

Knowledge Transfer in Support of the Development of Oxygen Concentrators in Emergency Settings During the COVID-19 Pandemic

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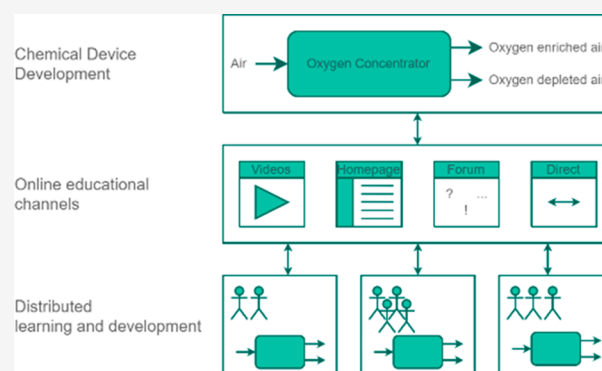
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ABSTRACT: The COVID-19 pandemic simultaneously disrupted supply chains and generated an urgent demand in medical infrastructure. Among personal protective equipment and ventilators, there was also an urgent demand for chemical oxygen. As devices to purify oxygen could not be manufactured and shipped rapidly enough, a simple and accessible oxygen concentrator based on pressure swing adsorption was developed at ETH Zurich in spring 2020. Instead of building devices locally and shipping them, it was decided to educate others in need of oxygen. The implementation encompassed education on process chemistry, material choice, and assembly and optimization of the concentrator and was realized using synchronous teaching tools, such as video call, and asynchronous ones, such as a website and video streaming. The project gained traction and interaction with engineering teams from universities and non-Governmental Organizations (Red Cross and the UN Development Program) in developing countries and emerging market economies, including Ecuador, Mexico, Somalia, and Peru. At the end of the project, the teams were surveyed regarding their experience in the educative knowledge transfer. It was reported that the learning experience prepared these groups well to build the device and to teach others as well. Major challenges were accessing some parts of the device and optimizing its performance. While synchronous communication is expected to be a very effective teaching method, the survey results showed that explanations via a website and video streaming have contributed the most to the implementation of the oxygen concentrator and thereby provide autonomous and sustainable education tools.

KEYWORDS: Continuing Education, Chemical Engineering, Distance Learning/Self-Instruction, Gases



INTRODUCTION

Between 2019 and 2021 the world was marked by one major event: the global pandemic of COVID-19 caused by the virus SARS-CoV-2, which can induce severe acute respiratory infection (SARI),¹ as well as acute respiratory distress syndrome (ARDS).² According to the World Health Organization (WHO), supplemental oxygen is vital for the treatment of these diseases and has no substitute.³ Oxygen is listed as an “essential medicine” by WHO,¹⁰ and it has been commonly used for example in the treatment of chronic obstructive pulmonary disease (COPD), for neonatal care in delivery rooms,^{8,9} and during surgery. The spiking demand for supplemental oxygen during this health crisis critically exposed the problem of its availability.⁵ Studies have shown that many patients in low-resource settings (LRSs) do not have access to supplemental oxygen even in hospitals.^{6,7}

The pandemic has impacted not only people’s health but also societies and economies. COVID-19 increased social

imbalance, restricted international mobility, and caused delays in supply chains, thus creating shortages of many resources.¹³ Oxygen is commonly delivered to health facilities in the form of pressurized gas, cryogenic liquid, or piped from an oxygen plant, whereas supply for private households is often realized through oxygen concentrators, as it is cost-effective and more broadly available.⁴

Especially in low-income countries or in times of crisis, an oxygen shortage is fatal but very prominent, for instance, in India¹¹ or Ukraine¹² lately. A way to work around the supply chain is distributed manufacturing systems (DMSs).¹⁴ The

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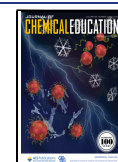


