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Application note—A novel, low-cost pH-controlled solenoid-based CO_2 dosing device for microalgal and cyanobacterial cultivation systems

Shoyeb Khan [a], Probir Das [a,*], Mahmoud Thaher [a], Mohammed Abdulquadir [a], Mohamed Faisal [a], Alaa H. Hawari [c], Hareb Al-Jabri [a,b]

[a] Algal Technology Program, Center for Sustainable Development, College of Arts and Sciences, Qatar University, Doha, Qatar
[b] Department of Biological and Environmental Sciences, College of Arts and Sciences, Qatar University, Doha, Qatar
[c] Department of Civil and Environmental Engineering, Qatar University, Doha, Qatar

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ABSTRACT

This application note proposes a novel, low-cost, pH-controlled solenoid-based CO_2 dosing device for microalgal and cyanobacterial cultivation systems. The device consists of an Arduino-Uno microcontroller, a (ph-4502c) module, a pH probe, a micro-SD card for data logging, and a relay-controlled solenoid valve. C functions are used to control, and data log the pH and operate the solenoid valve for CO_2 dosing in microalgal cultivation systems. With open-source programming, the device can be used for a wide range of applications in both industry and academia. The proposed device is flexible, customizable, and upgradable. This study aims to develop a low-cost pH-controlled, solenoid-based CO_2 dosing and data logging device and utilize it for pH control and CO_2 dosing in a 200 L outdoor raceway tanks utilized in cultivating and studying the growth of marine cyanobacterium *Geitlerinema* sp. and *Spirulina* sp.

1. Introduction

Climate change consistently poses a hazard to the ecosystem and environment. The average global temperature in 2020 has risen by 1.1 °C due to rising greenhouse gas emissions [18]. Carbon dioxide makes up the majority, or around 65 %, of the increased greenhouse gas effect [11,26]. Atmospheric CO_2 must be lowered to reduce the consequences of CO_2-induced climate changes [19]. Utilizing photosynthetic microorganisms for lowering CO_2 emissions is a potential strategy [21]. Like terrestrial plants, photosynthetic algae (i.e., cyanobacteria and microalgae) are capable of utilizing atmospheric CO_2 [22]. Instead of cultivating microalgae in fresh water, these photosynthetic microorganisms could also be cultivated in brackish and seawater, wastewater, and produced water [2,5]. Furthermore, cyanobacteria and microalgae can be cultivated at various temperatures on non-arable lands [6,7]. Microalgae and cyanobacteria require approximately 1.83 to 1.88 kg of atmospheric carbon dioxide to generate a kilogram (kg) of biomass with varying quantities of proteins, lipids, and carbohydrates [20,25]. Microalgae can be cultivated in open raceway ponds and photobioreactors.

The microalgal biomass productivity in photobioreactors and large-scale open raceway ponds can be enhanced by thoroughly controlling the pH of the cultivation system [12]. CO_2 or bicarbonate is added to algal cultivation systems to enhance biomass concentrations and productivity. In these systems, CO_2 or bicarbonate typically exists in the inorganic forms of bicarbonate (HCO_3^-), carbonate (CO_3^{2-}), and carbonic acid (H_2CO_3). A specific pH regulation between 7.4 and 8.5 is required for the aforementioned inorganic forms to be used effectively by microalgae and cyanobacterial strains [12–14]. The pH of microalgal cultivation systems are currently controlled utilizing a proportional-integral (PI) coupled to a feedforward controller and pulse width modulation (PWM) or an on-off control loop methods [8,10,24]. Integral control pH systems may be too expensive. Similarly, utilizing on-off algorithmic pH systems could cause oscillations around the desired pH, increasing the need for CO_2 in the microalgal culture system and increasing costs [10].

The objective of this application note is to develop to make available for the first time a low-cost, solenoid-based Arduino micro-controlled pH regulating device for microalgal and cyanobacterial culture systems. The application note will additionally provide background information on the critical role of pH in the cultivation of algae (section 2.1) and the various types of pH controllers utilized for microalgae

* Corresponding author.
E-mail address: probir.das@qu.edu.qa (P. Das).

