Net Zero Emission and Microalgae Biotechnology Carbon Dioxide Sequestration with Droplet and Digital Microfluidics

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***Abstract*—Global concerns about climate change and targets for achieving zero net emissions have grown as the concentration of carbon dioxide (CO_2) in the atmosphere has also risen, as a result of Industrialisation and fossil fuel usage. The biological sequestration technologies are being investigated as a potential solution because of the high photosynthetic efficiency of microalgae, their high growth rate, and their ability to convert CO_2 to valuable biomass and bio-based products. Nevertheless, the screening and selection of a strain with high performance is still a challenge. The recent development of droplet microfluidics and digital microfluidics has opened up new avenues in microalgae biotechnology, allowing a more precise handling, growth, screening and analysis of the microscale level of all single cells. These technologies enable high throughput isolation, detection and monitoring of microalgae, and automatic sorting of microalgal populations, to speed the identification of alternate strains of microalgae with greater carbon fixation capacity, biomass productivity, stress tolerance, and lipid accumulation potential. The droplet microfluidics allows for the creation of microenvironments for single-cell cultivation and analysis as a miniaturized bioreactor, and the digital microfluidics allows for the programmable control of discrete droplets for automated biological assays. These technologies, combined with microalgae research, boost the effectiveness of screening, use less amount of reagents, cut down on operational costs, and increase analytical accuracy. Moreover, the microfluidic platforms have the potential of enabling sustainable carbon capture and utilization systems by screening microalgal strains for their ability to efficiently make use of the CO_2 emissions from industry. The biomass produced can be used for renewable biofuels, bio-plastics, fertilizer, pharmaceutical and nutraceuticals, and other value-added products, which will help the development of the circular bioeconomy. Apart from carbon sequestration, the environmental benefits of the biotechnology of microalgae using the microfluidic technology are climate change mitigation, improvement of air quality, wastewater treatment, nutrient recycling, conservation of biodiversity and renewable energy production. Combining droplet and digital microfluidics with microalgae biotechnology is thus a promising and sustainable approach to improve carbon dioxide sequestration and global net-zero emission projects. This multi-disciplinary approach could be a key enabler for future carbon neutral technologies and sustainable environmental management.**

I. INTRODUCTION

Growing environmental detoriation and global detoriation is largely driven by human activities, which have augmented the search for carbon mitigation strategies. Initially, traditional carbon capture and storage(CCS) technologies were regarded as practical solutions. However, their widespread adoption is limited. Carbon dioxide is a major greenhouse gas which accounts for the largest part of global greenhouse emissions. Its atmospheric concentration continuously rises due to fossil fuel combustion and deforestation. While reducing the energy consumption and combustion efficiency limit the greenhouse gases emission and active removal of CO_2 is contributed to reduce these emissions. Achieving net zero emissions defined as balance between greenhouse gases emission and equivalent removal of GHG sinks, has become a global objective. In accordance with Paris agreement targets of limiting global temperature rise to 1.5–2 °C. Many countries committed to long term net zero emissions((Li et al., 2026)).

Carbon sequestration is the process of capturing storage of CO_2 via physical, chemical and biological approaches. Various chemical and biological sequestrations have been developed, which enabling captured CO_2 to be stored in deep ocean reservoir and saline aquifers or converted into various products such

as concrete, carbonates and fuels. However, conventional physical and chemical processes are highly consuming energy and more expensive. Biological sequestration gain more attention as it converts the CO_2 into biomass using solar energy. Although terrestrial and aquatic plants can fix the CO_2, their relatively slow growth limit their overall impact on CO_2 sequestration. Consequently, biological approaches, particularly microalgae-based CO_2 sequestration are gaining the attention as an alternative. The advantage of utilizing microalgae is a simple, fast growing unicellular or multicellular photosynthetic microorganism with higher CO_2 fixation efficiency than plants and biomass accumulation efficiency. Microalgae, including cyanobacteria, convert carbon into chemical energy during photosynthesis; producing biomass is further processed into biofuels. Thus, they offer a sustainable and recyclable pathway for carbon capture and utilization((Jeon & Han, 2026; Morales et al., 2018; Zhao et al., 2024)).