Table 1. Evaluation of Air Separation and Oxygen Generation Technologies most appropriate for DIY Oxygen Production

criteria	air separation technologies			oxygen generation technologies	
	fractional distillation	pressure swing adsorption	membrane separation	water electrolysis	decomposition of sodium chlorate
conventional use	industrial oxygen production	on-site oxygen production	on-site oxygen production	hydrogen production	single use emergency oxygen
DIY feasible	no	yes	yes	yes	no
continuous supply of material	air	air	air	water	sodium chlorate
external energy requirement	high (cooling air)	small (pressurizing air)	small (pressurizing air)	high (electricity)	none
system complexity	very high	medium	low	low	very low
controllability at required scale		easy	easy	easy	hard
safety concern	very low temperatures	compressed air	compressed air	flammable	oxidizing, skin irritation, hazardous

defining characteristic of DMSs is the division of the production of goods into different subprocesses and the proximity of the manufacturer to the end-user.¹⁵ The distributed manufacturing of an oxygen concentrator can decouple the access of oxygen from unreliable supply chains, making it more sustainable in the long term.¹⁵ Also, decentralized manufacturing comes with flexibility as it allows for local production of oxygen with easily accessible materials in a LRS.

Despite the unmet demand for oxygen, the existence of multiple production technologies, and the evidence of successful remote education strategies, there is little documentation that gives insight into whether it is possible to teach engineers in LRSs how to create and maintain access to this important medicine. In response to these challenges and the closing of most educational institutions at the beginning of the pandemic, we (the Functional Materials Laboratory at ETH Zürich) decided to develop a simple and accessible oxygen concentrator with the goal to support the decentralized production of a scarce but vital resource. Instead of aiming at a local manufacturing and shipping of the devices, we took into consideration the recent rise of digital access in LRS and started documenting each step of the development on a webpage, via educational videos on YouTube, and offered remote private consultations, in order to rapidly translate our know-how to others in need. Our target audience was not specifically chemists but rather engineers and other otherwise trained technicians, and their first language was never German or English. We mostly interacted with small teams (5–25 people each), which were organized by local Universities or Non-Governmental-Organizations (e.g., Red Cross and UNEP) in countries including India, Somalia, Ecuador, Peru, and others. Our efforts not only included traditional know-how transfer but also chemical education in the involved processes so that engineers would have the knowledge to adapt the technology to the local circumstances and constraints. As a follow-up of the educative efforts, we surveyed the effectivity of the employed know-how transfer tools by interrogating the information receiving teams via a short questionnaire. Consequently, we were able to assess to what extent it is feasible to implement the oxygen concentrator into LRS and to sustainably share the knowledge during and beyond the pandemic. In this work, we (a) describe the process of technology selection for locally produced oxygen generating devices, (b) the governing principles of the selected technology, (c) the assembly and optimization of such devices

from only a few commercially available parts, and, finally, (d) discuss the use of online tools to globally distribute knowledge and assist in device operation and maintenance. In addition, the resources generated, and included in this article as the [Supporting Information](#), may be useful in transforming the low-cost oxygen generation system into a practical activity in a practical undergraduate chemical engineering course.

■ BACKGROUND

Technology Selection

The many techniques to produce oxygen can be divided into air separation technologies, including fractional distillation, membrane separation, and pressure swing adsorption, as well as oxygen generation technologies, such as water electrolysis and chemical oxygen generation. An overview of the different oxygen production technologies is given in [Table 1](#).

Single use chemical oxygen generators are widely applied to deliver oxygen in emergencies, for instance, in aircrafts, submarines, and mining. However, this technology was ruled out due to the need for a constant supply of other chemicals (i.e., sodium chlorate) and the hazards associated with the chemical reaction.¹⁶ While water electrolysis can be demonstrated in smaller scales,¹⁷ at larger scales, the required amount of electricity (>1.62 kJ/L) is not supportable in low-resource regions, and hence, this technology is only applicable in a limited number of contexts, such as on the International Space Station (ISS).¹⁸ Furthermore, deionized water is needed for electrolysis, as otherwise, toxic chlorine is formed.¹⁹ Air separation technologies take advantage of the abundant availability of air, which consists mainly of nitrogen (~78%) and oxygen (~21%). Fractional distillation of air has been deemed inappropriate as well, because of its energy consumption and infrastructure demand. This technology relies on the different boiling points of liquids, but the liquefaction of air calls for great amounts of energy and requires specialized equipment.²⁰ Membrane gas separation is indeed a simple process and requires only few resources; however, the development of the appropriate membranes is not yet advanced enough.²¹ Pressure swing adsorption (PSA), as further described below, is a mature technology essentially requiring a suitable adsorbent material and common pneumatic parts.

