Estimation of gas transfer coefficient with micro bubble technology on green roof runoff water

Abdillah Luthfi[1], *Advent Cahyo* Jati[1], *Idham Ilyas Budhi* Mahendra[1], *Yohanes Aris* Purwanto[2], *Allen* Kurniawan[1], *Yudi* Chadirin[1*]

[1]IPB University, Civil and Environmental Engineering, 16680 Jawa Barat, Indonesia
[2]IPB University, Mechanical and Biosystem Engineering, 16680 Jawa Barat, Indonesia

Abstract. Green open spaces reduction serving as crucial water recharge areas, is a consequence of urban development. Green roofs, incorporating vegetation atop buildings, present a viable solution to mitigate this loss by replicating some functions of green spaces. However, the retention capacity of green roofs is limited, leading to runoff. Reusing this runoff can enhance rainwater capture efficiency, yet the water typically fails to meet clean water standards due to low dissolved oxygen (DO) levels. Micro bubble technology offers a potential remedy by injecting gas into the water to elevate DO levels. To optimize micro bubble usage, it is essential to determine the gas transfer coefficient (k_{La}), which is influenced by various parameters such as the type of gas and the duration of treatment. This study utilized 60L samples of green roof runoff water, subjected to micro bubble treatments of 30-min and 60-min. Two types of green roof media were tested: vegetated (*Portulaca grandiflora*) and unvegetated. The k_{La} values were derived by modeling DO levels during the treatments. The results indicated that the highest k_{La} values for both 30-min and 60-min exposure were observed in runoff water from green roof with *Portulaca grandiflora*, 0.2533/min and 0.3781/min of k_{La} values, respectively.

1 Introduction

Ongoing urban development significantly impacts the reduction of green open spaces, which is crucial for water recharge and flood prevention in low-lying areas [1]. This reduction in green spaces can lead to increased flooding, as evidenced in three major Southeast Asian cities, Jakarta, Kuala Lumpur, and Manila, which saw a decline in green open space from 45% to 20% between 1988 and 2014 [2]. To mitigate this issue, the implementation of green roofs has been proposed. Green roofs involve adding vegetation and plant growth media to the rooftop of buildings, providing numerous environmental benefits [3]. Previous research indicated that green roofs with a planting media thickness of 15 cm can reduce runoff volume by 13.8% to 34.4%. When the planting media thickness is increased to 20 cm, the effectiveness in reducing runoff volume rises significantly, ranging from 42.8% to 60.8% [4]. To optimize retention value necessitates the utilization of green roof runoff water. However, it is essential to note that green roof runoff water does not meet clean water standards due to various contaminants [5]. To fully harness the potential of green roofs in urban flood

---

[*] Corresponding author: yudi@apps.ipb.ac.id

management, additional treatment processes must be employed to purify the runoff water before it can be utilized. This approach not only addresses the immediate issue of urban flooding but also contributes to sustainable water management practices by integrating green infrastructure into urban planning. The dual benefits of reducing surface runoff and enhancing water quality underscore the immense potential of incorporating green roofs into the design of urban environments.

One of the most pressing contaminant parameters in green roof runoff water is the low level of dissolved oxygen (DO). DO is not just a critical indicator of water quality but a lifeline for aquatic organisms. Higher DO levels correspond to better water quality, while lower levels suggest poorer quality and potential harm to the ecosystem. The reduction in DO levels in green roof runoff water can be attributed to the water percolating through the planting media, which may contain substances such as urea, animal faeces, and decaying plant matter [6]. These organic materials consume oxygen during their decomposition, leading to decreased DO levels in the runoff. This is a serious issue that needs immediate attention. To address this issue, it is essential to implement further treatment processes to enhance the DO levels in green roof runoff water by involving various aeration techniques or biological treatments designed to increase oxygenation and improve water quality. Enhancing DO levels not only makes the runoff suitable for reuse and ensures it meets environmental standards for discharge, but also contributes significantly to sustainable urban water management practices. By effectively treating green roof runoff to improve DO levels, cities can better integrate green infrastructure solutions, thereby playing a vital role in preserving our environment and mitigating the adverse effects of urbanization on water quality.

Micro bubble technology, a specific type of fine bubble technology, has proven its potential over the past decade. This innovative technology uses fine bubbles of 1-100 μm infused with various gases to enhance water quality [7]. When these bubbles are introduced into the water, they rise to the surface, carrying contaminants. As the bubbles escape at the surface, the contaminants are effectively removed from the water, preventing their re-entry. This process continues until the water is sufficiently cleaned, all without the need for chemical additives [8]. The effectiveness of micro bubble technology is primarily due to the unique properties of the bubbles themselves. Their small size confers a large surface area, low surface velocity, high mass transfer efficiency, and a high gas dissolution rate [9]. These characteristics allow the bubbles to remain in the water for extended periods, increasing the residence time of the bubbles. The longer residence time enhances the solubility of the injected gases, improving the overall efficiency of the treatment process. Consequently, micro bubble technology elevates DO levels and effectively removes organic pollutants, making it a highly efficient and reliable method for water purification and treatment.

