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Educational Approaches to Bioprocess Engineering Using DIY Bioreactors for Scientific Literacy

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Abstract: The interdisciplinary nature of science, technology, engineering, and mathematics (STEM) offers the opportunity to implement educational approaches to biotechnology and process engineering issues. The focus should be on the promotion of scientific literacy in contexts relevant to research, industry, and society. This article specifically shows the development of suitable low-level experiments to provide a milestone for the implementation of biotechnological and process engineering issues in STEM education. The experiments show the successful transfer of inquiry-based bioprocess engineering experiments with a Do-It-Yourself (DIY) bioreactor and low-cost sensors. It was possible to achieve comparable trends of process-relevant state variables like mixing time and volumetric mass transfer coefficient (k_La) for the DIY bioreactor in comparison to established commercial systems. Furthermore, microalga *Microchloropsis gaditana* could be successfully cultivated under different cultivation conditions in the DIY system, and the respective growth curves could be observed. The DIY system is well suited for experimental application in schools and provides a scientifically substantiated basis for data interpretation. The scientific outreach approach and cooperation in a multiprofessional team for the transfer of process engineering questions to education can be evaluated as enriching. Experiments involving educational concepts offer a variety of connecting elements in the curriculum and opportunities to foster scientific literacy.

Keywords: STEM-education; interdisciplinary; science outreach; scientific literacy; socio-scientific issue; bioprocess engineering; do it yourself; bioreactor technology

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1. Introduction

1.1. STEM Challenges

Modern society is challenged by enormous tasks that require innovative solutions and expertise in science, technology, engineering, and mathematics (STEM). These challenges include socio-scientific issues, e.g., pandemic response, climate protection, discussions on alternative energy supply in the course of the energy transition, alternative raw or building materials, and digital transformation (acatech & Körber-Stiftung, 2021). To ensure that today's generation of school students can develop into tomorrow's STEM experts to solve these problems, STEM education is of crucial importance. Until now, there has been a

transformation of STEM education based on the following three key factors to achieve these goals: (i) a change in teaching to improve perception and increase enthusiasm for STEM subjects (Bettinger, 2010; Krapp & Prenzel, 2011), (ii) a bigger focus on connecting knowledge from the classroom to real-world problems (21st-century skills) (Krapp & Prenzel, 2011), and (iii) the breakdown of disciplinary silo thinking and promotion of interdisciplinary and connected thinking between STEM education and other disciplines (Stifterverband, 2022). In combination, these goals should lead to more STEM experts with developed scientific literacy who will be able to tackle the difficulties of 21st-century challenges with innovative solutions. Modern STEM courses in schools have to ensure that the interface between science and schools is tangible, with suitable teaching concepts. They should also create awareness of the fact that the sciences continually offer a wealth of new or further research topics that are important for the future. STEM education in schools needs to enable authentic participation in scientific, research-based learning processes in the classroom to create interesting and effective learning contexts (Bohrmann-Linde et al., 2021; Parchmann et al., 2001). Socio-scientific issues are perceived as an authentic and interesting context by school students (van Vorst et al., 2014), e.g., the role of microalgae in the course of climate protection. Authentic participation in scientific research-oriented knowledge processes in the course of instruction is essential for the development of scientific literacy. In addition to scientific literacy, 21st-century skills, such as adaptability, communication, problem solving, critical thinking, collaboration, and self-management, are important for the management of current and future tasks in the world of work and life (Bybee, 2013; Ohio Department of Education, 2016; Stehle & Peters-Burton, 2019).

1.2. The Importance of Inquiry-Based Learning

However, there is currently a gap between relevant research topics and experimental methods from research and teaching in STEM education, which often only transfer basic knowledge and do not include in-depth knowledge considering practical, future, and career-oriented aspects. The experimental methods explained in textbooks are often outdated by the time young people start their careers in science or have been replaced some time ago. In addition, the repertoire of experimental equipment of schools is limited due to financial constraints or teachers' expertise in research topics and experiments. The gap is also caused by the fact that technical issues are presented in an unfamiliar, inaccessible, or often incomprehensible way to people outside the scientific community (Miller, 1998; Miller & Pardo, 2000). Thus, the gap between science and school widens to a gap between science and society as a whole (Bensaude-Vincent, 2001; Holbrook & Rannikmae, 2007). This work is presented in the wake of the call in German national guidelines for schools to promote interdisciplinarity, inquiry-based learning and authentic inquiry experiences in STEM education, focusing on the transfer of relevant STEM problems to school education. In particular, the technology and engineering parts of STEM education are under-represented in the German curriculum, while the focus lies on science and mathematics. Although interest in biotechnology and (bio-) process engineering in Germany increased during the first decade of the 21st century, there was a decline in new students at universities, especially in the subject of (bio-) process engineering (−37.9 %) while the number of new biotechnology students remained unchanged (Statistisches Bundesamt, 2010).

1.3. Bridging the Gap with a DIY Bioreactor

The biotechnology industry offers a future-oriented market for STEM experts and is significantly involved in implementation strategies with respect to the Sustainable Development Goals (SDGs) (Olabi et al., 2023). No more than microbiological and biotechnological basics are taught in German schools. But large-scale production, e.g., of insulin from bacterium

Escherichia coli, and the associated challenges are virtually not covered. In order to teach these concepts and spark interest in biotechnology in young people, a practical demonstration is necessary. In 1992, Roberts et al. (1992) developed simple experimental procedures to determine the effects of stirring on oxygen mass transfer in a bioreactor. However, the implementation of such simple experiments to characterize bioreactors for process engineering parameters in a suitable educational setting requires appropriate hardware. But schools often have limited financial budgets, and even small-scale commercial bioreactors are too expensive for them. With the emerging idea of open-source projects and through the use of 3D-printed components, current low-cost technologies can be introduced into education with limited budgets to promote areas of technology and digital literacy (UNESCO, 2018). The idea of low-cost, open-source bioreactors is not new. Some studies have already proposed DIY bioreactor concepts (Gopalakrishnan et al., 2022; Steel et al., 2019) and used them in school experiments for the determination of bacterial growth and to demonstrate the evolution of drug resistance in bacterial cultures (Gopalakrishnan et al., 2022). These low-cost bioreactors and their possible applications leave a gap in process engineering issues that are often neglected in school lessons but that are just as important in terms of awakening students' interest in technology. The DIY bioreactor that was used in this study is intended to allow for the execution of experiments for the determination of characteristic parameters of a bioreactor, like mixing time and oxygen gas transfer, as well as cultivation of microalgae to a scale suitable for schools. These concepts are important cornerstones for students at universities in biotechnology or bioprocess engineering and are, therefore, well suited to get school students familiar with concepts taught at universities. This article sets a milestone towards the implementation of process engineering experiments in the classroom and offers a chance to teach these crucial concepts to students, helping to increase the interest of young people in the field of biotechnology and promote scientific literacy.

The central contributions of this article are outlined as follows:

i Construction of educational approaches to increase STEM expertise of future generations in a research-oriented context of bioprocess engineering and biotechnology;
ii Successful transfer of research-based bioprocess engineering experiments to school experiments with DIY bioreactors and low-cost sensors that reproduce trends of process-relevant state variables that are comparable to those achieved with conventional laboratory equipment;
iii Experimental protocol to determine the volumetric mass transfer coefficient (k_La) and mixing time of different apparatuses of the DIY bioreactor in a low-level experiment in order to discuss optimization steps in the industrial process;
iv Successful cultivation of microalga *Microchloropsis gaditana* for comparison of different cultivation conditions in the DIY bioreactor;
v Didactic analysis and integration of the developed experiments into science education curricula to promote scientific literacy.

2. Theoretical Background

2.1. Science Outreach

Studies show that many school students have mostly positive attitudes toward STEM subjects, but past science education seems to have failed to capitalize on these positive student attitudes (OECD, 2006; Sjøberg & Schreiner, 2019). This is reflected in the declining number of students choosing science and technology, with women still under-represented in STEM subjects (Domingo et al., 2019; OECD, 2008; UNESCO, 2017). As mentioned in the Introduction, there has been a transformation of STEM education. Previous studies have also showed ways to reduce this alarming decline in student interest in science. For example, Rocard et al. (2007) cite the promotion of students' self-concept in science,

especially among female students. In addition, approaches to inquiry-based learning and integration of more hands-on work are recommended (Boiko et al., 2019; Rocard et al., 2007), as well as face-to-face contact between students in the context of out-of-school learning opportunities (Lyons & Quinn, 2010). These recommendations are implemented in science outreach projects through active, hands-on experimentation activities, usually provided by science departments of universities, research institutions, and science centers. In return, this requires universities to share their knowledge, education, and joy for learning with the people around them. In addition, science outreach justifies projects to meet the increasing desire of civil society to participate (BMBF, 2021). Woithe et al. (2022) showed that intervention in a science outreach lab resulted in very high situational interest and self-concept of the students. In addition, the initial motivational difference between genders was equalized after the intervention. In a review, Vennix et al. (2017) present perceptions of STEM-based outreach learning activities in secondary education and highlight that outreach learning environments can create opportunities to increase students' motivation in STEM. Above all, this science communication applies especially with regard to current research on socially relevant topics, such as implementation strategies of the global SDGs (United Nations, 2015). However, very few inquiry-based statements exist to date on how to best engage the non-specialist public (Enzingmüller et al., 2019). One important prerequisite for successful science outreach is already known: Close collaboration between scientists and educators is essential to make research topics accessible to students and non-experts (Parchmann & Kuhn, 2016). The participation of students in this collaboration, in turn, has the effect of providing future teachers with an image of constantly evolving science during their education. Current challenges in terms of equitable educational opportunities and preparation for the challenges of the future world require close collaboration between all actors and institutions involved in teacher education. Transformation requires networking and collaboration, as well as the maintenance of interfaces between phases of teacher education and educational institutions, in order to manage the transfer of knowledge in an interdisciplinary and interinstitutional way. Thus, the content of current scientific research becomes part of the teacher education curriculum, enabling students to apply their acquired knowledge to new issues and to develop questions with reference to new scientific territory. These professionalization structures in university teacher education are necessary, as are continuing education concepts, and form the bridge from university collaboration between scientists and subject didactics to schools (Bohrmann-Linde et al., 2021).