Microfluidics technology has significant intrest in biological approaches due to its ability of precisely regulate cellular microenvironment in both spatial and temporal dimensions. Through the principles of laminar flow and microscale diffusion, these systems enables the creation of controlled biological conditions including nutrient variations, concentration gradients and various physical and chemical stresses. This study highlights the integration of microalgae to microfluidic technology by addressing key challenges encountered at different stages of the process. Crucial requirement for optimizing microalgal CO_2 sequestration is the accurate lipid droplet quantification. To achieve this, advanced fluorescence-based detection strategies are explored.

II. MICROALGAE AS A PLATFORM FOR CARBON DIOXIDE SEQUESTRATION

Microalgae are unicellular photosynthetic organisms capable of converting CO_2 into organic biomass with remarkable efficiency. Their ability to thrive in diverse environmental conditions, including wastewater and industrial flue gases, makes them suitable for large-scale carbon capture applications. Beyond sequestration, microalgal biomass can be converted into biofuels, pharmaceuticals, nutraceuticals, and other high-value bioproducts, creating a circular bioeconomy. Traditional large-scale algal cultivation systems, such as open ponds and photobioreactors, face challenges related to contamination, inefficient mass transfer, and limited process control. These limitations hinder the identification and optimization of high-performing algal strains. To address these challenges, microfluidic technologies provide precise control over microscale environments, enabling enhanced experimentation and rapid innovation in algal biotechnology. Microalgae are unicellular photosynthetic microorganisms capable of converting CO_2 into organic biomass with exceptional areal productivity and resource-use efficiency compared to terrestrial crops((Morales et al., 2018)). Their ability to grow in diverse and non-arable environments, including wastewater streams and industrial flue gases, positions them as promising biocatalysts for large-scale carbon capture and utilization. In addition to CO_2 sequestration, microalgal biomass can be valorized into biofuels, pharmaceuticals, nutraceuticals, and other high-value bioproducts, thereby supporting the development of a sustainable circular bioeconomy. However, current large-scale cultivation platforms—principally open raceway ponds and conventional photobioreactors—suffer from critical limitations, including high susceptibility to biological contamination, suboptimal light and mass transfer, and restricted spatiotemporal control over culture conditions. These constraints impede systematic interrogation of microalgal physiology, hinder high-throughput screening, and slow the discovery and optimization of robust, high-performing strains under industrially relevant stressors (e.g., variable CO_2 loads, fluctuating light, and complex wastewater matrices). Consequently, the full biotechnological potential of microalgae for carbon capture and bioproduct generation remains underexploited((Jeon & Han, 2026)).

Microfluidic technologies offer an attractive route to overcome these bottlenecks by enabling precise control of microscale environments, rapid manipulation of nutrients and gases, and high-throughput, single-cell to microcolony-level analysis. Yet, there is a lack of integrated, application-oriented microfluidic platforms specifically engineered for systematic screening, characterization, and process optimization of microalgae under realistic cultivation conditions. This gap underscores the need to develop and validate microfluidic systems tailored to algal

biotechnology, with the ultimate goal of accelerating strain selection, process intensification, and translation to scalable carbon capture and bioproduct pipelines.