Upon comparison of these different oxygen production pathways, the PSA technology was selected for this oxygen concentrator project because of its system simplicity and ease of applicability. As it mostly requires common pneumatic parts,

the oxygen concentrator can be decoupled from the unreliable supply chain and can be assembled locally only using the knowledge of its process (presented in this work). Also, the WHO acknowledges PSA as a cost-effective technology to produce medical grade oxygen and provides technical specifications for centralized PSA oxygen plants and smaller oxygen concentrators.

Pressure Swing Adsorption

Pressure swing adsorption (PSA) is a gas separation technology taking advantage of the gases' specific interactions with the surface of an adsorbent.^{22,23} During adsorption, molecules from a fluid, the *adsorbate*, bind to the surface of a solid, the *adsorbent*, and are thereby removed from the fluid phase. The reverse process, *desorption*, releases the adsorbed molecules to the fluid.

In thermodynamic equilibrium, the adsorbed amount of a pure gas q on a material, generally depends on temperature T , pressure p , and the specific interaction between the gas and the material.

$$q = f(T, p) \quad (1)$$

A popular model to describe q is the Langmuir model, which assumes a uniform surface containing homogeneous adsorption sites. All these sites shall be equivalent and each site hosts at most one molecule, while interactions between adsorbed molecules on adjacent sites are neglected. According to the Langmuir model, q depends on the temperature dependent equilibrium constant $K(T)$ and the pressure of the pure gas:

$$q \propto \frac{K(T) \cdot p}{1 + K(T) \cdot p} \quad (2)$$

For mixtures of gases competing for the same adsorption sites, the adsorbed amount of a species depends on the partial pressure and equilibrium constant of all species, e.g., for gas i in a binary mixture with gas j :

$$q_i \propto \frac{K_i(T) \cdot p_i}{1 + K_i(T) \cdot p_i + K_j(T) \cdot p_j} \quad (3)$$

Thus, the composition of a gas mixture in contact with a selective adsorbent ($K_i \neq K_j$) can be changed by altering the gas pressure. This principle is applied by the PSA technology to (semi-) continuously separate gas mixtures.

To produce concentrated oxygen by PSA of air, the atmosphere in a column packed with zeolite (adsorbent) is pressurized by feeding air through an inlet. As further described below, the zeolite's higher affinity for nitrogen ($K_{N_2} > K_{O_2}$) leads to the selective removal of nitrogen from the gas phase. The remaining atmosphere is consequently concentrated in oxygen and leaves the column via an outlet. As the adsorbent has only a limited capacity to adsorb nitrogen, it requires to be regenerated in cycles. Therefore, the feed of air is stopped and the column is depressurized via the inlet. Due to the drop in system pressure, the previously adsorbed nitrogen desorbs from the zeolite, leading to a nitrogen-rich atmosphere. This atmosphere is finally pushed out of the column by feeding some of the previously produced oxygen-rich atmosphere back into the column.^{23,24}

Zeolites and Chemical Interactions

The gas-specific interactions of the adsorbent material lie at the heart of the PSA process. While the driving force for

adsorption and desorption results from the change in (partial) pressure, the selectivity arises from different strengths of the electrostatic interactions between the gases and the adsorbent, which often consist of zeolites or other high-surface area solid materials.