This article expands on a previously published article by Geuer et al. (2023) in which biotechnological research topics are didactically reconstructed based on the Model of Educational Reconstruction (Duit et al., 2012). Therefore, a multiprofessional team of didacticians and bioprocess engineers collaborate to collect subject-specific concepts and student perspectives to put them in meaningful relationship to create a science outreach context for students (Duit et al., 2012; Saadat et al., 2019). The research-oriented experiments presented on the cultivation of microalgae and yeast cells suggest the idea of focusing on engineering and (bio)process concepts for the cultivation of microorganisms. The educational approaches to process engineering using DIY bioreactors for scientific literacy presented in the article are further examples of science outreach developed by a multiprofessional team consisting of scientists from the subject disciplines and the corresponding subject didactics. For the implementation of this process, the model of educational transfer serves as a theoretical framework (Bartram & Wilke, 2018). As already mentioned in the Introduction, the elaborated experiments have the task of bridging the existing gap between research and school education, in addition to creating important links between the scientific community and the general public (Crawford et al., 2019; Ledbetter, 2012; Trafton, 2014).

2.2. Microorganisms as Factories of the Future

Microorganisms have a long tradition of being used as cell factories for the large-scale production of biotechnological products such as alternative fuels, vaccines, pharmaceuticals, and food and feed ingredients, as well as basic chemical substances such as organic acids and amino acids. Microbial metabolic pathways have often been modified using molecular biology methods or supplemented with new properties to be used for the production of specific, tailor-made biotechnological products. With further research into new sources of raw materials or new medical treatment methods, microorganisms are laying the foundations for ongoing global changes in living conditions, especially in the medical and biotechnological fields. Therefore, microorganisms have a variety of functions that affect almost every aspect of our lives. Not all of these microorganisms whose abilities humanity uses for production of various products can be used as model organism to teach biotechnological concepts to students. In particular, the use of genetically modified organisms is heavily restricted in Germany, making them impossible to use in the school environment .

Microalgae and cyanobacteria are good candidates to demonstrate the growth of microorganisms in schools. In the context of climate change and our transformation towards more environmentally friendly industry, they have a relevant field of applications. They are used for the production of biodiesel and biofuels, as well as in the production of natural dyes (Chakdar et al., 2012; Dufossé et al., 2005; Yin et al., 2020). They also find applications as fertilizers (Kollmen & Strieth, 2022; Strieth et al., 2018), in cosmetics (Çağlaand et al., 2020), and as food supplements (Gantar & Svirčev, 2008). In addition, in the course of the ever-growing trend toward plant-based nutrition, phototrophic microalgae and cyanobacteria are making their way onto food shelves. In addition to its interesting field of application, the cultivation of microalgae and cyanobacteria can be as simple as cultivation in a salt-based culture medium without a source of sugar.

Thus, the diverse current research fields on microalgae and cyanobacteria as "factories of the future" can be crucial for students' conceptions of scientific contexts in the real world. The integration microorganisms in STEM education creates authentic contexts for inquiry-based learning, playing an influential role in building scientific literacy.

2.3. Cultivation and Process-Relevant State Variables in the Bioreactor

For the transfer of lab experiments to low-level school experiments, two parameters were selected that represent important process-relevant state variables in a bioreactor and enable learners to consider simple process engineering questions in the school context.

i Homogenization and mixing time: The mixing time is the time required to achieve a pre-defined grade of homogeneity in the liquid.

ii Volumetric mass transfer coefficient (k_La) value: The k_La describes the rate at which a gas, for example, oxygen or carbon dioxide, is transferred from the gas phase to the liquid phase of a bioreactor.

The principle of mass transfer of gases can be taught using either oxygen or carbon dioxide. In this paper, oxygen transfer was chosen for visualization, as affordable dissolved oxygen probes are readily available in the DIY sector, whereas probes for carbon dioxide are more expensive. In the following subsections, the important process-relevant state variables of "homogenization and mixing" and "oxygen transfer" in the system are discussed in more detail.

2.3.1. Homogenization and Mixing Time

Macroscopic mixing of the liquid in a bioreactor is of great importance for the overall bioprocess. If the liquid in a bioreactor is not mixed, local peaks or low points of, for example, nutrients, oxygen, carbon dioxide, pH values, or temperature may be formed

(Chmiel, 2011). Therefore, the objective of mixing in a bioreactor is to improve the homogeneity of the liquid concentrations, the suspension of particles or bacterial cells, the dispersion of gas bubbles in aerated bioreactors, and the improvement of the heat transfer to or from the liquid (Katoh et al., 2015). The mixing time is defined as the time that is required for a tracer that is inserted in the vessel to reach a certain deviation from the final concentration (Katoh et al., 2015). This deviation is dependent on the desirable degree of homogeneity in the system, which can be calculated as

$$H(t) = \frac{c_{T,0} - c(t)}{c_{T,0} - c_{T,\infty}} \quad (1)$$

2.3.2. Oxygen Transfer Efficiency and Volumetric Oxygen Mass Transfer Coefficient

Oxygen is an important nutrient for microorganisms in aerobic bioprocesses. Due to the low solubility of oxygen in culture media (water), a continuous supply of oxygen to the bioreactor is necessary to avoid deficiency of the microorganisms. Various methods for determining the k_La value are described in the literature (Garcia-Ochoa & Gomez, 2008; Van't Riet, 1979). One frequently used method is the outgassing method. In this method, oxygen is first depleted from the liquid, for example, by introducing nitrogen gas (Figure 1).

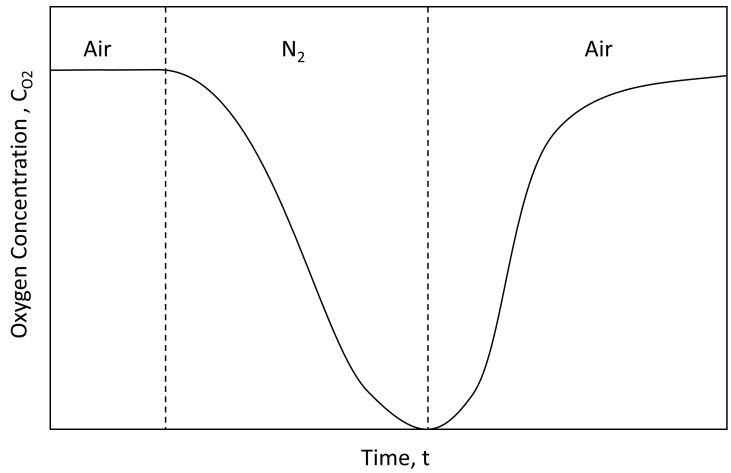

Figure 1. Schematic overview of oxygen concentration in a bioreactor during k_La measurement with the outgassing methodology. Modified from Hass and Pörtner (2011). The diagram shows the schematic progression of the oxygen concentration in a bioreactor during k_La measurement using the outgassing method. At the beginning, the oxygen is removed, causing the concentration to fall. It then rises as soon as oxygen is introduced into the system. The increase follows a typical saturation curve.

Air is then supplied according to the conditions during cultivation. During this process, the dissolved oxygen concentration (C_L) is monitored with a suitable sensor. Students can monitor this behavior to observe how the gas dissolves from the gas phase into the liquid phase through the increase in C_L up to a maximum concentration C^*. In addition to monitoring this qualitative behavior, students with basic knowledge of linear equations and logarithms can calculate the k_La based on C_L and C^*. To achieve this, they have to plot the following linear equation:

$$ln\left(1 - \frac{C_L}{C^*}\right) = -k_La \cdot t \quad (2)$$

From the slope of the logarithmic plot over time, the k_La value can be determined. Like the mixing time, the oxygen transfer and, thus, the k_La value are of great importance for the evaluation and scale up of bioprocesses. The k_La value can be determined with students

and can be used as a teaching aid for topics such as cellular respiration of microorganisms in the curricula of schools.