III. ROLE OF DROPLET MICROFLUIDICS IN MICROALGAL RESEARCH

Droplet microfluidics involves the generation of discrete microdroplets that serve as miniature reaction chambers. Each droplet can encapsulate individual microalgal cells, creating isolated microreactors for high-throughput experimentation. This technology enables researchers to study cellular behavior at the single-cell level, allowing precise assessment of growth rates, carbon fixation efficiency, and metabolic responses(Morales et al., 2018; Zhao et al., 2024).
Encapsulation within droplets improves nutrient diffusion and gas exchange, promoting optimal microenvironmental conditions. High-throughput screening of thousands of droplets simultaneously facilitates rapid identification of strains with superior CO_2 sequestration capabilities. Furthermore, droplet microfluidics supports directed evolution and strain engineering by enabling automated sorting of high-performing cells. These capabilities significantly accelerate the development of robust microalgal strains tailored for industrial carbon capture. Digital microfluidics complements droplet systems by enabling programmable manipulation of discrete liquid volumes on microfabricated surfaces. Through electrical actuation, small droplets can be transported, merged, split, or mixed with exceptional precision. This level of control allows automated cultivation of microalgae under varying environmental conditions, including CO_2 concentration, light intensity, and nutrient availability((Li et al., 2026; Zhao et al., 2024)). Digital microfluidic platforms support real-time monitoring and on-chip biochemical assays, reducing reagent consumption and experimental time. The integration of sensors and imaging systems enables dynamic tracking of photosynthetic activity and cellular metabolism. Such programmable systems are essential for developing adaptive cultivation strategies and optimizing carbon capture efficiency.

IV. SINGLE CELL ISOLATION IN MICROFLUIDIC

Single-cell isolation is one of the basic procedures for microalgae research, as it allows for the isolation of a single microalgal cell from a complex environmental sample and allows for the establishment of single cell culture to study. The traditional isolation methods, including micropipette isolation, serial dilution and culturing on agar plates, are often time-consuming and labor-intensive, and can only isolate a small proportion of the diverse microalgae found in natural ecosystems. These approaches can also not differentiate for rare or slow growing species, as often the dominant species will outcompete them in culture. To meet these challenges, an innovative technology has been developed: microfluidic technology, which offers a highly efficient platform for the single-cell isolation and cultivation((Florea et al., 2025)). A microfluidic system is a system in which individual microalgal cells are trapped in small water-in-oil droplets, each of which is a microenvironment or microreactor. The encapsulation process allows for a controlled distribution, so that most droplets hold one or no cells, which enables the cultivation and analysis of single cells in individual droplets. This physical segregation prevents direct interactions between the different species and reduces competition for nutrients, space and light. Consequently, it is possible for even slow-growing or uncommon species to survive and multiply without being outcompeted by faster-growing species. The study showed that more than 10% of the droplets had a single microalgal cell, making the system a very good candidate for large-scale screening applications of single cells. Preserving species diversity is one of the major benefits of single-cell isolation via microfluidics. In a conventional bulk culture, the dominant species can grow at the expense of other species and dominate the culture resulting in a decrease in biodiversity. Microfluidics, however, can separate cells within a separate droplet, so they are not in competition with other species and can grow separately. This method aims at better preserving the original community composition and better recovering rare, slow growing or previously untouched species of microalgae. This sort of diversification is especially critical for screening programs in environment and industry where new strains with different metabolic features of interest are very desirable. Single-cell isolation also allows a detailed study of the physiological and biochemical properties of each microalgal cell. Growth rates, pigment production, lipid accumulation, photosynthetic efficiency and other cellular responses can be monitored under

controlled conditions. This is particularly useful for the identification of strains that possess industrially relevant traits such as high biomass productivity, high biofuel production capacity, improved carbon dioxide fixation, and production of valuable compounds like carotenoids, polysaccharides, and bioactive metabolites. Each droplet is an independent culture unit which allows for more precise observation and analysis of variation between individual cells than in bulk culture((Li et al., 2026; Zhao et al., 2024)). A major benefit of microfluidic single-cell isolation is the extremely high throughput. Compared to traditional approaches, manual handling and a high workload, microfluidic devices can produce and process hundreds of thousands of droplets per minute. This enables researchers to quickly and effectively screen mass quantities of microalgal cells. The seamless integration of isolation, cultivation and analysis in a single platform significantly shortens the time to find promising strains for biotechnology, aquaculture, pharmaceuticals, environmental remediation and renewable energy applications. In addition, a single-cell isolation system using microfluidics is a basis of technology for high performance cell separation. The microalgae have different fluorescent properties depending on their photosynthetic pigments, so that droplets with target cells can be recognized and separated according to the intensity and/or the wavelength of the fluorescence. This allows selective recovery of microalgae having specific taxonomic and/or physiological properties, thereby further improving the screening efficiency and accuracy. Single-cell encapsulation, cultivation and fluorescence sorting are a strong tool for investigating and cultivating the biodiversity of microalgae. Finally, we believe that the single-cell isolation enabled by microfluidic technology is an important step in the study of microalgae. Microfluidics eliminates many of the drawbacks of traditional isolation techniques including the ability to isolate single cells, limit competition between cells within the same culture, maintain biodiversity and allow high throughput screening. It is an essential tool in the microalgae research field, providing insights into microalgal biology, as well as fast identification of valuable strains for industrial, environmental, and biotechnological uses.

