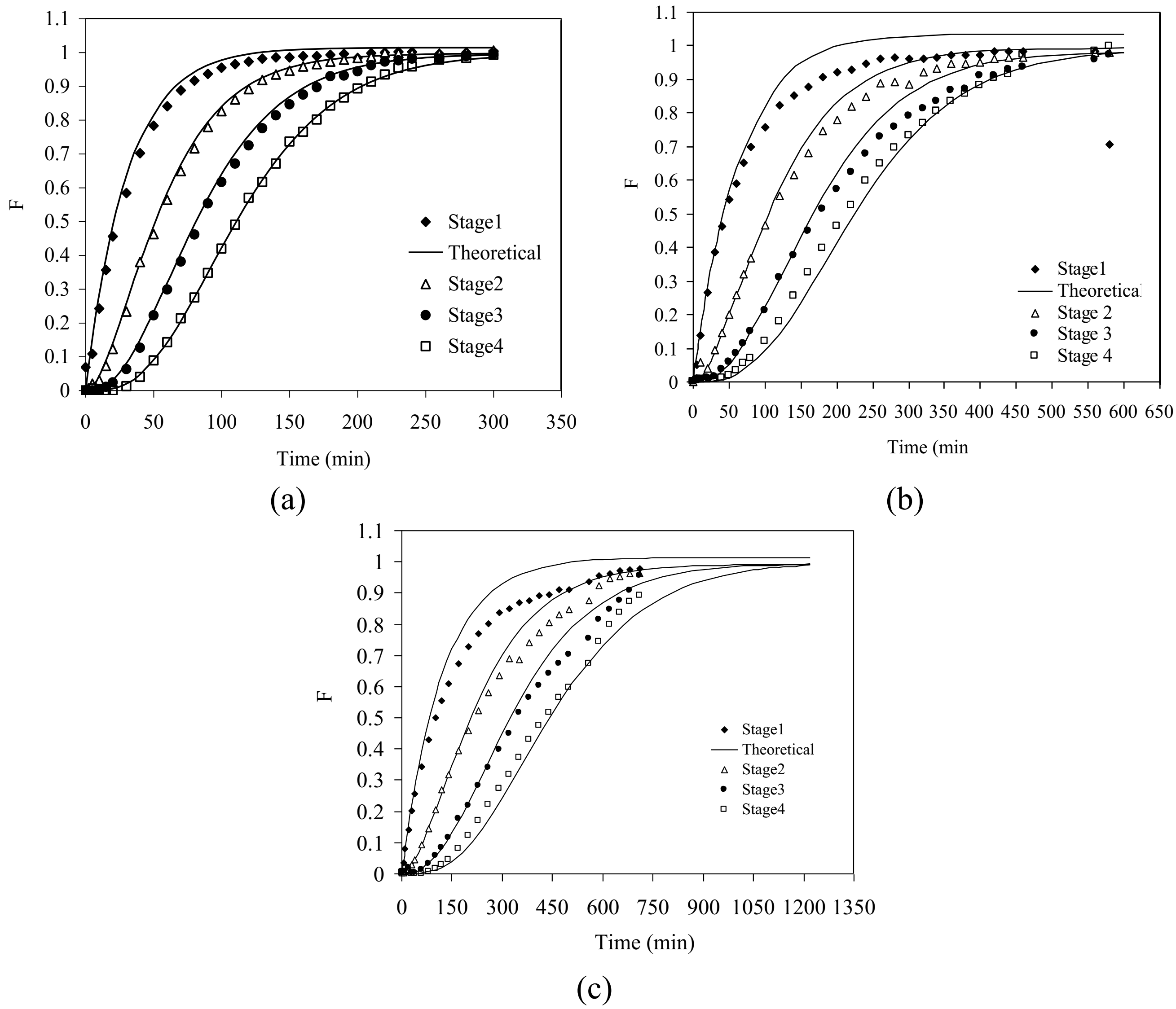


Fig. 3 Residence time distribution of F-curve for four compartments in series at various HRTs of **a** 2 h; **b** 4 h; and **c** 8 h