Zeolites are microporous, crystalline materials commonly used for ion-exchange, catalysis, and adsorption.²⁵ They consist of regularly assembled SiO_4 and AlO_4 tetrahedra sharing oxygen atoms that form a three-dimensional structure containing channels and micropores. The negative charges introduced by the AlO_4 tetrahedra are balanced by alkali and alkaline-earth cations that can be exchanged, for instance, to alter the adsorption properties of a given Si–O–Al framework.²⁶

The selectivity required for the separation of nitrogen and oxygen, which are both homonuclear diatomic gases of approximately equal size, arises from the different quadrupole moments of the molecules. As indicated in Figure 1 for

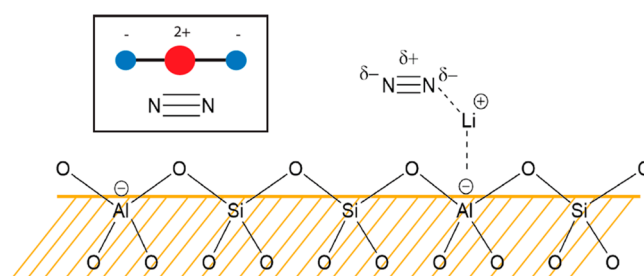


Figure 1. Scheme showing the interaction between the quadrupole moment of nitrogen with the EFG of the Li-cationic surface on the zeolite in analogy to Gallei and Strumpf.²⁹ The linear quadrupole moment is depicted in the upper left corner.

nitrogen, the electrostatic interactions between the electric field gradient of the zeolite's cationic surface with the quadrupole moment of the molecule lead to adsorption.²⁷ As the quadrupole moment of nitrogen is about three times higher than the quadrupole moment of oxygen, the electrostatic interactions are stronger and the adsorption energy is higher, resulting in a greater equilibrium constant (K).²⁸

Zeolites exist in many different structures,³⁰ but for air separation, common zeolites NaX and LiX, both assuming the faujasite structure shown in Figure 2, are used.³¹ As studies have shown that LiX gives better recovery and purity compared to other zeolites,^{32,33} it was selected for this project.

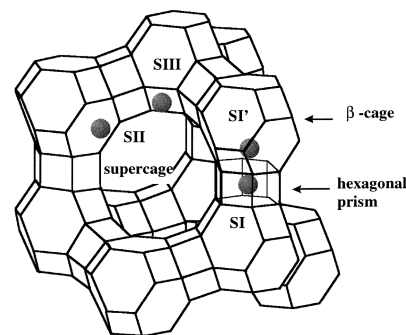


Figure 2. Cation locations in zeolite assuming faujasite structure. Reprinted with permission from ref 31. Copyright 1998 American Chemical Society.

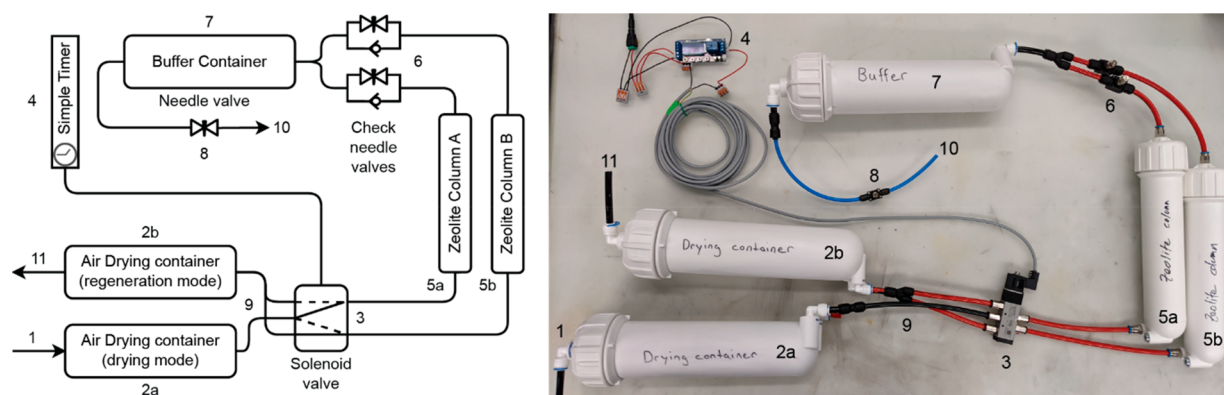


Figure 3. Setup of the DIY oxygen concentrator.