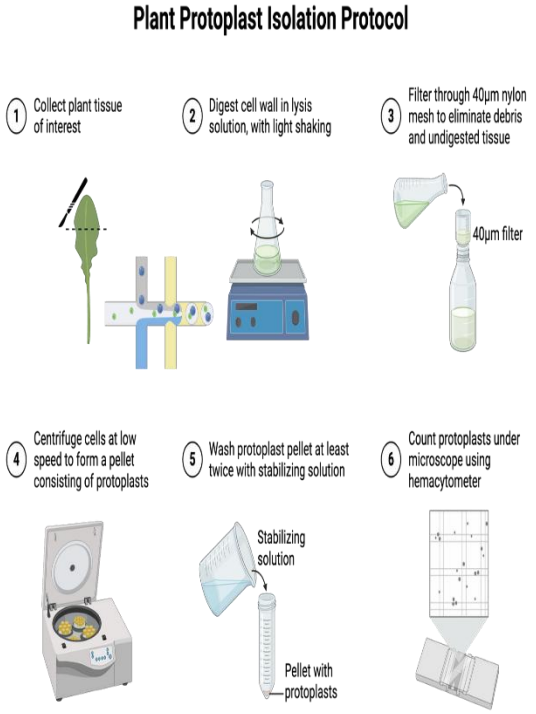

Fig 1- Plant protoplast isolation

Single-cell isolation is another critical application of the microfluidic technology in microalgae research since it allows precise and efficient separation, cultivation and analysis of single microalgal cells. Traditional techniques like serial dilution, micropipette isolation and agar plate culturing are often labor-intensive, time-consuming, are contamination susceptible and are not suitable for the vast variety of microalgae found in natural environments. Moreover, the traditional methods often are not able to separate rare or slow-growing species, because dominant species tend to overgrow when they are cultivated((Gomez, 2010; McRae et al., 2016)). Droplet-based microfluidics, in contrast, has been developed as a useful technique to isolate a single microalgal cell to circumvent these limitations. The microfluidic platform that the researchers studied allows them to individually encapsulate microalgal cells in micro-size water-in-oil droplets created by a T-junction microchannel configuration. The diameter of these droplets is about 60 µm and they serve as micro-reactors that create isolated environments for individual cells. The statistics describing the distribution of cells in the droplets during the encapsulation process is of Poisson type, so that there is a certain percentage of droplets which have only one