Given the relatively low contaminant levels in green roof runoff water, applying micro bubble technology is highly suitable. Various studies on water with similar properties have been substantiated. However, to maximize the effectiveness and efficiency of micro bubble technology, it is crucial to determine the optimum treatment duration by evaluating the gas transfer coefficient (k_{La}). The k_{La} value is a crucial indicator of gas transfer efficiency in the water; a higher k_{La} value suggests a more optimal treatment process [10]. This study selected two different exposure durations, 30-min and 60-min. These durations were chosen based on previous research and practical considerations. A 30-min exposure time is often sufficient for initial oxygenation and removal of specific contaminants, allowing for a quick assessment of the technology's effectiveness. Conversely, a 60-min exposure time provides a more prolonged exposure, which can enhance the dissolution of gases and improve the removal of more persistent or higher concentrations of contaminants [11]. These durations also offer a practical range for operational feasibility and efficiency in practical. The objectives of this study are to: (a) analyze the changes in DO levels in green roof runoff water when subjected to and removed from micro bubble exposure; (b) determine the k_{La} value in green roof runoff water after micro bubble exposure over different treatment durations; and (c) identify the optimum residence time—whether 30-min or 60-min—required for micro bubble technology to achieve the desired DO levels in green roof runoff water. By achieving these objectives, the study aims to enhance the practical application of micro bubble technology in treating green roof runoff, ensuring efficient and effective water quality improvement.

2 Methodology

2.1 Material

The tools meticulously selected for this study include two pieces of green roof media, two high-density polyethylene (HDPE) tanks with capacities of 220 L, two HDPE 120 L water harvesters, an aquarium, a micro bubble diffuser, a 125-watt pump, a DO meter, a thermometer, and various pipes and connections. The primary material used in this research is 60 L of green roof runoff water collected by each green roof models featuring *Portulaca grandiflora* plants and planting media. These models also include planting media composed of soil and manure. The data analysis and documentation applications are Desmos Calculator and Microsoft Office 2021. The data collected in this study includes accurate measurements of DO levels with the fine bubble system on and off. Additionally, temperature changes were recorded every 5-min during the 30-min and 60-min exposure periods.

2.2 Research procedure

2.2.1 Preparation of the green roof model

The green roof media were constructed with dimensions of 1 m in length, 1 m in width, and 0.3 m in height. These media were fabricated from multiplex boards with a thickness of 12 cm, which were coated with geotextile for added durability and functionality. Angle iron frames supported two green roof media units, each standing 1 m high, and the units were assembled into a single integrated structure. The installed green roof media were then connected to a 120 L water tank using modified ½-inch PVC pipes, which were also linked to a water meter to facilitate precise water measurement. As shown in Fig. 1, the planting media of the green roof included several layers: at the base, a drainage carpet layer was laid to ensure proper water drainage. Above the carpet layer, a 5 cm zeolite layer was added for its filtration properties followed by a 10 cm layer of soil mixed with 3 kg of manure to enhance nutrient content. Finally, a vegetation layer was placed on top, completing the green roof assembly. Thus, the type of green roof used is extensive green roof which is characterized by low weight with a growing medium thickness below 15 cm, minimal nutrient requirements and easy maintenance, so its very possible to be applied to roofs of the house [12-13].

The chosen green roof variation features *Portulaca grandiflora* plants (Box 1) and unvegetated media (Box 2). The purpose of selecting green roof models with *Portulaca grandiflora* vegetation and this specific unvegetated is to evaluate the impact of these plants on the initial water quality and its subsequent treatment using micro bubble technology. *Portulaca grandiflora* was selected for several reasons: it thrives in dry and wet tropical climates, has a high capacity for water and nutrient absorption, and grows rapidly, providing substantial ground cover. Additionally, the plant's morphology, characterized by short and filamentous roots, reduces the need for thick planting media, making it an ideal candidate for green roof applications [14-16]. This plant's attributes ensure efficient water uptake and contribute to the effectiveness of the green roof system.

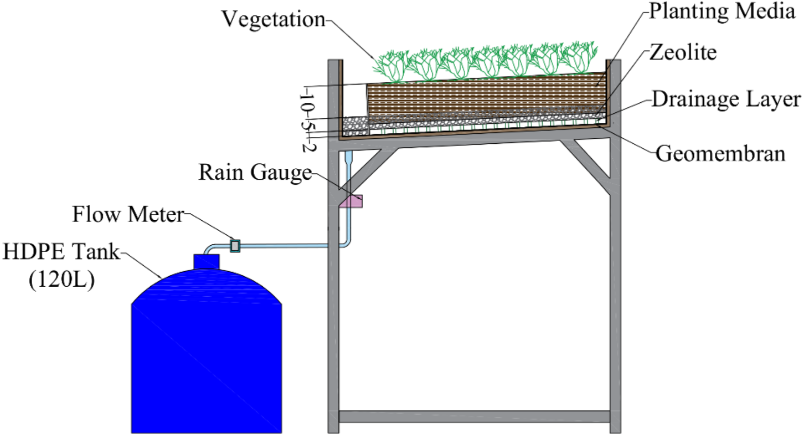

Fig. 1. Green roof model design

2.2.2 Development of gas transfer coefficient equation (k_{La})

Model development begins with the derivation of the gas volumetric mass transfer equation in the sample, which in this study is green roof runoff water. The mass balance equation in water can be seen in Eq. (1).