3. Experimental Section

A first aim was to transfer lab experiments to low-level school experiments to investigate the important process-relevant state variables of "homogenization and mixing" and "oxygen transfer". For this purpose, a DIY bioreactor with low-cost sensors is used. The experiments represent a first milestone in the transfer of process engineering issues to the school context. Therefore, as a first step, it was important to successfully transfer and reproduce comparable trends depending on these process-relevant state variables with respect to the variation of gassing and stirring with DIY bioreactors and low-cost sensors compared to a conventional laboratory apparatus. The second aim was to cultivate microalga *M. gaditana* in the DIY bioreactor with different cultivation conditions with regard to the variation of gassing and stirring. The variation of the cultivation conditions is closely related to the process-relevant state variables considered in the first experiments. The results of these experiments can be used as a basis for interpretation of the results of the comparison of the cultivation conditions. The aim of the experiments on cultivation was to observe effects of homogeneity by stirring and gassing with respect to the growth of a microalga in order to determine a transferable context of the theoretical experiments on characterization. In the didactic commentary, educational approaches and alternative strategies for integration into science education are discussed, learning objectives and competence domains are formulated, and further experiments based on the selected contexts of microorganisms are discussed in order to draw conclusions about cultivation conditions.

The objectives of the experiments are outlined as follows:

i Transfer of theoretical trends of mixing time in a stirred-tank bioreactor (Minifors Infors HT) to a DIY bioreactor with variation of the state variables of gassing and stirring, measured with a low-cost sensor;
ii Transfer of theoretical trends of k_La in a Minifors bioreactor (Infors HT) to a DIY bioreactor with variation of the state variables of gassing and stirring, measured with a low-cost sensor;
iii Determination of the effects on k_La in the DIY bioreactor depending on the type of gassing (gassing stone or sparger $\rightarrow$ influence of bubble size) with variation of the state variables of gassing and stirring;
iv Cultivation of microalga *M. gaditana* in the DIY bioreactor with different cultivation conditions in terms of variation of gassing and stirring.

4. Materials and Methods

4.1. DIY Bioreactor

The DIY bioreactor was developed as a plug-in box system without glue connections. The bioreactor is based on a canning jar (Weck 1590 mL) with a 3D-printed frame (see Figure 2A). The frame contains a fan (Arctic F9 92 mm), which was equipped with magnetic holders for stirring via a magnetic stir bar (length, 36 mm; diameter, 3 mm) (see Figure 2D). The bioreactor was equipped with low-cost sensors to measure various parameters—(i) conductivity (Electrical Conductivity Sensor DFR0300-H, DFRobot, Shanghai, China (ii) temperature (DS18B20, DFRobot, Shanghai, China), and (iii) liquid level (Grove Water Level Sensor, Seeedstudio, Shenzhen, China)—and a dissolved oxygen probe (Analog Dissolved Oxygen Sensor SEN0237-A, Gravity, DFRobot, Shanghai, China). The sensors were read using a microcontroller (SMD R3, Arduino, Arduino S.r.l., Monza, Italy) installed in the lid (see Figure 2B). Gassing was performed by a metallic ring sparger or by a gassing stone (ASC-100, Uniclife Co., Ltd., Beijing, China).

In order to avoid additional installations in the bioreactor during the experiments on mixing time and k_La value, which would influence the flow, the liquid level sensor was removed for the mixing-time and k_La experiments. The total price for the DIY bioreactor, including all sensors used in this study in 2023, was EUR 383.30. The cost of the bioreactor parts can be obtained from the supplementary data. Further information about the DIY bioreactor and its application areas can be found in Wallrath et al. (2023).



Figure 2. (**A**) Prototype of the 3D-printed DIY bioreactor; (**B**) lid with breadboard for wiring and microcontroller; (**C**) float with sensors and cable routing; (**D**) exhaust air and stirring mechanism; (**E**) LED lighting. Figure from Wallrath et al. (2023). The figure shows a prototype of the 3D-printed DIY bioreactor with individual detailed images of the lid with breadboard for cabling and microcontroller, the float with sensors and cable routing, the exhaust air and stirring mechanism, and the LED lighting.

4.2. Mixing Time

The mixing time was determined by conductometry. For this purpose, the bioreactors were filled with 80% tap water (Minifors 2 L, DIY bioreactor 1.2 L), since the availability of deionized water at schools cannot be guaranteed, and at least one minute was allowed to elapse so the flow regime could be established. For both bioreactor types, aeration was kept constant at a superficial gas velocity of 0.04 cm s^{-1}, with a stirrer speed of 350 rpm. Then, using a 25 mL disposable syringe, 6.7 mL (Minifors) or 4 mL (DIY reactor) of 4 M NaCl solution was injected through a riser tube to achieve the same final NaCl concentration during the experiment. The change in conductivity over time was measured using a conductivity probe (Electrical Conductivity Sensor DFR0300-H, DFRobot, Shanghai, China) and was read out using a single-board microcontroller (SMD R3, Arduino, Arduino S.r.l., Monza, Italy) and Arduino IDE software (version 1.8.19). At the same time, the temperature was read (DS18B20 Temperature Sensor, DFRobot, Shanghai, China) to account for the influence of temperature on the conductivity change. Before each series of measurements, the conductivity sensor was calibrated with a two-point calibration (standards: 12.88 mS cm^{-1},

1.41 mS cm^{-1}, DFRobot). The change in conductivity was recorded over a period of 5 min. The mixing time was determined as the time from when no deviation in homogeneity of 95% (According to Equation (1)) was observed until the final concentration was reached. For the experimental procedure, two cases were compared for the Minifors and the DIY bioreactor: stirred only and gassed only. A custom-made stainless-steel ring and a gassing stone (ASC-100, Uniclife Co., Ltd., Beijing, China) were used as aeration devices.

4.3. Volumetric Mass Transfer Coefficient (k_La)

The k_La value was determined by the outgassing method. The bioreactors were prepared and filled as described in Section 4.2. Instead of a conductivity probe, a dissolved oxygen sensor (Analog Dissolved Oxygen Sensor SEN0237-A, Gravity, DFRobot, Shanghai, China) was installed in the bioreactor. After switching on the stirrers (350 rpm), at least one minute was allowed to elapse for the flow regime to settle. Oxygen was outgassed from the system by introducing nitrogen gas. Then, aeration with air (Superficial gas velocity = 0.04 cm s^{-1}) was turned on, and the dissolved oxygen concentration was logged using a microcontroller (SMD R3, Arduino, Arduino S.r.l., Monza, Italy). To calculate the k_La value, the oxygen concentration was plotted logarithmically versus time (see Equation (2)). Three cases were compared for the Minifors and DIY bioreactors: stirred only, gassed only, and simultaneous gassing and stirring. The same aeration device was used as in the mixing-time experiments: a custom-made stainless steel ring sparger and a gassing stone (ASC-100, Uniclife Co., Ltd., Beijing, China).

4.4. Cultivation

Analogous to the prescription for the cultivation experiment in a low-cost bubble column from a previously published article (Geuer et al., 2023), microalga *M. gaditana* (Culture Collection of Algae SAG 2.99) was cultivated in the DIY bioreactor under three different cultivation conditions in BG11 medium (Geuer et al., 2023) with an initial OD of 0.07: (i) simultaneous gassing and stirring, (ii) gassed only, and (iii) stirred only. The aeration rate was kept constant at a superficial gas velocity of 0.04 cm s^{-1} through a gassing stone (ASC-100, Uniclife), and the stirrer speed was kept at 350 rpm. Thus, the variation of cultivation conditions is closely related to the experiments on characterization of the DIY bioreactor regarding mixing time and oxygen transfer efficiency. In a cultivation period of 17 days, samples were taken daily for photometric measurement of optical density at 650 nm, and the filling volume of 1.2 L was replenished with deionized water. For photometric measurement, a modular low-cost photometer was used (desklab gUG, Schriesheim; https://desk-lab.de), which was specially developed for science and technology teaching. The experimental set-ups were permanently illuminated with an LED band (light illumination of 15 µmol/s/m^2) of the DIY bioreactor, which is located in the lower part of the bioreactor (see Figure 2). As an additional light source, ambient sunlight (European summer) was provided.

5. Results and Discussion

In this section, we describe the results of experiments to determine the mixing time and k_La, as well as the results from the comparison of cultivation conditions in the cultivation of *M. gaditana* in the DIY bioreactor based on the transfer of laboratory experiments to low-level experiments. From the perspective of transferability of the results, the use of these experiments in the classroom is discussed and evaluated. Special focus is placed on possible implementations in STEM teaching in secondary education or vocational education.

5.1. Transfer of Bioreactor Characterization

In a first step of transfer to DIY, we need to evaluate whether we can reproduce comparable trends of k_La and mixing time with conventional laboratory apparatus and a DIY system. The goal was to compare k_La and mixing-time values of the bioreactors for the following states of operation:

i Stirred only (S);
ii Gassed only (G);
iii Gassed and stirred simultaneously (GS).