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cultivation (section 2.2). Furthermore, introduction part of this application note also discusses the advantages and disadvantages of the existing pH-controlling devices. The developed pH-controlling device's source code (subsection 3.2.1 and 3.2.2), hardware, and comparative microalgae cultivation (section 3.1) are all described in the methodology (section 3), the hardware and source code can be upgraded and adjusted to meet the requirements of microalgae or cyanobacteria cultivation. The proposed device (section 4) is tested for controlling the pH of a cyanobacterium *Geitlerinema* sp. and *Spirulina* sp. in an outdoor 200 L raceway tank.

2. Background

2.1. The influence of pH regulation on the growth of microalgae and cyanobacteria

Several variables regulate algae growth, including pH, temperature, nutrients, and light. The growth of algae is significantly affected by the aforementioned parameters, particularly pH. In microalgae and cyanobacteria, the pH of the growth medium affects the uptake of organic and inorganic ions, nutrients, enzyme activity, and toxicity toward ammonia [27]. Additionally, any specific pH level in the algal production system can induce microalgae or cyanobacteria to flocculate or form big and small loosely grouped conglomerates, which can cause the culture to collapse or be contaminated by undesirable microalgal strains [15]. When cultivating microalgae or cyanobacteria in wastewater, pH is crucial. If the pH is not controlled and increases above 9, nitrogen in the form of ammonia may be lost by means of volatilization, and ammonia could be toxic to photosynthesis, and this could inhibit microalgal growth [10].

Acid-base titration type pH control devices can be useful for monitoring the growth and metabolites of microalgae and cyanobacteria in small-size indoor photobioreactors. As an alternative to acid and base solutions, pH buffers can be used in titration-based pH control systems. However, using acid, base, and organic buffers to adjust the pH of microalgal growth systems may have negative side effects or even be toxic to some algal strains [4]. The use of the titration type pH control system may be restricted to small-volume photobioreactors and may not be appropriate for large-scale culture systems like open raceway ponds (ORPs) and high-rate algal ponds (HRAPs).

In large-scale microalgal growing systems, the on/off type pH controlling system has considerably improved microalgal biomass productivity [10]. The on/off pH controller systems function on set point oscillations, and these oscillations may require the addition of extra CO_2, which could be expensive. In addition, extra CO_2 added to cultivation systems might escape into the atmosphere, acting as a greenhouse gas (GHG) and contributing to global warming [3]. Comparatively, some studies report that PI-controlled pH systems utilize less CO_2 than on/off pH control systems, while other studies claim that CO_2 use is increased [10]. Using multiple independent components, such as a controller, a personal computer (PC), communication circuits, and connectivity via wireless, renders the PI-based pH control system expensive and installation in indoor and outdoor production challenging [10].

2.2. Types of pH controllers utilized in the algal cultivation system

Presently, the types of pH controllers used in microalgal growing systems are 1) Titration acid-base type pH controller [9], 2) PI-feed forward-PWM pH controller [8], 3) on/off type pH controllers [24]. The two-point relay system used by the acid-base type pH controller has relays connected to acid and base pumps. The reservoirs for sodium hydroxide (NaOH) and hydrochloric acid (HCl) are linked to the acid and base pumps. The pH is controlled until the culture alters by 0.1. The relay is configured to start titrating 30 s after a 0.1 increase or decrease from the pH set point [9].

The universal asynchronous reception and transmission (UART) and inter-integrated circuit (12 C) protocol-equipped myRIO controller and a pH sensor kit with a UART and 12 C that transmits and receives pH data to myRIO controller make up the PI-feed forward-PWM pH system. The output of the myRIO controller is wired to a 12 Vs direct current (VDC) solenoid valve, which controls the CO_2 gas dosage in the microalgae raceway pond. The pH data was recorded using the LabVIEW program in.csv format. During microalgae growth, the pH readings were recorded every 30 s [10].

Another on/off type pH controller from the algae research Centre at Murdoch University is reported to have a triple phase shift (TPS) module; the data was transferred using USB and logged to a 20 mA powered data logger at every 30 s interval. For CO_2 dosing, a TPS controller module was connected to a 12 VDC solenoid valve similar to the aforementioned PI controller [10].