$$\frac{\mathrm{d}C}{\mathrm{d}t} = \mathrm{GTR} - \mathrm{GCR} \quad (1)$$

where,
GTR : Gas transfer rate
GCR : Gas consumtion rate

The gas transfer rate value can be found with Eq. (2).

$$\mathrm{GTR} = \frac{\mathrm{d}C}{\mathrm{d}t} = k_{\mathrm{La}}\,(C^{*} - C_{\mathrm{L}}) \quad (2)$$

where,
k_{La} : Gas transfer coefficient (min^{-1})
C^{*} : Saturated gas concentration (mg/L)
C_{L} : Gas concentration in the water sample at the time of treatment (mg/L)

The saturated gas concentration value C^* is affected by the temperature state of the sample at the time of testing. The C^* value under 760 mmHg pressure conditions can be seen in Table 1.

Table 1. Saturated dissolved oxygen concentration at 760 mmHg pressure [17]

Temperature (°C)	Saturated DO levels (mg/L)	Temperature (°C)	Saturated DO levels (mg/L)
20	9.09	28	7.83
21	8.91	29	7.69
22	8.74	30	7.56
23	8.58	31	7.43
24	8.42	32	7.30
25	8.26	33	7.18
26	8.11	34	7.06
27	7.97	35	6.95

Given that green roof runoff water is classified as low-contamination waste, the concentration of air is higher than that of the contaminants reacting in the sample.

Consequently, the gas transfer rate follows a pseudo-first-order reaction, as described by Eq. (3).

$$\mathrm{GCR} = \frac{\mathrm{d}C\ \mathrm{gas}}{\mathrm{d}t} = k_\mathrm{d}\ \times C_\mathrm{L} \tag{3}$$

where,
k_d : Gas consumption rate constant (min^{-1})

The k_d value was obtained by looking at the graph of the decrease in DO value after the micro bubble treatment was stopped [11]. The decrease in DO levels is recorded according to the time of micro bubble treatment. The graph will be matched with curve fitting with Eq. (4).

$$\frac{C_\mathrm{L}}{C^*} = \mathrm{e}^{-k_\mathrm{d}.t} \tag{4}$$

where,
t : time (min)

By matching Eq. (4) with the curve of the effect of time on the decrease in DO concentration, the k_d value will be obtained. Thus, the net rate of gas mass transfer can be calculated using Eq. (5) and Eq. (6).

$$\frac{\mathrm{d}C}{\mathrm{d}t} = k_\mathrm{La} \times (C^* - C_\mathrm{L}) - k_\mathrm{d} \times C_\mathrm{L} \tag{5}$$

$$\frac{\mathrm{d}C}{\mathrm{d}t} = k_\mathrm{La} \times C^* - (k_\mathrm{La} + k_\mathrm{d}) \times C_\mathrm{L} \tag{6}$$

Both sides are multiplied by the constant $\left(\frac{1}{k_\mathrm{La}+k_\mathrm{d}}\right)$, it becomes Eq. (7).

$$\left(\frac{1}{k_\mathrm{La} + k_\mathrm{d}}\right)\frac{\mathrm{d}C}{\mathrm{d}t} = \left(\frac{k_\mathrm{La} \times C^*}{k_\mathrm{La} + k_\mathrm{d}}\right) - C_\mathrm{L} \tag{7}$$

The variables in the equation are rearranged together and will form Eq. (8).

$$\frac{\mathrm{d}C}{\left(\frac{k_\mathrm{La} \times C^*}{k_\mathrm{La} + k_\mathrm{d}}\right) - C_\mathrm{L}} = (k_\mathrm{La} + k_\mathrm{d}) \times \mathrm{d}t \tag{8}$$

Equation $\left(\frac{k_\mathrm{La} \times C^*}{k_\mathrm{La}+k_\mathrm{d}}\right)$ is converted into a constant u to simplify the calculation process, then substitute it into Eq. (9).

$$\left(\frac{1}{k_\mathrm{La} + k_\mathrm{d}}\right)\frac{\mathrm{d}C}{\mathrm{d}t} = \left(\frac{k_\mathrm{La} \times C^*}{k_\mathrm{La} + k_\mathrm{d}}\right) - C_L \tag{9}$$

Both sides are integrated to become Eq. (10).

$$-\ln\left(\frac{u - C_\mathrm{L}}{u}\right) = (k_\mathrm{La} + k_\mathrm{d}) \times t \tag{10}$$

Component u which was originally a constant, is converted into the original equation, forming Eq. (11).

$$\mathrm{e}^{-(k_\mathrm{La}+k_\mathrm{d})\times t} = \frac{u - C_\mathrm{L}}{u} = \frac{\left(\frac{k_\mathrm{La}\ \times C^*}{k_\mathrm{La} + k_\mathrm{d}}\right) - C_L}{\left(\frac{k_\mathrm{La}\ \times C^*}{k_\mathrm{La} + k_\mathrm{d}}\right)} \tag{11}$$