These conditions are suitable to demonstrate to students the necessity of gassing and stirring in a bioreactor to achieve good oxygen transfer and mixing in the cultivation medium. For the Minifors bioreactor, a mixing time of 14.6 ± 4.5 s (see Figure 3) was observed for the stirred operation. For the aerated vessel without stirring, the mixing time increased to 27.0 ± 8.6 s. This trend can also be observed in the DIY bioreactor. For the stirred bioreactor, a mixing time of 22.0 ± 3.5 s was observed, while the aerated operation with a ring sparger showed a mixing time of 40.2 ± 17.9 s. When switching the aeration device to a gassing stone, the mixing time increased even further to 160.8 ± 17.2 s. This trend is to be expected, since the mixing time for stirred bioreactors is an expression of the reactor geometry, the viscosity of the culture medium, and the specific power input (Nienow, 1997). In addition to the mechanical power input by a stirrer, gassing also contributes power to the bioreactor. However, the power input by gassing is much lower compared to the mechanical power input and is therefore often neglected (Doran, 2012). Although the absolute values of mixing times deviate between the commercial bioreactor and the DIY bioreactor, the results can demonstrate to students how commercially available bioreactors behave. Based on observable trends, the STEM teacher can demonstrate how the stirring of a bioreactor has a significant impact on the mixing time and oxygen mass transfer (k_La). Furthermore, they can teach that gas transfer, although the surface of the liquid is not suitable for oxygen transfer because of the surface-to-volume ratio of the bioreactor. The necessity of a gassing device for bioreactors and the differences between the two types of gassing devices (sparger and gassing stone) should also be considered. The possibility of deriving new experiments based on the needs of the class is also imaginable. For example, the influence of internals like baffles or the geometry of the magnetic stirrer can be discussed. In addition to the mixing time, the k_La value can be a valuable factor to vividly teach students the concept of oxygen input into a bioreactor.

For the Minifors bioreactor, simultaneous gassing and stirring achieved the highest k_La value of 35.23 ± 1.66 h^{-1} (see Figure 4). When the stirring was shut of while maintaining aeration, the k_La dropped to 18.98 ± 0.47 h^{-1}. This effect is expected, as the additional power input of the Rushton turbine leads to a smaller bubble size, which increases the surface area of the bubbles and, thus, the k_La. If the bioreactor is stirred without aeration, the k_La drops close to zero. With the DIY bioreactor, similar trends could be observed. During simultaneous gassing and stirring, a k_La of 19.01 ± 2.90 h^{-1} was achieved. Similar to the Minifors system, when the reactor was not stirred, the k_La dropped to 13.94 ± 1.27 h^{-1}. When the aeration was shut off while keeping the stirrer on, the k_La dropped once again to nearly zero, since gassing could only be achieved through the surface of the medium in the bioreactor head space. Although the absolute k_La values differ between the Minifors and DIY bioreactor, the overall trend is similar. Furthermore, the type of gassing device was compared for the DIY bioreactor between a sparger and a gassing stone, which are used in aquaristics and are even easier and cheaper to include in a DIY bioreactor system. In comparison to the DIY bioreactor gassed with a sparger, higher k_La values of 33.45 ± 1.83 h^{-1} and 26.58 ± 7.12 h^{-1} were observed for the stirred and non-stirred conditions, respectively. Once again, a trend of a drop in k_La can be observed when switching the stirrer off. Overall,

higher k_La values were obtained when switching from the sparger to a gassing stone. This trend is due to the smaller and more numerous bubbles produced by the porous gassing stone in comparison to the sparger. Although this trend could be taught on a Minifors bioreactor through observation of the decrease in bubble size at the Rushton turbine, the stirring of the DIY bioreactor happens with a magnetic stirrer. Therefore, the trend of the gas bubbles being broken down on the stirring device is harder to demonstrate. The usage of a different gassing device can help to make the concept of bubble size clearer to students. Overall, these trends are in accordance with the expected trends of oxygen transfer. The k_La value in a stirred tank is dependent on the volumetric power input and the superficial gas velocity (Van't Riet, 1979). And as a combined parameter of the mass transfer coefficient (k_L) and the interfacial area (a), a decrease in bubble size results in a higher interfacial area and, thus, higher k_La values. Since a commercial bioreactor is usually not possible to obtain for schools, the transfer of these trends to a low-cost DIY bioreactor is desirable. The results show that basic concepts in bioprocess engineering can be transferred to the DIY system, enabling schools to demonstrate to students in laboratory experiments, in addition to the cultivation of microalgae (Wallrath et al., 2023), concepts of bioreactor characterization. If desired, these experiments can be extended to include, for example, the influence of stirrer speed, superficial gas velocity, and the installation of baffles on k_La and mixing time. Furthermore, the concepts of k_La and oxygen transfer can be transferred to experiments with microorganisms, for example, yeasts, as described by Roberts et al. (1992). These parameters could be investigated without major adjustments to the existing DIY design. The installation of baffles can be achieved through 3D printing, and the variation of the stirrer speed can be controlled by adjusting the voltage of the fan.

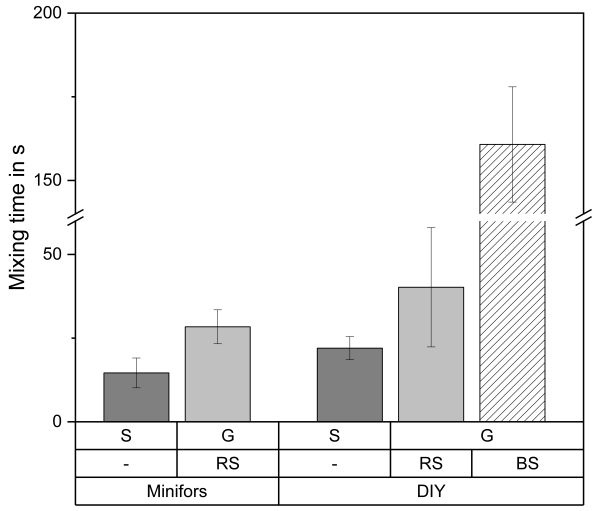

Figure 3. The mixing time of the Minifors and DIY bioreactors for two states of operation: stirred only (S) and gassed only (G) with a ring sparger (RS) or gassing stone (BS). The aeration rate was 2 L/min for the Minifors bioreactor and 1.86 L/min for the DIY bioreactor. For stirring of the Minifors bioreactor, a Rushton turbine was adjusted to 350 rpm. For the DIY bioreactor, a magnetic stirrer was adjusted to 350 rpm. The bar chart shows the mixing time of the Minifors and DIY bioreactors for two states of operation.

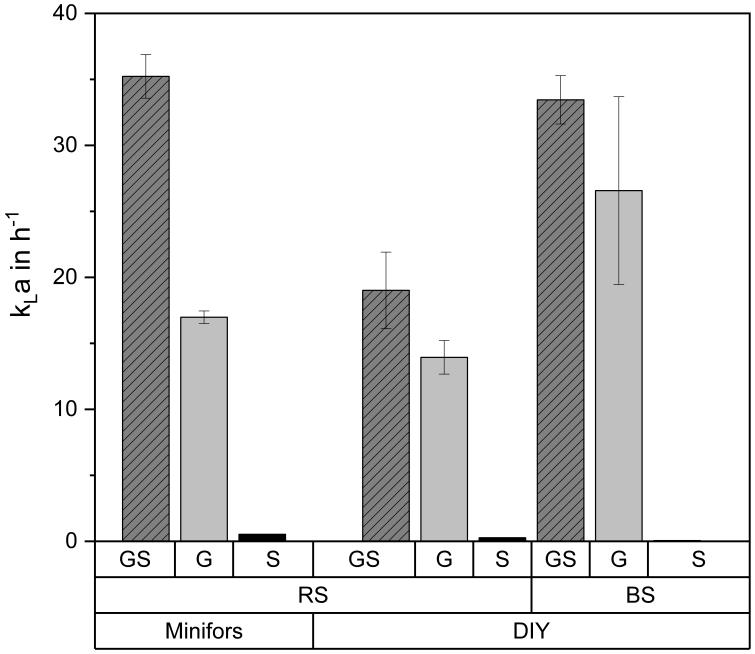

Figure 4. k_La values measured in in the DIY bioreactor and in the Minifors bioreactor (Infors HT) for three states of operation (GS—stirring and gassing; G—gassing; S—stirring) depending on the type of gassing: with a gassing stone (BS) or ring sparger (RS). The aeration rate was 2 L/min for the Minifors bioreactor and 1.86 L/min for the DIY bioreactor. For stirring of the Minifors bioreactor, a Rushton turbine was adjusted to 350 rpm. For the DIY bioreactor, a magnetic stirrer was adjusted to 350 rpm. The bar chart shows the k_La values measured in in the DIY bioreactor and in the Minifors bioractor (Infors HT) for three states of operation.