The values of oxygen mass transfer coefficients obtained from the MS-FFBR (K_La of 11.955 1/h at AFR/WFR of 47) were lower than those reported by Chen et al. (K_La of 15 1/h at AFR/WFR of 40) (Chen et al. 2009). On the other hand, these values were higher than those achieved by Rodgers et al. in a vertically moving biofilm system used for industrial wastewater treatment (Rodgers et al. 2004). In a study conducted by Wutz et al. (2016), K_La of around 4.3 1/h was reported at AFR of 20 L/h in stirred tank reactors (Wutz et al. 2016). In another research, the K_La value was obtained to be 20 1/h at 70 rpm in a spin filter bioreactor (Niño-López and Gelves-Zambrano 2015). Salehpour et al. (2019) achieved the maximum K_La of 0.031 1/s in an airlift reactor (ALR) with a net draft tube (NDT).

In the MS-FFBR, the oxygen mass transfer coefficient seemed to be less sensitive to variations in the AFR/WFR ratio. Hence, the existence of flexible fibre packing may slow down the oxygen mass transfer rate. This may be attributed to the interference caused by the flexible fibre on the distribution of the air bubbles within the individual compartments of the reactor. It can be said that the capacities of the oxygen

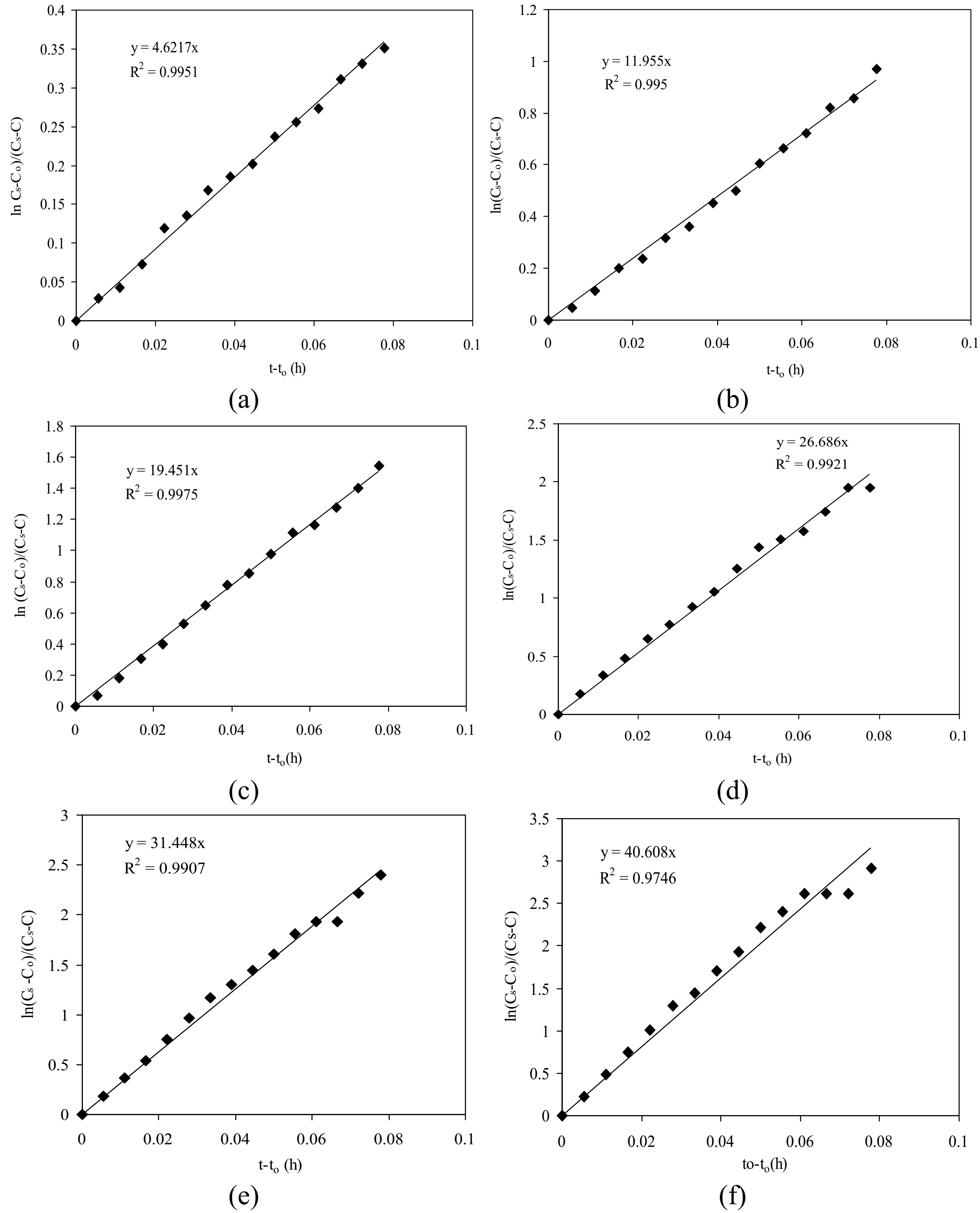


Fig. 4 Regression plots used for determination of oxygen mass transfer coefficient at various AFR/WFR of **a** 14.4; **b**; 47.5 **c** 93; **d** 140; **e** 187; and **f** 235

Table 1 Values of AFR/WFR ratio and corresponding K_La

AFR/WFR	K_La (1/h)
15	4.6
47	11.955
93	19
140	26
187	31
235	40

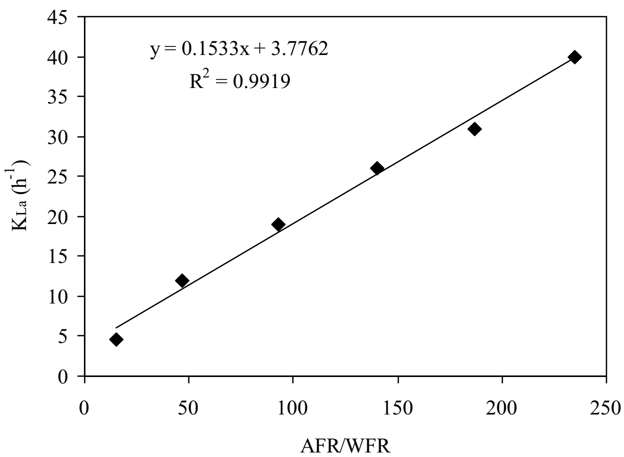


Fig. 5 Relationship between oxygen mass transfer coefficient and AFR/WFR for MS-FFBR

mass transfer in the MS-FFBR are similar to those previously reported for a single-stage FFBR (Chen et al. 2009). Other studies showed a positive effect of media on oxygen mass transfer (Dias et al. 2018). However, K_La values reported by Salehpour et al. and Yazdian et al. are much higher than those of values reported in this study, which may be due to differences in the configuration of reactors (Yazdian et al. 2010; Salehpour et al. 2019).

Conclusion

The residence time distribution of MS-FFBR developed to treat milk processing wastewater (MPW) has been evaluated at various HRTs using tracer experiments. The results of experiments revealed that the residence time distributions in the MS-FFBR were very close to the theoretical values of the *C*-curve and also *F*-curve especially at 2 h HRT. Therefore, it can be concluded that the flow regime is not affected by the flexible fibre as packing media, and the reactor can be described as a CSTR. In this study, K_La values were lower (K_La of 11.955 at AFR/WFR of 47) in comparison with those obtained from the literature (K_La of 15 at AFR/WFR of 40). As a conclusion, the presence of packing media may reduce the oxygen mass transfer coefficient due to their interference on the distribution of the air bubbles.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s13762-023-04835-7.

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Declarations

Conflict of interest The authors declare no competing interests.

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Consent to participate Not applicable.

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