3. Methodology

3.1. Outdoor cultivation of Geitlerinema and Spirulina sp. in 200 L open raceway tanks

For this study, two locally isolated strains one marine —*Geitlerinema* sp., and brackish *Spirulina* sp. were selected. The isolated samples were taken from Qatar University Culture Collection of Cyanobacteria and Microalgae (QUCCCM). Colonies of *Geitlerinema* and *Spirulina* sp. were transferred from agar plates to a 250 mL Erlenmayer flask that contained 100 mL of modified Guillard (3 x f/2) nutrients nutrient media in an Innova 44 shaker with light and temperature control. After that, 80–100 mL of microalgal cultures from the Erlenmayer flasks were transferred to 1 L photobioreactors (PBRs), where they were grown for 7 days in the same trace metal concentrations as recommended in the f/2 medium with 26 mg/L urea and 5 mg/L mono sodium hydrogen phosphate as sources of nitrogen and phosphorus. 1 L of PBR culture was transferred to a 10 L plastic PBR with a 20 cm diameter after seven days. For each strain, three plastic PBRs were utilized. White fluorescent light at a density of 500 mE/m2/s was used to illuminate the 10 L plastic PBRs. The PBRs were sparged with air using an air stone that had a flow rate of 0.5 L/L/min. The subsequent stage required transferring 20 L of each microalgal strain grown in PBRs to 1 sq. m. open raceway tanks with a working capacity of 200 L.

The salinities for *Geitlerinema* and *Spirulina* sp. were maintained at 40 and 5 ppt (parts per thousand). The evaporated water loss in the 200 L raceway tank was compensated by adding freshwater. *Geitlerinema* sp. was grown in two 200 L open raceway tanks: one was utilized as a control (no CO_2 addition), and the other was given a CO_2 dose using a solenoid-based pH dosing device. However, *Spirulina* sp. was cultivated in three 200 L tanks: one was left as a control (i.e., without CO_2 and bicarbonate), the second tank had pH-based CO_2 dosing using the developed Arduino microcontroller, and the third tank contained 2.0 g/L sodium bicarbonate as a carbon source. To determine the biomass growth as (g/L) of the selected strains, 50 mL samples were taken daily from each of the 200 L open raceway tanks containing *Geitlerinema* and *Spirulina* sp.

3.2. Hardware and software development

3.2.1. pH module, relay-controlled solenoid valve, and arduino microcontroller

The pH controlling device (Fig. 1), comprises of a pH(4502C) module, capable of detecting pH ranging from 0 to 14, and a temperature working range of 10 to 50 °C, the working voltage is 5 V, and the output is an analog pin (A2) voltage signal.

As shown in Fig. 1, the analog PO pin of the pH(4502C) module is connected to pin A2 of the Arduino microcontroller. The Arduino's pin 10 is connected to the relay pin that controls the solenoid valve. The pH is calculated as voltage and can be modified in the source code to trigger the opening or closing of the relay, which then opens or closes the