cell inside. The researchers were able to reduce the number of cells in droplets and boost the likelihood of getting single-cell droplets that would be needed for downstream applications by adjusting cell concentration appropriately. One advantage of the microfluidic system described herein is that the system includes a single microfluidic chip which encapsulates the cells, inspects the droplet, sorts the droplet, and collects the droplet on the same microfluidic chip. Once the droplets have been generated, the droplets then pass through a deceleration zone where they slow down enough to be viewed by microscopy. Researchers can see the individual microalgal cells in droplets and isolate them from empty droplets or droplets with more than one microalgal cell. This screening process significantly increases the percentage of single-cell droplets and enhances the accuracy of droplet isolation(McRae et al., 2016). A low cost solenoid microvalve system is used for sorting of single droplets. A small suction force is applied to the droplet which contains the single cell when it hits the sorting region, causing it to be sucked into a dispensing channel while the other droplets are directed to waste channels. The isolated droplet is then conveyed through a capillary interface and captured in standard laboratory containers like microplates or PCR tubes. This provides a one-cell-in-one-tube isolation method such that all samples collected are derived from one cell of the microalgae. The system's effectiveness was tested with cells of micro algae like Chlamydomonas reinhardtii. The experimental results revealed that the platform could obtain the single-cell isolation success rate exceeding 90%, and the average efficiency was about 1 cell per 20 seconds. This is much better than standard single cell isolation techniques. Continuous droplet generation, accurate on-demand sorting and precise visual inspection were responsible for the high success rate achieved. Preserving cell viability is an important advantage of microfluidic single cell isolation. The study showed that isolated cells have been biologically active following encapsulation and sorting. Minimal stress or damage to cells and successful cultivation of isolated microorganisms were achieved through the gentle microfluidic handling process. After microfluidic collection, about 80% of single cells remained viable and capable of proliferation, which indicates that the microfluidic process did not compromise the viability of the cells. This is very helpful for microalgae studies, for which living cells are needed for physiological studies, strain improvement, and biotechnological applications. Single-cell isolation also provides a way to perform detailed genetic and physiological analysis of microalgae. Once isolated, single cells can undergo whole genome amplification, quantitative PCR, RNA analysis and DNA sequencing. The study was able to obtain high quality DNA and RNA from isolated single cells and show that it was appropriate for genomic and transcriptomic studies. These analyses aid in the understanding of metabolic diversity, gene expression, stress responses and genetic heterogeneity at the individual-cell level. This is especially helpful as bulk population analysis may obscure significant cell-cell variation. Single-cell isolation is also a significant advancement in the field of microalgae research that has led to the identification of new strains and to the isolation of new and uncultivated species. The microbes in natural water environments are highly diverse and many of these species are difficult to culture in laboratories. Isolation of individual cells directly from environmental samples, together with genomic sequencing will enable the identification of new microalgae species and their ecological functions and biotechnological potential. This ability will greatly facilitate the search for strains of interest for biofuel, carbon capture, pharmaceutical, aquaculture and environmental remediation applications. Furthermore, the microfluidic platform is relatively easy to use, inexpensive, and straightforward compared to the advanced methods like the fluorescence activated cell sorting (FACS), Raman-activated cell sorting, optical tweezers and magnetic tweezers. The system uses standard laboratory equipment like syringe pumps, microscopes and relatively inexpensive solenoid valves, and can be readily available in many research laboratories. Droplet-based microfluidics is an appealing solution for contemporary research on microalgae, due to its simplicity, efficiency and ability to be readily integrated with downstream molecular analysis.

V. FACS INTEGRATED WITH MICROFLUIDICS

The combination of Fluorescence-Activated Cell Sorting (FACS) and microfluidic technology has proven to be a powerful tool for the rapid separation, screening and characterization of microalgal cells.