5.2. Cultivation

In order to investigate the effects of the process-relevant variables of stirring and gassing, not only regarding bioreactor technology but also the growth of microorganisms, three cultivation experiments with microalga *M. gaditana* were carried out under different cultivation conditions as examples:

i Cultivation condition of "gassed and stirred simultaneously (GS)";
ii Cultivation condition of "gassed only (G)";
iii Cultivation condition of "stirred only (S)".

Figure 5 shows the growth in terms of OD, biodrymass (BDM), and cell density of microalga *M. gaditana* under the cultivation conditions studied over a period of 17 days. A cell density of 34.1×10^6 cells mL^{-1} was achieved over a period of 14 days for the stirred-only reactor (S). Cell densities of 118.2×10^6 cells mL^{-1} and 103.3×10^6 cells mL^{-1} were obtained For the gassed reactor (G) and the gassed and stirred (GS) reactor, respectively in the same time period. With the obtained results, comparisons of different cultivation conditions can be optimally mapped in a school context and can be linked to previous results on power input and gas input in bioreactors. Cultivation conditions without gassing the reactor show significantly slower growth of microalgae compared to growth with gassed reactors. The influence of stirring and the associated increase in the k_La value are less pronounced. However, the influence of the additional power input on biofilm formation in the reactor can be observed. Stirring in the reactor keeps the microalgae in suspension, which greatly reduces biofilm formation at the bottom of the bioreactor (see Figure 6). These results demonstrate the roles of gassing and agitation of bioreactors addressed in the theoretical background in a visually appealing experiment. Similar growth behavior was described by Bo et al. (2021) for *M. gaditana*. Here, *M. gaditana* was cultured in 50 mL artificial seawater in 250 mL shake flasks. Cell densities of 60×10^6 cells mL^{-1} were

achieved within 9 days. Budisa et al. were able to achieve similar growth of *M. gaditana* in 2.6 L photobioreactors using aged seawater enriched with Guillard's F/2 medium and 50% diluted oil refinery wastewater. A maximum BDM of 0.25 g L^{-1} was achieved after a cultivation period of 11 days, which is significantly lower than the maximum BDM achieved in this study (0.75 g L^{-1}). However, the focus of Budisa et al. was the study of the inhibition of algal growth by wastewater, which may have led to this reduced yield. Although these studies involved varying cultivation systems, it is possible to compare the data on the growth of *M. gaditana* in a DIY bioreactor system with data from the literature. This shows that it will be possible to obtain data comparable to actual scientific research in classroom experiments, opening up a new inquiry-based context for students and teachers.

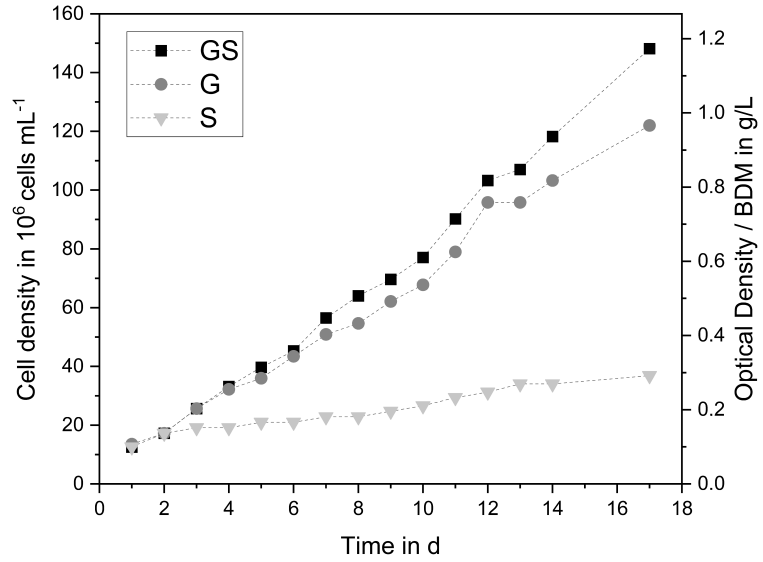

Figure 5. Growth of *M. gaditana* cultivated in the DIY bioreactor for 17 days in terms of OD, biodrymass (BDM) in g L^{-1}, and cell density in $\times 10^6$ cells mL^{-1} for three cultivation conditions (BG11 medium): GS—stirring and gassing; G—gassing; S—stirring. The aeration rate was 1 L/min. For stirring, a magnetic stirrer was adjusted to 350 rpm. The bar chart shows the growth of *M. gaditana* cultured in the DIY bioreactor over 17 days in terms of OD, biological dry mass (BDM) in g L^{-1}, and cell density in $\times 10^6$ cells mL^{-1} for three cultivation conditions (BG11 medium).

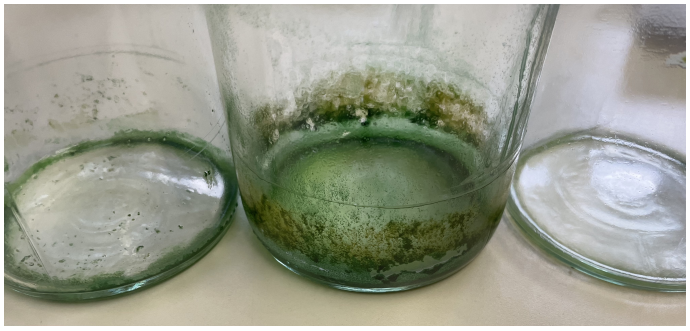

Figure 6. Caption: Biofilm formation in the lower section of the DIY reactor for visual comparison. From right to left: experimental set-up 1—gassing and stirring; experimental set-up 2—gassing only; experimental set-up 3—stirring only. The figure shows the three DIY reactors for the different test conditions. The influence of the additional power supply on biofilm formation in the reactor can be seen here. The stirring in the reactor keeps the microalgae in suspension, which minimizes biofilm formation at the bottom of the bioreactor.

5.3. Didactic Comment on the Experiments

Our future STEM experts are recruited from the current generation of school students. This is why STEM education in Germany is characterized by a diverse educational landscape.

Outside of school, non-school educational institutions (e.g., universities and after school programs) are engaged in teaching young STEM professionals the relevant scientific skills and in-depth STEM knowledge. In the mentioned call to link STEM education in schools and current scientific research, interdisciplinary structures must be developed. The following didactic and methodological comments on the transfer process from complex research experiments to school experiments in bioprocess engineering visualize first steps towards achieving this interlinking. These experiments also offer the opportunity to integrate all STEM disciplines.

The previous sub-chapter demonstrated the successful transfer of inquiry-based bioprocess engineering experiments to school experiments using DIY bioreactors and low-cost sensors. The curricular design and didactic framework of these experiments are aligned with the competence domains outlined in Germany's national educational standards for science subjects. National educational standards are defined for science subjects of biology, chemistry, and physics on behalf of the Standing Conference of the Ministers of Education and Cultural Affairs (KMK, 2005). von Arx and Bernholt (2015) relate the development and integration of diverse competency models in Germany to the concept of scientific literacy, the recommendations of the Klieme et al. (2003), the results of the international school performance studies TIMSS and PISA, and existing curricula (Bernholt et al., 2009; KMK, 2005; Labudde, 2007; Neumann et al., 2007; Schecker & Parchmann, 2006). The national educational standards (in German, "Mittlerer Schulabschluss" (KMK, 2004a, 2004b, 2004c) and "Allgemeine Hochschulreife" (KMK, 2020a, 2020b, 2020c)) follow a normative competency structure model with four competence domains of "technical knowledge", "knowledge discovery", "communication", and "evaluation". These competence domains are designed to help students develop a wide understanding and solid basis in science disciplines and to strengthen their skills in scientific reasoning, experimentation, communication, and critical thinking. In the sense of promoting scientific literacy, the experiments provide a variety of didactic educational approaches that can be assigned to the competence domains. The following didactic commentary focuses on the competence domain of "technical knowledge" shown in Figure 7 but also shows conceptual approaches for the other competence domains that can be derived from the experiments. Figure 7 shows a thematic classification of a possible educational concept to the experiments on bioreactor technology described in the following.

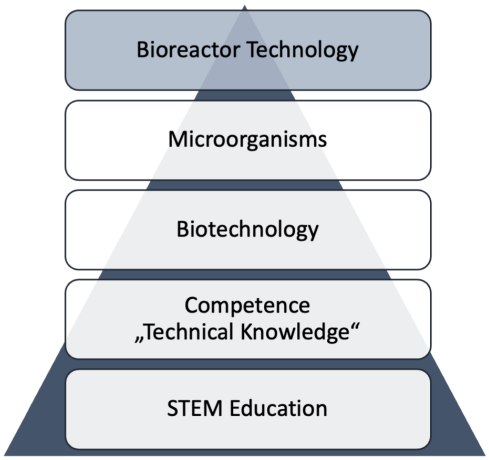

Figure 7. Caption: Exemplary implementation of a proposed educational concept for the competence domain of "technical knowledge". The competence domain of "technical knowledge" is structured in an increasing progression, which visualizes the ever-increasing specification of the subject areas within the competence. The basis is formed by STEM education, followed by the competence development in the domain of technical knowledge, which is specified in the area of biotechnology, then further in the area of microorganisms and, finally, in the area of bioreactor technology.