■ OXYGEN CONCENTRATOR

Commercial Concentrators and Simplifications

Commercial oxygen concentrators are commonly used by patients with a prescription for oxygen therapy and are based on a PSA process with nitrogen-selective zeolites.²² Generally, during PSA, a column is operating in four different steps following the Skarstrom cycle: pressurization, adsorption, blowdown, and purge.^{34,35} The main disadvantage of the commercial devices is that the access to oxygen or maintenance of the device is fully coupled to the manufacturer, as well as that the concentrators may not be globally available, not to mention affordable.

For our own oxygen concentrator development, focus was put on simplicity. The two-bed system was adopted for the presented concentrator as well, but instead of a computer controlling the valves, the cycles are controlled by a simple timer. While efficiency is important to compete on the global market, it was decided that in times of crisis the priority for an oxygen concentrator lies in its accessibility. The given system enables the user to modify, replace, and fix units of the device, making it better applicable and sustainable in LRSs. Additionally, applying DMS, all the materials for the parts can be inexpensively purchased at local manufactures or online (with the exception of the zeolite) and assembled on-site, avoiding the long supply chain of a commercial oxygen concentrator. It should be mentioned that, for final use, the oxygen stream should be filtered or bubbled through water, to remove any particles and rehumidify the gas; however, these steps have not been accounted for in the setup.

Process of the DIY Oxygen Concentrator

In the first step of the process designed for the emergency-use oxygen concentration, air is pressurized by a compressor and is dried in a container filled with silica gel. Using a 5-2 solenoid valve, the dried air enters one of the columns filled with LiX zeolite, where mainly nitrogen is adsorbed. The oxygen-rich air reaches a buffer tank via a unidirectional check needle valve, which lets the air pass into the tank and limits the flow in the other direction to a small amount only. The idea here is to keep most of the generated concentrated oxygen in the buffer tank and to only use a small amount of oxygen escaping the tank via the needle valve to purge the (other) column from any remaining nitrogen during depressurization. Depressurization of the column occurs after a shift in position of the solenoid valve and releases the adsorbed nitrogen. The nitrogen-rich air in the column leaves the system through a second drying

container, restoring the silica inside. While one column is depressurizing, the other can be pressurized with air again, providing a continuous production of oxygen. As both adsorbent beds are connected to the inlet and outlet containers, the process requires that the position of the solenoid valve is controlled by a timer. The timer is set to switch the position of the valve after each cycle. A constant oxygen stream can be then accessed from the buffer tank through a further needle valve (see Figure 3).

Optimization

Usually, oxygen-concentrators are produced as a ready-to-use item. Our experience in constructing such devices and educating others in replicating the devices showed that device by device optimization was required. In some cases, even if other teams were provided with every part of the device and detailed instructions on how to assemble them, it was very difficult to produce high-quality oxygen. This is due to a precise flow and timing optimization required for the different units. In commercial devices, the manufacturer presets the system to the optimal operating conditions, while the LRS oxygen concentrator needs to be manually optimized. This process is crucial but also time-consuming, which is why we have established optimal working conditions for the LRS system through meticulous testing.

Nonetheless, adjustments in the valve settings for the needle valves, the check needle valves, inlet pressure as well as cycle time can be made, to optimize the concentrator further to a specific requirement. Therefore, a set of experiments was conducted, where those four parameters were varied independently from one another and the input flow rate, output flow rate, and the oxygen concentration were measured. This systematic experimental optimization as well as the base values for the working DIY oxygen concentrator can be found in the Supporting Information.

■ EXPERIMENTAL SECTION

Material and Setup of the LRS Oxygen Concentrator

LiX zeolite (ZEOX Z12-49 Li-LSX, Zeochem AG, Ruti, Switzerland; 700 g) was placed inside two cylindrical housings (5, see Figure 3), which are usually sold in the context of low-pressure water purification. A layer of scourer and a perforated metal disk were placed at both ends of the column, as well as a steel spring at the top, to constrict the zeolite beads, which is important to avoid the beads grinding against each other into a powder and potentially clogging the valves.