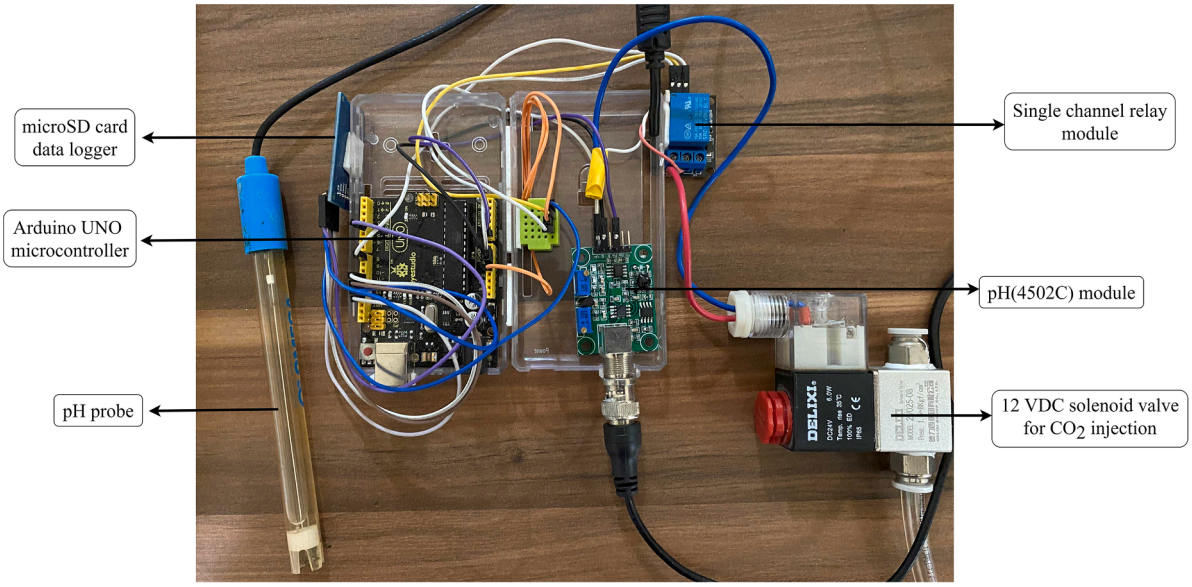

Fig. 1. Arduino-controlled pH measuring device with relay-controlled solenoid valve with microSD data logger.

solenoid valve. The pH reading minimum time option ranges from 0.1 s to any suitable time restriction setting. According to the needs of microalgal cultivation, the higher and lower pH values can be regulated. A microSD card module needs secure digital (SD) and serial peripheral interphase (SPI) libraries included in the source code for data logging. A microSD card module uses (SPI) to connect with a microcontroller. Data is logged in a.txt file created on the microSD card, which may then be later copied to Microsoft Excel for further data analysis and interpretation. The source code uploaded pH controlling device could be installed next to the culture system (see supplementary), and the pH monitoring probe could be kept directly in the microalgal raceway tank or photobioreactors. A 12 V AC to DC power adaptor can be used to power the device and connected to an arduino UNO microcontroller. The CO_2 injecting solenoid valve connected to the 5 V relay requires a 24 V AC to DC converter. The maximum working pressure for the CO_2 injecting solenoid valve is 5 bar. The solenoid valve opens and closes based on the HIGH and LOW signals it receives from the Arduino microcontroller-controlled 5 V single-channel relay module.

3.2.2. *Source code for the pH controlling device*

```
#include <Arduino.h>
#include <SPI.h>
#include <SD.h>
int pH = A2;
int samp = 5;
float dc_resol = 1024;
int relayswitch = 10;
const int chips = 2;
void setup()
{
pinMode(10, OUTPUT);
Serial.begin(9600);
Serial.println("CF");
Serial.begin(9600);
while (!Serial) {;
}
Serial.print("Initialize");
if (!SD.begin(chips))
{
Serial.println("CF");
while (1);
}
Serial.println("sdinitiated.");
}
float ph (float pvolt) {
return 7 + ((2.5 - pvolt) / 0.18);
}
void loop()
{
int measures=0;
for (int i = 0; i < samp; i++)
{
measures += analogRead(pH);
delay(5);
}
float volt = 5 / dc_resol * measures/samp;
Serial.print("pHval");
Serial.println(ph(volt));
delay(600000);
if (ph(volt)>8.3)
{
digitalWrite(8,HIGH);
}
else if (ph(volt)<7.0)
{
digitalWrite(8,LOW);
}String dataString = "pH";
for (int AP = A0; AP < 3; AP++) {
int sensor = analogRead(A2);
dataString += String(ph(volt));
if (AP > 2) {
dataString += "(ph(volt))";
}}
}
File DF = SD.open("DFlog.txt", FILE_WRITE);
if (DF) {
DF.println(ph(volt));
DF.close();
// print to the serial port too:
Serial.println(ph(volt));
}
}
```