Eq. (11) is simplified to Eq. (12), Eq. (13) and takes the final form in Eq. (14).

$$\mathrm{e}^{-(k_\mathrm{La}+k_\mathrm{d})\times t} = 1 - \frac{C_\mathrm{L}}{\left(\frac{k_\mathrm{La} \times C^*}{k_\mathrm{La} + k_\mathrm{d}}\right)} \tag{12}$$

$$1 - \mathrm{e}^{-(k_\mathrm{La}+k_\mathrm{d})\times t} = \frac{C_\mathrm{L}\ \times\ (k_\mathrm{La} + k_\mathrm{d})}{k_\mathrm{La} \times\ C^*} \tag{13}$$

$$\frac{C_\mathrm{L}}{C^*} = \frac{k_\mathrm{La}}{k_\mathrm{La} + k_\mathrm{d}}\left(1 - \mathrm{e}^{-(k_\mathrm{La}+k_\mathrm{d})\times t}\right) \tag{14}$$

Eq. (14) is the final expression used to determine the k_{La}. Eq. (14) elucidates the relationship between k_{La}, time, and the degradation rate constant (k_d), which can be derived using Eq. (4). To ascertain the values of k_{La} and k_d, one can perform curve fitting with Eq. (14) and Eq. (4) against the empirical data representing the relationship between DO concentration and time. The resulting k_{La} value will be expressed in units per min (time^{-1}). The effectiveness of gas transfer is directly proportional to the magnitude of the k_{La} value; thus, a higher k_{La} value indicates greater effectiveness and efficiency in utilizing micro bubble technology at that given time.

2.2.3 Data collection and processing

The primary data collection focuses on measuring the parameters of DO and temperature conditions in the runoff water both during and after the operation of the micro bubble system. Data is recorded every 5-min, with two different operational time variations for the micro bubble system: 30-min and-60 min. During the operation of the micro bubble system, an absorption event occurs where air dissolves into the water, increasing the DO concentration. Conversely, after the micro bubble system ceases operation, a desorption event takes place, where oxygen is released from the water back into the air, leading to a decrease in DO concentration over time. Fig. 2 illustrates these processes, with the left side representing the absorption phase and the right side depicting the desorption phase. During the absorption phase, the DO concentration in the water increases as oxygen is absorbed from the air. In the desorption phase, the DO concentration decreases as oxygen is released from the water back into the air. The determination of the k_{La} is based on data collected during the absorption process using the curve fitting method to model the relationship between DO concentration and time. Similarly, the k_d is determined from data collected during the desorption process using the same curve-fitting approach. By comparing the k_{La} values obtained from the two different operational time variations, the highest k_{La} value is selected as the optimum.

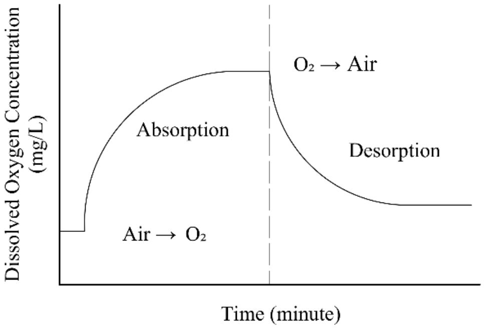

Fig. 2. Data visualization of micro bubble treatment results

3 Results

3.1 Effect 0f 30-min micro bubble exposure

The experimental results, a product of meticulous research, from the 30-min micro bubble exposure of runoff water from green roof system that planted with *Portulaca grandiflora* plants and the unvegetated green roof, provide profound insights into the dynamics of DO levels and the overall effectiveness of the micro bubble technology. At the start of the experiment, the runoff water from vegetated green roof had a DO concentration of 2.8 mg/L (Fig. 3). The water temperature during the treatment was 33.47 °C, resulting in a calculated saturation concentration (C^*) of 7.124 mg/L (Table 2). The DO levels increased consistently throughout the 30-min exposure period, indicating effective oxygen transfer from the micro bubbles to the water. The DO concentration rose rapidly from 2.8 mg/L to 4.5 mg/L within the first 5-min, demonstrating a quick initial oxygen uptake. This upward trend continued, with DO levels reaching 5.9 mg/L at 10-min, 6.5 mg/L at 15-min, and peaking at 7 mg/L at 30-min (Fig. 3). This peak value, close to the saturation concentration, signifies near-optimal efficiency in oxygen transfer during the active treatment phase, with a total increase of 4.2 mg/L.

As the micro bubble treatment progressed, the runoff water samples passing through the unvegetated media in Box 2 showed a steady increase in DO concentration. The initial DO concentration was 2.4 mg/L. During the treatment, the water temperature was maintained at 33.59°C, corresponding to a saturation concentration (C^*) of 7.109 mg/L (Table 2). The DO levels increased steadily throughout the 30-min exposure, reaching a maximum concentration of 5.8 mg/L at the end of the treatment period (Fig. 3). At the 60-min mark (30-min post-treatment), the DO concentration was measured at 4.9 mg/L, signifying a net increase in DO concentration of 3.4 mg/L during the treatment. After the cessation of the micro bubble treatment for both types of runoff water, a desorption phase began, characterized by a gradual decrease in DO levels as oxygen diffused out of the water. This phase underscores the temporary nature of the oxygenation achieved through micro bubble treatment. For the vegetated media runoff, the DO level dropped to 6.8 mg/L at 35-min, 4.6 mg/L at 40-min, 4.3 mg/L at 45-min and stabilized around 4.0 mg/L between 50 and 55-min, finally settling at 3.9 mg/L at 60-min (Fig. 3). For the unvegetated media runoff, the DO level dropped to 5.7 mg/L at 35-min, 5.3 mg/L at 40-min, 5.1 mg/L at 45-min, 5.0 mg/L at 50-min, and stabilized at 4.9 mg/L between 55 and 60-min (Fig. 3).