The experiments are an enhancement of the biotechnology learning field in the German secondary-level science curriculum and offer a view beyond the horizon. In addition, the technology focus allows the teaching concept to be integrated into vocational teaching with a focus on biotechnology and bioengineering. The concept aims to teach students about the production process and bioreactor technology. It also integrates industrial applications to enable students to make informed and well-founded evaluations on these topics. Thus, the concept complements the consideration of necessary steps from the production to the further processing of a biotechnological product, which is shown in a model-like manner using examples. In order to consider the construction and characterization of bioreactors in relation to the cultivation conditions of microorganisms, school students must be familiar with the growth requirements of the respective organism and have prior knowledge of, for example, biotechnological changes in the metabolic pathway of genetically modified organisms. In addition, it is possible to discuss the subsequent processing step to isolate the product, as well as the preparative procedures and analytical methods, in relation to the respective product. In order to address biotechnological research topics in an appropriate way for the target group, taking a didactic look at supermarket shelves, current nutritional trends, or students leisure activities is worthwhile. For example, microalgae are in line with the trend of alternative plant-based nutrition and currently play a significant role in the question of alternative fuels or fertilizers in agriculture. The contrasting picture between algae on the beach, the rather negatively assessed algae bloom, and the "superhero power" in the course of climate protection, characterizes algae as an interesting and versatile teaching subject, from natural science basics such as photosynthesis and ecology to modern biotechnology. The cultivation of microalgae creates an authentic learning context in connection with the construction and characterization of bioreactors. The empirical and theoretical findings related to the cultivation conditions of microalgae in the DIY bioreactor allow us to derive the designs of bioreactors, production processes, and optimization steps. Concretely considering the construction of the DIY bioreactor, the experiments to characterize it, the process-relevant parameters of mixing time and $k_L a$, and cultivation, it becomes clear to school students that the supply of the bioreactor with carbon dioxide or oxygen by gassing and mixing is important for the cultivation of microorganisms. For example, the availability of light and CO_2 in the cultivation of microalgae can be discussed with regard to possible effects on the photosynthesis process and its efficiency. Based on this, the typical day–night rhythm of phototrophic organisms can be worked out, where a sufficiently high partial carbon dioxide pressure during the day for photosynthesis and a sufficiently high partial oxygen pressure at night for respiration must be ensured. In this context, CO_2 supply and O_2 removal must be discussed as an important factor in terms of increasing productivity. The background is that CO_2 is an essential element in photosynthesis and increased O_2 concentrations lead to a reduced photosynthetic performance (Borowitzka et al., 2016; Hirayama et al., 1996; Kazbar et al., 2019). Students should also be shown that the most homogeneous mixing possible of the bioreactor serves to reduce concentration and temperature gradients (Moser, 2013). In addition, the effects due to the variation of the process-relevant variables on possible products from the cultivation of microalgae can be discussed, for example, the composition of industrially relevant dyes such as phycocyanin (blue), allophycyanin (red), carotenoids (orange), and chlorophyll-a (green) depending on the selected bioreactor design and setting of the parameters during cultivation. Geuer et al. (2023) have already developed experiments to visualize the colorful world of photopigments from microalgae and cyanobacteria. Using photometers, it is also possible to determine the concentration of pigments produced under different cultivation conditions. In the learning context of yeast, on the other hand, the availability of oxygen, i.e., anaerobic and aerobic cultivation, and

its effects on the metabolic pathway in yeasts can be considered. Topics such as alcoholic fermentation, which are firmly anchored in the curricular standards, can be addressed in this educational context.

In order to further deepen research-oriented experimentation, experiments can also be focused on the competence domain of "knowledge discovery". With the aim of an inquiry-based teaching concept, problem-based questions can be framed accordingly. The problem of developing an appropriate bioreactor design and cultivation conditions for a particular microorganism culture or for a particular product target may represent a research-related scenario. For example, the selection of the gassing method and gassing rate depends on the growth and metabolic performance of the microorganism, respectively. In addition to solution-oriented trading to answer the problem question, the corresponding hypotheses are generated and tested experimentally. The controlled handling of variables has an important role in the promotion of experimentation competence. Here, according to the hypothesis to be investigated, for example, that the gassing rates should be kept constant and the type of gassing should vary or the type of reactor design should vary, for the competence domain of "communication", the teaching concept can be focused on the scientific protocol, documentation, and presentation of data in an appropriate way. Students are expected to prepare experimental data in a scientific presentation and are guided to empirically analyze and interpret their results obtained in the experiment to compare reactor types in terms of cultivation conditions and research questions/hypotheses. In addition, school students are encouraged to bring their own knowledge, ideas, and interpretive approaches to the discussion of the data. A discussion from personal and local to global and societal perspectives brings aspects of the competence domain of "evaluation" into the educational concept. For example, in a plant, investment and operating costs are equally significant factors in assessing efficiency. The input of mixing and mass-transfer energy mainly determine the operating costs (Ugwu et al., 2008). However, the resulting chemically bonded energy of the microalgae produced in conventional bioreactor systems such as vertically oriented tubular bioreactors is not enough to compensate for the expended energy. Therefore, mass production is unprofitable for such plants (Katzenmeyer, 2020; Posten, 2009). Reflection on the economic aspects of biotechnological production, possible hazards of these processes, ethical perspectives, and sustainability aspects should motivate students to make well-founded decisions and to participate in society. In summary, the experiments offer a wide range of potential for the promotion of STEM expertise. Scientifically relevant and research-oriented competencies are encouraged, in which the topics of bioreactor technology, microorganisms in industrial production, fermentation, bioreactor technology, processing of biotechnological products, economic aspects of biotechnological production, and possible hazards of these processes can be didactically and methodologically elaborated in a variety of ways. The developed experiments contribute significantly to the transformation of STEM education based on key factors to achieve interdisciplinarity, inquiry-based learning, and authentic inquiry experiences in STEM education to promote the working practices of scientists and foster scientific literacy and critical thinking.

5.4. Future Directions

On the basis of the successful development of the experiments, studies in the field of educational research and the development of a corresponding teaching–learning concept for school lessons will follow. According to the results of previous studies, a systemic measurement of the attitudes of school students and environmental factors provides extremely valuable information about science outreach projects and how to optimize their effectiveness (Woithe et al., 2022). Therefore, the next step is to conduct studies with school students to analyze motivational factors, situational interest, and self-concept. For this pur-

pose, the well-validated motivation test instrument adapted originally from Häußler and Hoffmann (1995) can be used, as has been done in previous studies (Hochberg et al., 2018; Kuhn & Müller, 2014; Woithe et al., 2022). Woithe et al. (2022) also observed that studies should explore the long-term effects of interventions at science outreach labs and ways to enhance them through appropriate instructional measures such as follow-up activities. Therefore, a study with follow-up activities is planned to be implemented in an already established student activity at the Bioprocess Engineering Institute at the University of Kaiserslautern-Landau (RPTU).

Experimental investigation and the application of different concepts are necessary for the development of scientific competencies. In order to facilitate the transfer of scientific experiments to science lessons, teachers must be provided with new methods, tools, and instructions that make it easier to implement inquiry-based school experiments. Therefore, in the future, the materials for the experiments will be packaged in a box and offered in a lending system. A special feature of this is that the box contains all the materials for use and consumption, as well as didactic and methodological instructions with worksheets. They serve as a basis and orientation guide that teachers can use to individually select the appropriate teaching method for their school class. This creates a close cooperation structure between the university institution and school teachers. Thus, the mentioned aspects of science outreach projects, such as contact with scientists and transformation of STEM lessons with research-related topics, can be fulfilled.

6. Conclusions

This study aimed to construct educational approaches to increase the STEM expertise and scientific literacy of future generations in a research-oriented context of bioprocess engineering. In the study, we developed experimental protocols to determine the k_La and mixing time of a DIY bioreactor in a low-level experiment in order to facilitate discussion of the steps in the industrial process. A successful transfer of inquiry-based bioprocess engineering experiments to school experiments with DIY bioreactors and low-cost sensors can be investigated. The results show comparable trends of process-relevant state variables compared to a conventional laboratory apparatus. With subsequent cultivation of microalga *M. gaditana* in the DIY bioreactor, various observations could be made regarding growth under different cultivation conditions. These cultivation experiments with microalgae complement the discussion of the construction and characterization of bioreactors for the cultivation of microorganisms and create an authentic learning context. The didactic analysis shows a variety of possibilities for integration into science lessons, with a focus on promoting scientific literacy, training and reflecting on methods of scientific thinking and working and discussing the meaning and limitations of scientific knowledge with students. In summary, this article represents a milestone in the integration of process engineering issues with DIY bioreactors and low-cost sensors into the school curriculum.