4. Results and discussion

4.1. Cultivation of Geitlerinema sp

The growth of *Geitlerinema* sp. in the control and a pH-based CO_2 injection conditions are shown in Fig. 2a. The final biomass density of the *Geitlerinema* sp. in the Arduino-based CO_2 injection culture system was 0.18 g/L higher than the control cultivation system, as shown in Fig. 2b. It is evident that the atmospheric diffusion of CO_2 is a limiting factor for high biomass yield – undermining the potential of microalgae based application. Therefore, a pH-controlled CO_2 dosing system, such as the one developed in this study, could increase the biomass yield while reducing CO_2 loss. Similar to the above, a further study found that *Geitlerinema* sp. biomass density at ambient CO_2 conditions could reach 0.802 g/L while it achieved 0.96 g/L in a CO_2 enhanced culture system, a 0.15 g/L difference in biomass density [1].

The device utilized in this work had been programmed to inject CO_2 if the pH was over 8.3 and to stop injecting CO_2 once the pH was below 7.0. The device was also capable of monitoring pH at intervals of 10 min (Fig. 2c), storing the results in a.txt file, and recording the data in real time, as shown in Fig. 2c. The pH of the *Geitlerinema* sp. cultivation system ranged from 7.7 to 8.7 on average during the 12 h of daylight, whereas it ranged from 6.6 to 7.9 on average during the early hours of the night. According to Fig. 2b, the device could only have injected CO_2 during the day because the pH increased over the setpoint of 8.3 pH for CO_2 injection, indicating greater photosynthetic development of marine cyanobacterium. The absence of CO_2 injection during the nighttime implies lower photosynthetic activity and lower biomass productivity. (Fig. 2c). The pH measurement was done using one point, and the injected CO_2 might have required some time to solubilize throughout the culture uniformly. For commercial microalgal biomass production, the cultivation system is expected to be several orders larger in size. The average value of multiple pH sensors, high concentrations of pulsed CO_2, or a combination of these strategies could minimize errors and better control the culture pH.

4.2. Cultivation of Spirulina sp

As shown in Fig. 3a, *Spirulina* sp. was cultivated in three 200 L tanks; Fig. 3b displays the biomass densities attained for all three tanks. The pH

Fig. 2a. Left - *Geitlerinema* sp. cultivation tank with CO_2 dosing device, Right - Control tank.

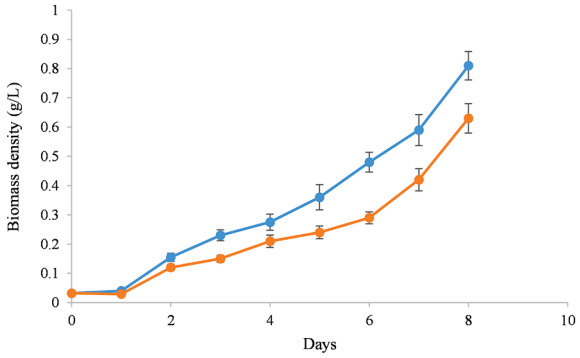

Fig. 2b. Growth comparison of *Geitlerinema* sp. cultivation in 200 L outdoor raceway tank.

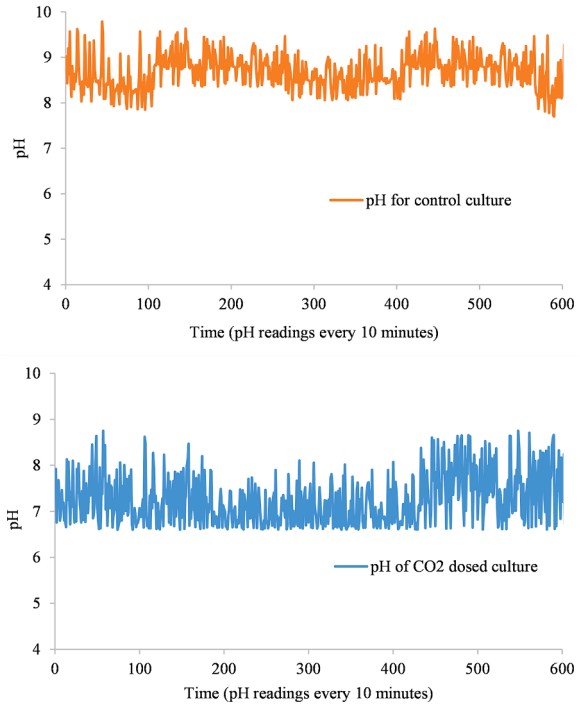

Fig. 2c. pH monitoring in 200 L *Geitlerinema* sp. cultivation system using pH-controlled solenoid-based CO_2 dosing device.