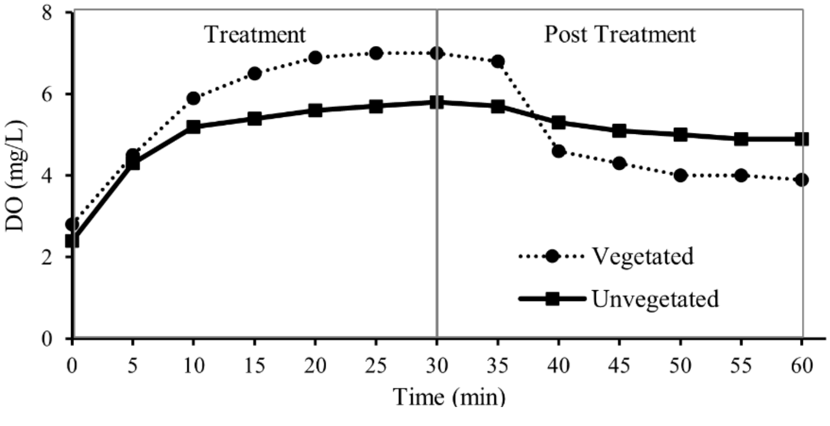

Fig. 3. DO conditions in vegetated and unvegetated media runoff water during 30-min exposure

These results highlight the temporary nature of the oxygenation achieved through micro bubble treatment, with the final DO levels improving significantly over the initial values. This underscores the importance of continuous or periodic micro bubble exposure to maintain optimal DO levels for sustained water quality improvements. Curve fitting methods were applied to the DO concentration data to quantify the efficiency of the gas transfer. For the vegetated media runoff, the k_d was determined to be 0.026/min, and using this value, the k_{La} was calculated to be 0.253/min (Table 2). The k_d was determined to be 0.017/min for the unvegetated media runoff, with a resulting k_{La} of 0.141/min (Table 2).

Table 2. k_d and k_{La} values generated in the 30-min exposure

Sample	**Temperature (°C)**	**C^* (mg/L)**	**k_d (min^{-1})**	**k_{La} (min^{-1})**
Vegetated	33.47	7.124	0.026	0.253
Unvegetated	33.59	7.109	0.017	0.141

3.2 Effect of 60-min micro bubble exposure

The experimental results from the 60-min micro bubble treatment of runoff water from vegetated and unvegetated media provide comprehensive insights into the dynamics of DO levels and the overall effectiveness of the micro bubble technology. Initially, the DO concentration in the vegetated media runoff water was 2.9 mg/L, while the unvegetated media runoff water had an initial DO concentration of 2.6 mg/L (Fig. 4). During the treatment, water temperature was 32.32°C for vegetated media and 32.52°C for unvegetated media, which led to the C^* (Table 3). These C^* values, 7.262 mg/L and 7.238 mg/L, respectively, indicate the maximum DO levels that can be achieved at the given temperatures (Table 3). The DO levels in both treatments increased steadily, reaching a maximum of 7.3 mg/L between 50 to 60-min for vegetated media and between 50 to 65-min for unvegetated media. After the treatment ceased, the DO levels gradually decreased to 3.8 mg/L at the 120-min mark for both cases, signifying an increase in DO (DO max - initial DO) of 4.4 mg/L for vegetated media and 4.7 mg/L for unvegetated media, with differences of 0.9 mg/L and 1.2 mg/L between initial and final DO levels, respectively.

The effectiveness of the micro bubble treatment is evident from the rapid rise in DO concentrations, reaching 5.8 mg/L within the first 5-min for vegetated media and 5.7 mg/L for unvegetated media, continuing to increase to 6.6 mg/L and 6.7 mg/L at 10-min, and peaking at 7 mg/L and 6.9 mg/L at 15-min, respectively, showcases the system's efficiency in enhancing oxygenation quickly (Fig. 4). After the exposure stopped, the DO levels began to decline, reflecting the natural desorption process, where oxygen is released from the water back into the atmosphere. For both runoff types, the DO levels stabilized at 3.8 mg/L by the 120-min mark, indicating that while the treatment significantly boosts DO levels, maintaining these elevated levels over time would require ongoing or repeated application of the technology.