Two cylindrical housings (2a and b, see Figure 3) filled with silica gel (Giebel Absorber, 1300 g) were connected to a solenoid valve (3), so that there is one port to pressurize, connected to the inlet (1) and one port to release the pressure (11) for each cycle. The pneumatic valve (3) was connected to the timer (4). The outlets of the valve were connected to a zeolite column (5) each. The columns in turn were connected to the check needle valves (6). Both check needle valves were connected to the storage tank (7), which in turn was connected to the needle valve (8). The oxygen could be released through the outlet (10).

Commercial solenoid valves were used to control the individual phases of the PSA cycles. After testing several combinations of different valves ($4 \times 2/2$, $2 \times 2/3$, $1 \times 5/2$) it was decided to implement a single 5-2 valve (Festo) as it seemed particularly simple, robust, and most suited for the rapid prototyping phase. This valve was controlled by a simple timer. Standard fittings and tubing (Festo and Legris) were used to connect the components.

For the set of experiments, compressed air (2–4 bar g) was provided either from the lab infrastructure or using a commercial air compressor (MX-AC 260/50/10, Merox). The oxygen concentration in the outlet stream was measured by means of a commercial oxygen sensor (GOX 100 Oxymeter, Greisinger). Further information concerning the assembly of the concentrator can be found in the Supporting Information.

Teaching Platforms

The website (<http://oxygenator.getechprojects.com/>) was launched in April 2020 and contains an introduction to oxygen concentration by pressure swing adsorption in written form and illustrations, including the required chemical background knowledge. In the system section, a general scheme of a typical PSA oxygen concentrator and its components was provided, and two different types of PSA systems (single-/double-column) were explained each with schematics. On the prototype blog, each new prototype was presented together with a summary of parameters and performance characteristics. Each page of the website contained one or several videos from the YouTube channel, and thereby, the webpage provided metadata to the videos. Several sections of the homepage entailed a comment function, allowing for interaction with the development team and others by leaving a post.

On the video streaming platform YouTube, a channel was operated (Project Oxygenator <https://www.youtube.com/@projectoxygenator4562>). The channel contains the videos mentioned on the website. The comment function allowed the community to interact. From 04/2020 to 10/2022, the channel content increased to 19 videos, with a total of 1800 subscribers and 186,000 views. Most videos were very technical, with one 30 min educational video (<https://www.youtube.com/@projectoxygenator4562/playlists>) on the PSA process, in which the chemical principles of the process are explained.

The forum (<http://oxygenator.getechprojects.com/phpbb/>) was dedicated to share information and details about the rapid construction of the oxygen concentrator in a more structured way compared to the comment sections on the website and YouTube. Thus, topics such as zeolites, desiccants, and system pressure could be discussed.

Personal correspondence was conducted by email and video calls. It served individuals and groups to discuss their ideas,

questions, and problems for developing an oxygen concentrator directly with the development team over the course of several months.

While these teaching materials were constructed to educate engineering teams in LRS settings, they may also be found useful in teaching the theoretical and practical aspects of pressure swing adsorption processes to undergraduate Chemical Engineering (ChE) students in university settings. The Supporting Information of this manuscript includes a step-by-step manual to construct a PSA device. Many of the components required to build the devices (Table SA1) are available at such undergraduate laboratories. Consequently, the manual could either be adapted to construct a practical course for early stage ChE students. Alternatively, the material could be used without modification as a self-learning practical course for more advanced engineering students, especially in conjunction with the available online streaming videos. We, and several of our students, found this process very engaging and rewarding: with the use of a rather simple set of materials and components, in conjunction with general chemistry and engineering knowledge and an optimization according to the Supporting Information (optimization protocol), air can be separated into its main components with quite little effort.