sensor was programmed to start injecting CO_2 when the pH value reached 8.3 and to cease when the pH reached 7.0. In Fig. 3c, the sensor readings recorded for 10 min are shown. Similar to *Geitlerinema* sp., the biomass density for the pH-dosed *Spirulina* cultivation system was 0.17 g/L higher than that of the control culture and 0.07 g/L higher than sodium bicarbonate-added culture. For this study, a fixed amount of sodium bicarbonate (2 g/L) was added at the beginning of the experiment. Further optimization of sodium bicarbonate addition could have resulted better yield. Similar to this, another study found that carbon dioxide injection increased the growth of *Spirulina* when compared to a control system, or a cultivation system without CO_2 [23].

The maximum pH values recorded in the control and CO_2-dosed Geitlerinema sp. cultures were 9.79 and 8.75, respectively. The maximum pH values for the control and CO_2-dosed Spirulina sp. cultures were 9.6 and 9, respectively. Controlled CO2 dosing increased dissolved CO2 concentration in the culture – supporting higher biomass productivity.

Typically, sodium bicarbonate is used to grow *Spirulina* sp. commercially. For every ton of *Spirulina* biomass production, almost 2

Fig. 3a. *Spirulina* sp. cultivation in 200 L outdoor raceway tank, from left to right (Tank A) - pH controlled CO_2 dosing device, (Tank B) – Control.

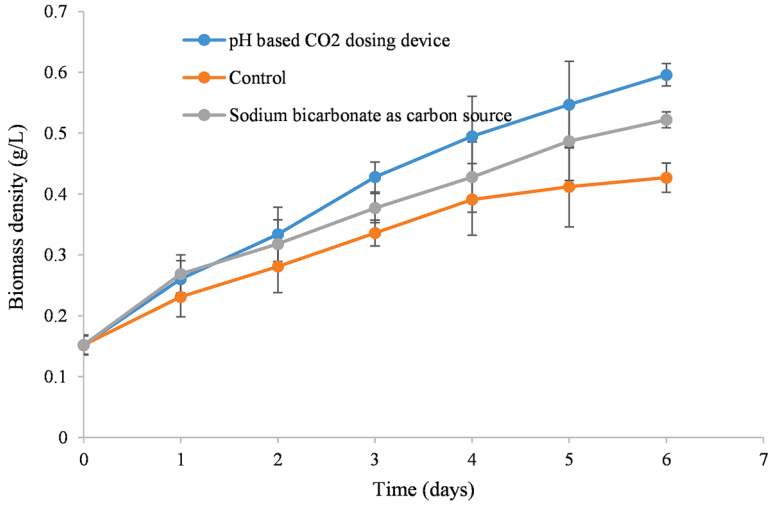

Fig. 3b. Growth comparison of *Spirulina* sp. cultivation in 200 L outdoor raceway tank.

ton of sodium bicarbonate is required [17]. The bulk price of sodium bicarbonate is approximately 400$/ton; hence, almost 800$ will be required for sodium bicarbonate alone to produce one ton of *Spirulina* biomass. Recently, Direct Air Capture (DAC) of carbon dioxide is being studied extensively to remove CO_2 from the atmosphere [16]. Captured CO_2 then could be utilized efficiently using an Arduino-based, pH-controlled, low-cost CO_2 dosing system. For any microalgae, an optimum culture pH range needs to be maintained for higher CO_2 utilization and more optimization would be needed for such Arduino-based pH-dosing system for efficient CO_2 utilization and enhanced biomass productivity.