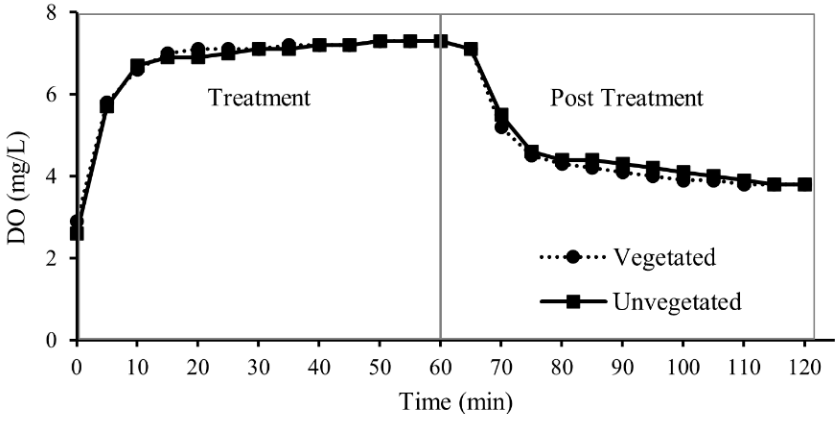

Fig. 4. DO conditions in vegetated and unvegetated media runoff water during 30-min exposure

Curve fitting methods were applied to the DO concentration data to quantify the gas transfer dynamics. Gas transfer dynamics refer to the process by which gases, in this case, oxygen, are transferred between the water and the air. For vegetated media runoff, the k_d was determined to be 0.016/min, which represents the rate at which DO is lost from the water. The k_{La} was calculated to be 0.378/min, which indicates the efficiency of oxygen transfer from the air to the water. Similarly, the k_d was 0.015/min for the unvegetated media runoff, with a resulting k_{La} of 0.364/min (Table 3). These coefficients provide quantitative measures of the treatment's efficiency, highlighting the high effectiveness of the micro bubble technology in enhancing DO levels in green roof runoff water.

Table 3. k_d and k_{La} values generated in the 60-min exposure

Sample	**Temperature (°C)**	**C^* (mg/L)**	**k_d (min^{-1})**	**k_{La} (min^{-1})**
Vegetated	32.32	7.262	0.016	0.378
Unvegetated	32.52	7.238	0.015	0.364

4 Discussions

4.1 Comparative analysis of water quality on gas transfer coefficient based on green roof media

The trend in DO levels observed in this study indicates that micro bubble technology can significantly enhance water oxygenation within a short period. The rapid increase in DO concentrations during the treatment, followed by a gradual decline post-treatment, suggests that while the micro bubble treatment is highly effective during operation, maintaining elevated DO levels would require continuous or periodic application. This observation is supported by the higher k_{La} values, indicating efficient oxygen transfer during the treatment phase. The differences in k_{La} and k_d values between the two types of runoff water—vegetated and unvegetated media—suggest variations in gas transfer efficiency, potentially due to differences in the physical and chemical properties of the media.

These coefficients (k_d and k_{La}) provide quantitative measures of the treatment's efficiency, underscoring the high effectiveness of the micro bubble technology in enhancing DO levels [10]. Both vegetated and unvegetated media runoffs, through the application of micro bubble treatment, showed significant improvements in DO levels. The vegetated media setup achieved a higher peak DO level and k_{La} value, indicating more efficient oxygen transfer. The high increase in DO and k_{La} values in vegetated media runoff water is supported by cleaner water conditions due to natural filtration by Portulaca grandiflora roots [18]. However, both systems showed substantial potential for water quality improvements, highlighting the efficacy of micro bubble technology in enhancing oxygenation in green roof runoff water.

Specifically, the more apparent characteristics of vegetated media runoff water, which indicates lower dissolved solids, can be attributed to the morphology of Portulaca grandiflora roots. These soft and smooth roots cover the soil and prevent solid contaminants from entering the runoff. This characteristic of vegetated media (Portulaca grandiflora) contrasts with the unvegetated media runoff water, which lacks vegetation and root structures that could improve water quality by reducing dissolved solids. Higher contaminant levels in the unvegetated media runoff water can inhibit oxygen dissolution, necessitating more time for adequate oxygen transfer into the water. These conditions directly influence the magnitude of k_d and k_{La} values observed during the gas injection process with micro bubbles [19]. For instance, higher contaminant levels in the unvegetated media runoff water can result in lower k_{La} values, reflecting a less efficient oxygen transfer process than the Portulaca grandiflora runoff water. These conditions underscores the crucial role of water characteristics, driven by the presence or absence of vegetation, in significantly influencing the efficiency of the micro bubble treatment.

The trend in DO levels observed in this study indicates that micro bubble technology can quickly enhance water oxygenation. The rapid increase in DO concentrations, followed by a gradual decline, suggests that while the treatment is highly effective during operation, maintaining elevated DO levels would necessitate continuous or periodic application. The higher k_{La} values observed indicate efficient gas transfer during the treatment phase. However, the slight differences in k_{La} and k_d values between the two types of runoff water suggest variations in gas transfer efficiency, potentially due to differences in its runoff water properties, both the physical or chemical.