IMPLEMENTATION OF THE OXYGEN-CONCENTRATOR FOR LRS

Soon after developing the first prototype, our team installed a webpage, a forum, and a YouTube channel to document and share the ongoing progress of development, displaying the project status and various prototypes. During several months of extensive trial and experimentation, the website and YouTube channel received tens of thousands of views and comments, which led to the realization that there is demand in education on the oxygen concentrator. When multiple teams of engineers and scientists from around the globe contacted us looking for help to build an oxygen concentrator, the focus was extended to bring this project to people in LRSs.

Evidently, this education had to be realized remotely, either in an asynchronous, synchronous, or combined fashion.³⁶ With asynchronous communication, the instructor's and the student's simultaneous presence is not required, which includes communication means such as email, videos, or explanations on the process and assembly via the webpage. It has been shown that educational videos posted on YouTube or other social media have a positive learning effect as they are available to consult whenever and as often as needed.^{37,38} However, prerecorded videos or contributions on a webpage do not offer much variation or address specific concerns,³⁶ which limits the educational benefit.

Furthermore, according to the WHO and other studies,^{4,39,40} the success of the implementation of oxygen concentrators in a LRS depends on extensive training of the staff and maintenance of the devices; thus, synchronous communication was introduced. For instance, explications and optimization consultations via video call were offered to help understand the process and install the oxygen concentrator. While synchronous online teaching offers a deeper understanding and a better-tailored support, it requires a stable Internet connection, which is not always provided everywhere.³⁶ This can lead to disturbances during the learning process, confusion, or even miscommunication.⁴¹

Aside of directly contributing to anonymous education and knowledge transfer, our webpage and Youtube channel

resulted in several direct interactions with engineering teams in low-resource settings. These teams were either organized by Non-Governmental Organizations or by local universities, and we engaged with these teams via direct interaction (e-mails and video calls) and pointed them to the device and engineering documentation we had generated and published via the website and on-demand video streaming service. Many of the teams used our (and potentially other educational efforts) to locally manufacture oxygen generation units.

In order to assess the educational benefit of the device's implementation and to address the aforementioned obstacles, a short anonymous interview was conducted among these teams at the completion of the project (April 2022). We were in contact with seven different groups of people around the world, including students from technical universities in Ecuador and Somalia, as well as engineering groups from Scotland, South-Africa, Peru, and India. The questionnaire can be found in the [Supporting Information](#).

INTERNATIONAL FEEDBACK

Out of the seven scientist/engineering groups we interacted with, four filled out the questionnaire (57%). It should be pointed out that, even though the number of groups that participated in the survey is low, the questionnaire was completed by the group leader only, and each group consisted of between 5 and 25 team members. Many more people interacted via YouTube comments or on the forum, but we have no intelligence on their progress in building oxygen concentration devices and the state of their learning progress.

Concerning the learning media, 100% of the interviewees found YouTube the most useful out of all given information channels. The webpage was rated useful to very useful by most of the groups, and the forum, where people could ask questions to which we responded, was rated neutral to barely useful. Regarding the personal correspondence (e.g., meetings and emails), the opinions were divided, as half of the groups found it to be useful to very useful, meanwhile the other half found it barely useful.

Additionally, the groups were asked how well the sum of these teaching methods prepared them to build the oxygen concentrator, where the majority felt mostly prepared, with only one group feeling rather unprepared. Nonetheless, all groups indicated that they understood the process of oxygen separation in the oxygen concentrator to the extent that they could explain it to others without any problem or with just little help. Furthermore, it was inquired whether the project was continued, to which the majority responded that the concentrator is still mostly to fully running two years later and one group had work on the oxygen concentrator in progress.

Lastly, the interviewees were invited to rate several challenges based on their difficulty. Everyone answered that the assembly of the oxygen concentrator, as well as the understanding of the process was neutral to not difficult at all. Further, the optimization of the device was rated very difficult by most of the groups except for one, which had no difficulty in device optimization. This displays the technical challenge of the device implementation and, also, that the teams had gone through the complete engineering and setup of prototype devices. Finally, the groups were asked how challenging the access to the required material was, where the answers varied the most. Half of the groups felt the accessibility was a medium challenge, while one group had no difficulty acquiring the material and another found it most challenging.