5. Conclusion and future trends

This application note discusses a low-cost CO_2 injection-controlled solenoid pH-controlling device for microalgal cultivation systems. The proposed device does not need additional controllers, a PC, or expensive data-logging software like those discussed in this article. The proposed device could save data directly into Microsoft Excel or on a microSD card with just a little source code modification. In addition to managing pH for the growth of algae, the device might be used to control the pH of chemical and fermentation reaction processes. The study's source code can be modified, updated, and used to control the pH's range of values between 0 and 14. Furthermore, the solenoid function of the proposed device could be linked to CO_2 gas mass flow controllers to quantify the amount of CO_2 gas injection and determine algal CO_2 utilization efficiency. The implementation of a newly developed CO_2 dosing device could successfully improve the biomass densities of *Geitlerinema* and *Spiruilna* sp grown in 200 L open raceway cultivation tanks. Therefore, the device could be a low-cost option for an efficient and sustainable CO_2 capture for various microalgal cultivation systems. The proposed device could be 3D printed and compacted as a modular unit for research labs, industry, and academia.

Ethics statement

Not applicable: This manuscript does not include human or animal research.

CRediT authorship contribution statement

Shoyeb Khan: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft. **Probir Das:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Visualization, Writing – review & editing. **Mahmoud Thaher:** Data curation, Investigation, Resources, Validation, Writing – original draft. **Mohammed Abdulquadir:** Data curation, Investigation, Resources, Validation, Writing – original draft. **Mohamed Faisal:** Data curation, Investigation, Resources, Validation. **Alaa H. Hawari:** Supervision, Writing – review & editing. **Hareb Al-Jabri:** Resources, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

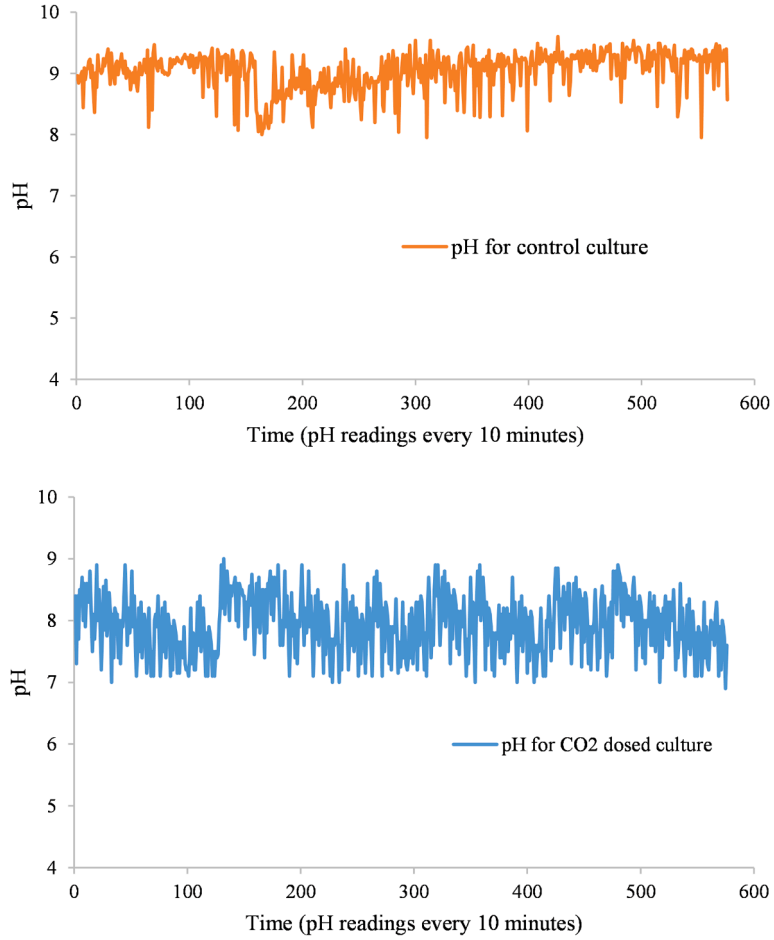

Fig. 3c. pH monitoring in 200 L *Spirulina* sp. cultivation system using pH-controlled solenoid-based CO_2 dosing device.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.atech.2023.100373.

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