4.2 Comparative analysis of micro bubble exposure times and their effects on DO dynamics

The impact of different treatment times using micro bubbles on the dynamics of DO in runoff water samples from vegetated and unvegetated media was evaluated through the analysis of k_d and k_{La}. The data indicate that the k_d value, representing the rate of DO desorption post-treatment, was higher for the 30-min exposure compared to the 60-min exposure for both types of runoff water (Fig. 5). A higher k_d value suggests a greater rate of oxygen desorption following the cessation of the micro bubble treatment, indicating that shorter treatment times result in less sustained oxygen levels.

Conversely, the k_{La} values, which indicate the efficiency of oxygen transfer during the treatment, were higher in the 60-min exposure compared to the 30-min exposure for both vegetated and unvegetated media runoff water (Fig. 6). This increase in k_{La} values with longer treatment times can be attributed to the extended contact time between air and water, allowing more opportunities for oxygen to diffuse into the water [20]. The trend in k_{La} values highlights the importance of treatment duration in maximizing the oxygenation efficiency of micro bubble technology.

The differences in k_d and k_{La} values between the two types of runoff water can be further explained by the characteristics of the water samples. Vegetated media runoff water, which exhibited clearer characteristics and lower dissolved solids, demonstrated higher k_{La} values. This can be attributed to the morphology of *Portulaca grandiflora* roots, which effectively cover the soil and reduce solid contaminants. In contrast, the unvegetated media runoff water, which lacked vegetation and root structures, contained higher levels of contaminants, potentially inhibiting the oxygen dissolution process and resulting in lower k_{La} values.

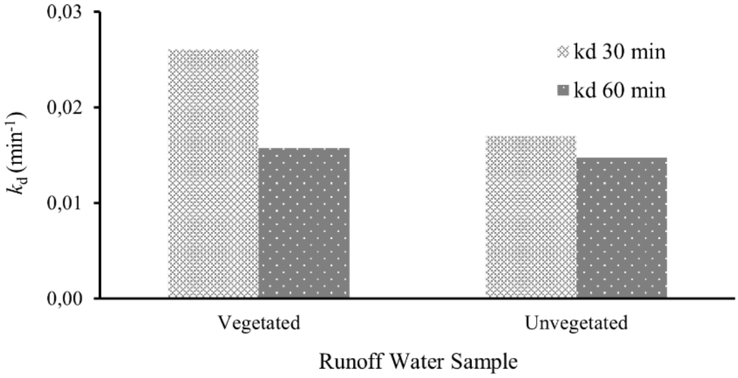

Fig. 5. The difference in the k_d value of each sample in the 30-min and 60-min exposure

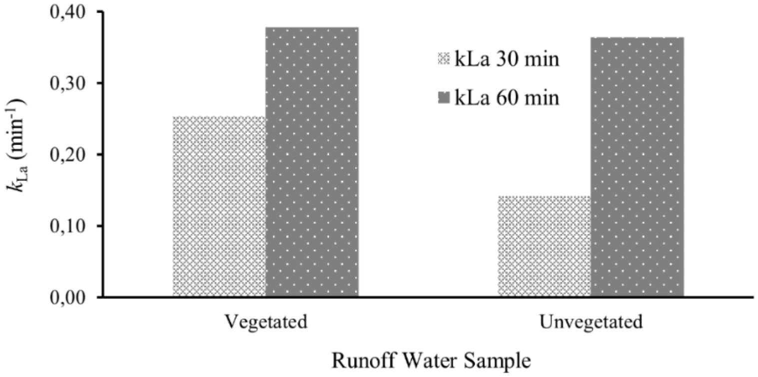

Fig. 6. The difference in k_{La} values for each sample in the 30-min and 60-min exposure

The scientific approach to analyzing these trends involves understanding the physical and chemical interactions between oxygen and the water matrix. The presence of solid contaminants in the water can hinder the diffusion of oxygen, thereby affecting the overall efficiency of the micro bubble treatment. The clear runoff water from vegetated media, with fewer contaminants, allows for more efficient oxygen transfer, as reflected in the higher k_{La} values. The prolonged exposure time of 60-min enhances this efficiency further by increasing the duration of air-water contact, thereby maximizing oxygen diffusion [21].

In conclusion, the comparative analysis of different treatment times reveals that a 60-min micro bubble exposure significantly enhances the efficiency of k_{La} compared to a 30-min exposure. The higher k_{La} values observed in the 60-min exposure highlight the importance of extended contact time for effective oxygenation. The differences in k_d and k_{La} values between vegetated and unvegetated media runoff water underscore the influence of water quality on the efficiency of micro bubble technology. These findings provide a scientific basis for optimizing micro bubble treatment protocols to improve water quality in urban green infrastructure systems. By tailoring treatment durations and understanding the specific characteristics of different runoff water sources, the application of micro bubble technology can be optimized to achieve sustainable and effective water management solutions.