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Abbreviations

The following abbreviations are used in this manuscript:

DIY	Do It Yourself
STEM	Science, Technology, Engineering, and Mathematics
SDGs	Sustainable Development Goals
OD	Optical Density
BD	Bodydrymass

References

acatech & Körber-Stiftung. (2021). *MINT nachwuchsbarometer*. Available online: https://www.acatech.de/publikation/mint-nachwuchsbarometer-2021 (accessed on 19 February 2025).

Bartram, B., & Wilke, T. (2018). Aus der forschung in die schule-gestaltung einer lernortübergreifenden summer school zum thema nanotechnologie durch fachdidaktische transferforschung. In K. Fereidooni, K. Hein, & K. Kraus (Eds.), *Theorie und praxis im spannungsverhältnis. beiträge für die unterrichtsentwicklung* (pp. 67–82). Waxmann.

Bensaude-Vincent, B. (2001). A geneology of the increasing gap between science and the public. *Public Understanding of Science*, *10*, 99–113. [CrossRef]

Bernholt, S., Parchmann, I., & Commons, M. (2009). Kompetenzmodellierung zwischen forschung und unterrichtspraxis. *Zeitschrift für Didaktik der Naturwissenschaften*, *15*, 219–245.

Bettinger, E. (2010). To be or not to be: Major choices in budding scientists. In *American universities in a global market* (pp. 69–98). University of Chicago Press.

BMBF. (2021). *Grundsatzpapier des BMBF zur partizipation*. Available online: https://www.bmbf.de/SharedDocs/Downloads/DE/2016/bmbf_grundsatzpapier_partizipation.pdf?__blob=publicationFile&v=4 (accessed on 19 February 2025).

Bo, D., Magneschi, L., Bedhomme, M., Billey, E., Deragon, E., Storti, M., Menneteau, M., Richard, C., Rak, C., Lapeyre, M., Lembrouk, M., Conte, M., Gros, V., Tourcier, G., Giustini, C., Falconet, D., Curien, G., Allorent, G., Petroutsos, D., … Collin, S. (2021). Consequences of mixotrophy on cell energetic metabolism in microchloropsis gaditana revealed by genetic engineering and metabolic approaches. *Frontiers in Plant Science*, *12*, 628684. [CrossRef]

Bohrmann-Linde, C., Meuter, N., Kremer, R., Pereira, V., & Venzlaff, J. (2021). Forschung trifft Schule. Chemie-Labothek als innovatives, vernetzendes Format Lehrkräftebildung neu gedacht. In M. Kubsch, S. Sorge, J. Arnold, & N. Graulich (Eds.), *Lehrkräftebildung neu gedacht. ein praxishandbuch für die lehre in den naturwissenschaften und deren didaktiken* (pp. 108–112). Waxmann Verlag.

Boiko, A., Nistor, A., Kudenko, I., & Gras-Velazquez, A. (2019). *The attractiveness of science, technology, engineering and mathematics subjects. Results from five countries*. European Schoolnet.

Borowitzka, M., Beardall, J., & Raven, J. (2016). *The physiology of microalgae*. Springer.

Bybee, R. (2013). *The case for stem education. Challenges and opportunities*. NSTA Press.

Chakdar, H., Jadhav, S., Dhar, D., & Pabbi, S. (2012). Potential applications of blue green algae. *Journal of Scientific and Industrial Research*, *71*, 13–20.

Chmiel, H. (2011). *Bioprozesstechnik*. Springer.

Crawford, G., Kloepper, K., Meyers, J., & Singiser, R. (2019). Communicating chemistry: An introduction. In *Communication in chemistry* (pp. 1–15). American Chemical Society. Available online: https://pubs.acs.org/doi/abs/10.1021/bk-2019-1327.ch001 (accessed on 19 February 2025). [CrossRef]

Çağlaand, Y., Gürlek, C., & Oncel, S. (2020). Potential of microalgal compounds in trending natural cosmetics: A review. *Sustainable Chemistry and Pharmacy*, *17*, 100304. [CrossRef]

Domingo, M., Sharp, S., Freeman, A., Freeman, T., Harmon, K., Wiggs, M., Sathy, V., Panter, A., Oseguera, L., Sun, S., Williams, M., Templeton, J., Folt, C., Barron, E., Hrabowski, F., Maton, K., Crimmins, M., Fisher, C., & Summers, M. (2019). Replicating Meyerhoff for inclusive excellence in STEM. *Science*, *364*(6438), 335–337.

Doran, P. (2012). *Bioprocess engineering principles*. Academic Press.

Dufossé, L., Galaup, P., Yaron, A., Arad, S., Blanc, P., Murthy, K., & Ravishankar, G. (2005). Microorganisms and microalgae as sources of pigments for food use: A scientific oddity or an industrial reality? *Trends in Food Science and Technology*, *16*(9), 389–406. [CrossRef]

Duit, R., Gropengiesser, H., Kattmann, U., Komorek, M., & Parchmann, I. (2012). The model of educational reconstruction—A framework for improving teaching and learning science. In *Science education research and practice in Europe. Retrospective and prospective* (pp. 13–37). Sense Publishers. [CrossRef]

Enzingmüller, C., Kampschulte, L., & Parchmann, I. (2019). Science outreach in sonderforschungsbereichen. In C. Maurer (Ed.), *Naturwissenschaftliche bildung als grundlage für berufliche und gesellschaftliche teilhabe* (p. 548). Universität Regensburg, Gesellschaft für Didaktik der Chemie und Physik.

Gantar, M., & Svirčev, Z. (2008). Microalgae and cyanobacteria: Food for thought. *Journal of Phycology*, *44*(2), 260–268. [CrossRef] [PubMed]

Garcia-Ochoa, F., & Gomez, E. (2008). Bioreactor scale-up and oxygen transfer rate in microbial processes: An overview. *Biotechnology Advances*, *27*, 153–176. [CrossRef]

Geuer, L., Erdmann, N., Lorenz, M., Albrecht, H., Schanne, T., Cwienczek, M., Geib, D., Strieth, D., & Ulber, R. (2023). Colorful diversity. modified methods for extraction and quantification of photopigments and phycobiliproteins isolated from phototrophic micro- and macroalgae. *Journal of Chemical Education*, *100*(2), 852–860. [CrossRef]

Geuer, L., Liese, G., Roth, M., Liese, A., Schlindwein, A., Perret, S., & Ulber, R. (2023). Experimente aus der kiste. Kultivierung von mikroorganismen. *Chemie in unserer Zeit*, *57*(5), 216–223. [CrossRef]

Gopalakrishnan, V., Crozier, D., Card, K., Chick, L., Krishnan, N., McClure, E., Pelesko, J., Williamson, D., Nichol, D., Mandal, S., Bonomo, R., & Scott, J. (2022). A low-cost, open-source evolutionary bioreactor and its educational use. *bioRxiv*. [CrossRef] [PubMed]

Hass, V., & Pörtner, R. (2011). *Praxis der bioprozesstechnik mit virtuellem praktikum*. Spektrum Akademischer Verlag.

Häußler, P., & Hoffmann, L. (1995). Physikunterricht—An den interessen von mädchen und jungen orientiert; Physics instruction—Based on girls' and boys' interests. *Unterrichtswissenschaft*, *23*(2), 107–126. [CrossRef]

Hirayama, S., Ueda, R., & Sugata, K. (1996). Evaluation of active oxygen effect on photosynthesis of chlorella vulgaris. *Free Radical Research*, *25*(3), 247–254. [CrossRef] [PubMed]

Hochberg, K., Kuhn, J., & Müller, A. (2018). Using smartphones as experimental tools—Effects on interest, curiosity, and learning in physics education. *Journal of Science Education and Technology*, *27*, 385–403. [CrossRef]

Holbrook, J., & Rannikmae, M. (2007). The nature of science education for enhancing scientific literacy. *International Journal of Science Education*, *29*, 1347–1362. [CrossRef]

Katoh, S., Horiuchi, J., & Yoshida, F. (2015). *Biochemical engineering—A textbook for engineers, chemists and biologists*. John Wiley and Sons.

Katzenmeyer, M. (2020). *Effizienzerhöhung in der kultivierung von mikroalgen—Prozessoptimierung und bioreaktorentwicklung* [Ph.D. thesis, KIT-Fakultät für Chemieingenieurwesen und Verfahrenstechnik des Karlsruher Instituts für Technologie (KIT)].

Kazbar, A., Cogne, G., Urbain, B., Marec, H., Le-Gouic, B., Tallec, J., Takache, H., Ismail, A., & Pruvost, J. (2019). Effect of dissolved oxygen concentration on microalgal culture in photobioreactors. *Algal Research*, *39*, 101432. [CrossRef]

Klieme, E., Avenarius, H., Blum, W., Döbrich, P., Gruber, H., Prenzel, M., Reiss, K., Riquarts, K., Rost, J., Tenorth, H., & Vollmer, H. (2003). *Zur entwicklung nationaler bildungsstandards; Eine expertise*. BMBF. [CrossRef]

KMK. (2004a). *Bildungsstandards im fach biologie für den mittleren schulabschluss.* KMK.