DISCUSSION

During the outbreak of COVID-19, an accessible oxygen concentrator was developed, and multiple remote learning channels were set in place to educate and support groups of scientists and engineers in LRS with theoretical chemical and practical know-how to generate oxygen supply units. Results show that all groups were mostly successful in the implementation of the oxygen concentrator and were not only able to understand but also teach the process of oxygen separation via PSA. Furthermore, the groups succeeded in installing a sustainable access to oxygen, seen as the devices were still running 18–24 months later.

After having transferred the required chemical- and process-knowledge, the next layer of problems mainly included access to materials. While main components could be acquired from different local workshops, personal correspondence with the groups revealed that the access to zeolite LiX presented the biggest difficulty. Alternatively, the more accessible and cheaper zeolite NaX may be used as well, even though not being as efficient.^{32,33} Given zeolite NaX, the efficiency could be improved by synthesis of LiX through ion exchange with a neutral aqueous LiOH solution.⁴³ Another technical problem could be the measuring of the oxygen concentration, as oxygen sensors can also be quite expensive or hard to acquire. As an alternative, an automotive oxygen sensor can be used.⁴⁴

Regarding the learning process, the YouTube channel and the website were reported by the scientist/engineering teams to be the most useful tools to learn about the oxygen concentrator. It was a surprise to us that personal synchronous consultations have not been uniformly seen as helpful, as other studies show that the immediate feedback as well as personal monitoring and interactions are critical for a successful learning environment.^{36,41,42} Additional communication challenges involved in this project included language, social, and time-zone related issues, which may be at least partly resolved using asynchronous digital communication and appropriate tools.

YouTube and other on-demand streaming services have proven to be a tool to reach people all over the world in a very small amount of time; hence, they have a high impact on education.⁴⁵ Contrary to e-mail correspondence and a forum, which can be characterized as one-to-one communication and one-to-few, respectively, the website and the YouTube channel are communication tools that reach a lot of people with a global spread and very minimal latency.

The major learnings to our team during the course of this project are that on-demand video streaming provides extreme speed and scalability, making it a powerful, asynchronous teaching platform that is often overlooked in the scientific world. As an example, our content was initially chemically and conceptionally oriented, but from feedback, we rapidly learned about the importance of hands-on and practical videos for the construction of the oxygen concentrator so that others felt confident to replicate the system. Such a quick adaption process requires that the teaching platform remains bilateral and direct, for instance, by providing a comment section. All of this is not possible or significantly slower by using traditional, non-scalable knowledge transfer methods. Further, knowledge transfer via video possibly increases confidence in tackling seemingly complicated and dangerous processes involving gases above ambient pressure.

CONCLUSION

An accessible and sustainable oxygen source based on PSA has been developed in early 2020 and successfully implemented in several low-resource settings, with the help of remote educational tools during the pandemic. Explanations via YouTube and a website have massively contributed to the understanding of the gas separation process in an oxygen concentrator and have helped with its assembly. A survey and extensive correspondence with people in LRS via comments and emails have helped to summarize this experience into several documents surrounding the device, including an assembly manual and an optimization report, that can be found in the [Supporting Information](#). Additionally, this oxygen concentrator might be used as a tool to teach the concepts of pressure swing adsorption and systematic experimental optimization to undergraduate chemistry students.

We envision that, in periods of extreme stress for the health care system, such as those recently experienced during the pandemic or in war, this knowledge can be used to rapidly construct oxygen concentrators thanks to the collaboration between health-care personal and local manufacturers. Given the omnipresent necessity of oxygen and its potential insufficient supply, we aim to promote lasting learning of the chemical concepts behind oxygen generation and to share this knowledge, so that educators and scientists around the world can use, adapt, and improve the process.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at <https://pubs.acs.org/doi/10.1021/acs.jchemed.2c00925>.

Manual for oxygen concentrator assembly (PDF, DOCX)

Optimization report (PDF, DOCX)

Survey questions (PDF, DOCX)

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Notes

The authors declare no competing financial interest.

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