5 Conclusion

Micro bubble treatment significantly affects DO levels in green roof runoff water samples, specifically those from vegetated and unvegetated media. During the micro bubble treatment, DO levels increase, reaching their peak, and subsequently decrease after the treatment ceases. The highest k_{La} value in the 30-min exposure was observed in the vegetated media runoff water sample, with a value of 0.253/min, compared to 0.141/min for the unvegetated media. A similar trend was noted in the 60-min exposure, where the k_{La} value for vegetated runoff water was 0.378/min, higher than the 0.364/min observed for the unvegetated media. The superior k_{La} values for vegetated media runoff water can be attributed to the lower levels of dissolved solids compared to the unvegetated media runoff water. Vegetation roots influence this difference on the green roof, which helps filter out solid contaminants. The study results indicate that the 60-min micro bubble exposure yields a higher k_{La} value than the 30-min exposure due to the longer air contact time with the water, which enhances the opportunity for oxygen to diffuse into the water. Therefore, the 60-min exposure is more effective than the 30-min exposure, providing optimal conditions for oxygen diffusion and improving water quality in green roof runoff systems

References

1. P.J. Osly, I. Mardiana, N. Tinumbia, I. Ihsani, Analysis Of The Need For Green Open Space Based On Oxygen Requirement In The City Of Bogor. Jurnal Artesis. **2**, 67 (2022)
2. A.N.M. Nor, H.A. Aziz, S.A. Nawawi, R.M. Jamil, M.A. Abas, K. A. Hambali, A.H. Yusoff, N. Ibrahim, N. H. Rafaai, R. Corstanje, J. Harris, D. Grafius, H.L.P. Baldivieso, Evolution of Green Space under Rapid Urban Expansion in Southeast Asian Cities. J. Sustainability. **13**, 1 (2021)
3. D. Becker, D. Wang, Green roof Heat Transfer and Thermal Performance Analysis, Undergraduate Thesis, Carneige Mellon University, United States, (2011)
4. J.Y. Lee, M.J. Lee, M. Han, A Pilot Study to Evaluate Runoff Quantity from Green Roofs. J. Environmental Management. **1**, 171 (2015)
5. F. Khairani, Analisis Kualitas Air Hujan dan Limpasan Green Roof melalui Berbagai jenis Media Tanam. Undergraduate Thesis, IPB University, Indonesia, (2018)
6. Y. Li, R.W. Babcock, Green roofs against pollution and climate change (a review), J. Agronomy for Sustainable Development. **4**, 695 (2014)
7. International Organization for Standaritation (ISO), Fine bubble technology – General principles for usage and measurement of fine bubbles – Part 1: Terminology (2017)
8. C. Rameshkumar, G. Senthilkumar, R. Subalakshmi, R. Gogoi, Generation and characterization of nanobubbles by ionization method for wastewater treatment, J. Desalination and Water Treatment. **13**, 98 (2019)
9. F.F. Peng, X. Yu, Pico–nano bubble column flotation using static mixer-venturi tube for Pittsburgh No. 8 coal seam, International Journal of Mining Science and Technology. **3**, 347 (2015)
10. L.D. Bennefield, C.W. Randall, Biological Process Design for Wastewater Treatment, (Teleprint Publishing, Charlottesville, Va, (1985)
11. T.T. Terfasa, Enhancing Gas-Liquid Mass Transfer and (Bio) Chemical Reactivity using ultrafine/Nanobubble in Water and Wastewater Treatments, Ph.D. dissertation, Seoul National University, Department of Civil and Environmental Engineering (2017)
12. M.A. Hossain, M. Amin, S. Shams, M.S. Reza, T.U. Chowdhury, Perception and barriers to implementation of intensive and extensive green roofs in Dhaka, Bangladesh. Journal Buildings. **9**, 79 (2019)
13. H. Feng, K.N. Hewage, Economic benefits and costs of green roofs, Nature Based Strategies for Urban Building Sustainibility. **4.5**, 307 (2018)
14. S.M. Shafique, R. Kim, M. Rafiq, Green roof benefits, opportunities and challenges – A review. Renew Sustain Energy Rev. **90**, 757 (2018)
15. A. Talebi, S. Bagg, B.E. Sleep, D.M. O'Carroll, Water retention performance of green roof technology: A comparison of canadian climates. **126**, 1(2019)
16. K. Vijayaraghavan, F.D. Raja, Design and development of green roof substrate to improve runoff water quality: Plant growth experiments and adsorption. J. Water Research. **63**, 94 (2014)
17. G.A. Cole, Textbook of Limnology. 3rd edition, (Waveland Press, USA, 1983)
18. M.R. Bloomberg, D. Burney, M.A. Wolley, K. Krieble, K. Carnahan, DDC "Cool & Green Roofing Manual" (Gruzen Samton Architects LLP., Amis Inc., Flack + Kurtz Inc., Mathews Nielsen Landscape Architects P.C., SHADE Consulting, LLC, USA, 2007)
19. S.I. Patty, M.P. Rizqi, R. Huwae, Oksigen Terlarut di Perairan Bolaang Mongondow Timur, Sulawesi Utara. J. Ilmiah Platax. **1**, 2016 (2022)
20. M.M. Harfadli, M.N.I.L. Saud, I.C. Hikmah, Estimasi Koefisien Transfer Oksigen (KLa) pada Metode Aerasi Fine Bubble Diffuser : Studi Kasus Pengolahan Air Lindi

TPA Manggar Kota Balikpapan. J. Sains Terapan. **2**, 107 (2019)
21. R.D. Letterman, Water Quality and Treatment: A Handbook of Community Water Supplies, (McGraw-Hill, USA, 1999)