KMK. (2004b). *Bildungsstandards im fach chemie für den mittleren schulabschluss*. KMK.

KMK. (2004c). *Bildungsstandards im fach physik für den mittleren schulabschluss*. KMK.

KMK. (2005). *Bildungsstandards der kultusministerkonferenz. Erläuterungen zur konzeption und entwicklung*. KMK.

KMK. (2020a). *Bildungsstandards im fach biologie für die allgemeine hochschulreife*. KMK.

KMK. (2020b). *Bildungsstandards im fach chemie für die allgemeine hochschulreife*. KMK.

KMK. (2020c). *Bildungsstandards im fach physik für die allgemeine hochschulreife.* KMK.

Kollmen, J., & Strieth, D. (2022). The beneficial effects of cyanobacterial co-culture on plant growth. *Life*, *12*(2), 223. [CrossRef]

Krapp, A., & Prenzel, M. (2011). Research on interest in science: Theories, methods, and findings. *International Journal of Science Education*, *33*(1), 27–50. [CrossRef]

Kuhn, J., & Müller, A. (2014). Context-based science education by newspaper story problems: A study on motivation and learning effects. *Perspectives in Science*, *2*(1), 5–21. [CrossRef]

Labudde, P. (2007). *Bildungsstandards am gymnasium. Korsett oder katalysator?* Hep.

Ledbetter, M. (2012). Vision and change in undergraduate biology education: A call to action presentation to faculty for undergraduate neuroscience, July 2011. *Journal of Undergraduate Neuroscience Education*, *11*, A22–A26. [PubMed]

Lyons, T., & Quinn, F. (2010). *Choosing science: Understanding the declines in senior high school science enrolments*. University of New England.

Miller, J. (1998). The measurement of civic scientific literacy. *Public Understanding of Science*, *7*(3), 203–223. [CrossRef]

Miller, J., & Pardo, R. (2000). Civic scientific literacy and attitude to science and technology: A comparative analysis of the European Union, the United States, Japan, and Canada. In *Between understanding and trust. The public, science, and technology* (pp. 81–130). Routledge.

Moser, A. (2013). *Bioprozeßtechnik—Berechnungsgrundlagen der reaktionstechnik biokatalytischer prozesse*. Springer.

Neumann, K., Kauertz, A., Lau, A., Notarp, H., & Fischer, H. (2007). Die Modellierung physikalischer Kompetenz und ihrer Entwicklung. *Zeitschrift für Didaktik der Naturwissenschaften*, *13*, 101–121.

Nienow, A. (1997). On impeller circulation and mixing effectiveness in the turbulent flow regime. *Chemical Engineering Science*, *52*(15), 2557–2565. [CrossRef]

OECD. (2006). *Pisa assessing scientific, reading and mathematical literacy a framework for pisa 2006—A framework for pisa 2006*. OECD Publishing.

OECD. (2008). *Encouraging student interest in science and technology studies*. OECD Publishing.

Ohio Department of Education. (2016). *Partnership for 21st century skills-core content integration*. Ohio Department of Education.

Olabi, A., Shehata, N., Sayed, E., Rodriguez, C., Anyanwu, R. C., Russell, C., & Abdelkareem, M. (2023). Role of microalgae in achieving sustainable development goals and circular economy. *Science of The Total Environment*, *854*, 158689. [CrossRef]

Parchmann, I., Demuth, R., Ralle, B., Paschmann, A., & Huntemann, H. (2001). Chemie im kontext. begründung und realisierung eines lernens in sinnstiftenden kontexten. *Praxis der Naturwissenschaften. Chemie in der Schule*, *50*(1), 2–7.

Parchmann, I., & Kuhn, J. (2016). Exzellenzstrategie und hochschuldidaktik—(Neue) chancen und herausforderungen für fachdidaktik? *CHEMKON*, *23*(4), 161–162. [CrossRef]

Posten, C. (2009). Design principles of photo-bioreactors for cultivation of microalgae. *Engineering in Life Sciences*, *9*(3), 165–177. [CrossRef]

Roberts, R. S., Kastner, J. R., Ahmad, M., & Tedder, D. W. (1992). The effect of agitation on oxygen mass transfer in a fermentor. *Chemical Engineering Education*, *26*(3), 142–163.

Rocard, M., Csermely, P., Jorde, D., Lenzen, D., Walberg-Henriksson, H., & Hemmo, V. (2007). *Science education now: A renewed pedagogy for the future of europe*. European Commission Directorate General for Research Information and Communication Unit.

Saadat, R., Bartram, B., & Wilke, T. (2019). Made to measure: Easy synthesis and characterization of nanocomposites with tailored functionalities for chemistry education. *World Journal of Chemical Education*, *7*(2), 65–71. [CrossRef]

Schecker, H., & Parchmann, I. (2006). Modellierung naturwissenschaftlicher kompetenz. *Zeitschrift für Didaktik der Naturwissenschaften*, *12*, 45–66.

Sjøberg, S., & Schreiner, C. (2019). *ROSE (The relevance of science education). The development, key findings and impacts of an international low cost comparative project. Final report, Part 1 (of 2)*. Oslo University.

Statistisches Bundesamt. (2010, July). *21311-0012: Studienanfänger: Deutschland, semester, nationalität, geschlecht, studienfach*. Available online: https://www-genesis.destatis.de/genesis//online?operation=table&code=21311-0012#astructure (accessed on 27 June 2024).

Steel, H., Habgood, R., Kelly, C., & Papachristodoulou, A. (2019). Chi.Bio: An open-source automated experimental platform for biological science research. *bioRxiv*. [CrossRef]

Stehle, S., & Peters-Burton, E. (2019). Developing student 21 Century skills in selected exemplary inclusive STEM high schools. *International Journal of STEM Education*, *6*, 39. [CrossRef]

Stifterverband. (2022, September 26). Ohne MINT kein fortschritt. *Onlinemagazin des Stifterverbandes*.

Strieth, D., Ulber, R., & Muffler, K. (2018). Application of phototrophic biofilms: From fundamentals to processes. *Bioprocess and Biosystems Engineering*, *41*, 295–312. [CrossRef] [PubMed]

Trafton, A. (2014). *Francis collins: Scientists must engage with the world*. Available online: https://news.mit.edu/2014/francis-collins-compton-lecture-1029 (accessed on 19 February 2025).

Ugwu, C., Aoyagi, H., & Uchiyama, H. (2008). Photobioreactors for mass cultivation of algae. *Bioresource Technology*, *99*(10), 4021–4028. . [CrossRef]

UNESCO. (2017). *Cracking the code: Girls' and women's education in science, technology, engineering, and mathematics (stem) [final report]*. UNESCO Publishing.

UNESCO. (2018). *UNESCO ICT competency framework for teachers*. UNESCO.

United Nations. (2015). *Transformation unserer Welt: Die Agenda 2030 für nachhaltige Entwicklung. Resolution der Generalversammlung, verabschiedet am 25. September 2015.* Available online: https://www.un.org/Depts/german/gv-70/band1/ar70001.pdf (accessed on 19 February 2025).

Van't Riet, K. (1979). Review of measuring methods and results in nonviscous gas-liquid mass transfer in stirred vessels. *Industrial & Engineering Chemistry Process Design and Development*, *18*(3), 357–364. [CrossRef]

van Vorst, H., Dorschu, A., Fechner, S., Kauertz, A., Krabbe, H., & Sumfleth, E. (2014). Charakterisierung und strukturierung von kontexten im naturwissenschaftlichen unterricht—Vorschlag einer theoretischen modellierung. *Zeitschrift für Didaktik der Naturwissenschaften*, *21*(1), 29–39. Available online: https://app.dimensions.ai/details/publication/pub.1010423780 (accessed on 19 February 2025). [CrossRef]

Vennix, J., den Brok, P., & Taconis, R. (2017). Perceptions of STEM-based outreach learning activities in secondary education. *Learning Environments Research*, *20*, 21–46. [CrossRef]

von Arx, M., & Bernholt, S. (2015). Ein Kompetenzstrukturmodell für den handlungsaspekt "ordnen, strukturieren, modellieren" im fach chemie. *Perspectives in Science*, *5*, 36–44.

Wallrath, S., Engl, A., Erdmann, N., Kollmen, J., Strieth, D., & Risch, B. (2023). Mikrocontroller als low-cost technologie: Monitoring von wachstumsparametern bei mikroalgen in einem 3D-gedruckten IoT-photobioreaktor. *MNU Journal*, *76*, 5.

Woithe, J., Müller, A., Schmeling, S., & Kuhn, J. (2022). Motivational outcomes of the science outreach lab S'Cool LAB at CERN: A multilevel analysis. *Journal of Research in Science Teaching*, *59*(6), 930–968. [CrossRef]

Yin, Z., Zhu, L., Li, S., Hu, T., Chu, R., Mo, F., Hu, D., Liu, C., & Li, B. (2020). A comprehensive review on cultivation and harvesting of microalgae for biodiesel production: Environmental pollution control and future directions. *Bioresource Technology*, *301*, 122804. [CrossRef] [PubMed]

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