FACS is a very useful method to detect and isolate cells by their fluorescence characteristics and microfluidics allows exact manipulation of single cells and single droplets at the microscale. The use of these technologies allows for high throughput, automated and highly selective analysis of microalgae, which is highly beneficial for strain improvement, biodiversity studies, and biofuel research. Photosynthetic pigments like chlorophyll, carotenoids and phycobiliproteins are naturally present in microalgae, and they are known to release characteristic fluorescent signals upon exposure to a specific light(Florea et al., 2025). FACS uses those fluorescent characteristics to separate various species and/or physiological condition of the microalgae. Individual cells are first encapsulated in small droplets or flowed through micro channels, when combined with microfluidic devices. Lasers get absorbed by the pigments as each cell moves through a detection region, and the resulting signals are detected by fluorescence detectors. The target cells can be identified based on the fluorescent intensity, and the cells with spectral characteristics can be selected for further analysis. The big advantage of FACS-integrated microfluidics is the use of high throughput single cell screening. Manual observation and cell isolation is time consuming and labor intensive and the traditional screening methods. Microfluidic-FACS systems, on the other hand, can analyze thousands to millions of cells in a short time. The ability to work with environmental samples that can have very high diversity is very helpful for the study of microalgae, as can be valuable strains be very rare in these samples. The use of high throughput sorting greatly improves the chances of finding rare species that possess desirable properties. The technology is especially useful for screening of the lipid-rich microalgae, which is critical for biofuel production. Intracellular lipids can be stained with fluorescent dyes, e.g. Nile Red or BODIPY. As cells pass through the microfluidic-FACS platform, the brighter the fluorescence signals from the cells, the more lipid that the cells contain, and the brighter cells can be automatically sorted into separate collections. This will enable quick identification of better biodiesel-producing strains. A second application which is important is choosing high growth strains. Chlorophyll fluorescence is tightly correlated with photosynthetic activity and cell health. Fluorescence intensity can be used to determine more efficient photosynthetic cells and growth performance. These selected strains can be grown further for biomass production, carbon sequestration, aquaculture feed production etc. Single-cell physiological analysis is another use of the FACS-integrated microfluidics. The cells of single microalgal species can be highly variable within a culture. Certain cells might contain more lipid, make more pigments, or react differently to any environmental stress. Bulk measurements are an average of these responses and do not show differences between cells. Microfluidic-FACS systems, however, allow the ability to analyze individual cells, giving detailed information on metabolic diversity, stress tolerance and adaptive mechanisms. This will enable researchers to gain a deeper insight into the biology of microalgae and to find the best conditions for microalgae cultivation. When combined with droplet microfluidics, FACS is even more accurate. In droplet based systems each microalgal cell is surrounded by a single droplet which serves as a microreactor. Fluorescence measurements made on the whole droplet and not on free flowing cells. When a cell with a desired fluorescence property is present within the droplet, a directing mechanism such as an electric, pneumatic or valve sorting device directs the droplet into a collection channel. This process helps in reducing contamination and helps in maintaining selected cells as isolated cells during cultivation and further downstream analysis. FACS-microfluidic systems are useful for the recovery of rare and uncultivable microalgae from natural samples in biodiversity studies. Unique fluorescent markers can then be used to isolate individual cells from a mixed population and later used for cultivation, sequencing of the genome or transcriptomes of the cells. This ability opens up access to a vast new and unexploited diversity of microalgae and enhances opportunities for finding new species with interesting biochemical properties. Although there are benefits to FACS technology, it can be costly and require a high level of instrumentation. Microfluidic integration allows to decrease the amount of reagents, sample volume and cost of operation, improving sorting precision. Cell encapsulation, fluorescence detection, cell sorting, cell cultivation and molecular analysis can be carried out in a single microfluidic platform, allowing to develop a compact and efficient "lab-on-a-chip.

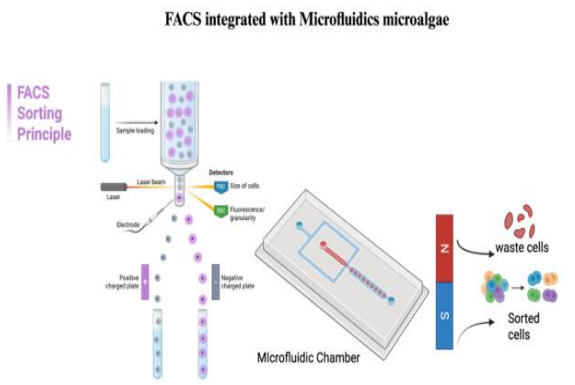

Fig -2 Integration of FACS With MIcrofluidic

Fluorescence-Activated Cell Sorting (FACS) and microfluidic technology have demonstrated a great ability to rapidly separate, screen and characterize microalgal cells(Hammami et al., 2022; Tsai et al., 2023). The detection and isolation of cells are extremely useful using the technique of FACS, while the manipulation of single cells/droplets at the microscale can be achieved with great precision by microfluidics. The application of such technologies enable high throughput, automated and highly selective analysis of microalgae, which is very useful for strain improvement, biodiversity study and research into biofuels. Microalgae contain naturally occurring photosynthetic pigments, such as chlorophyll, carotenoids and phycobiliproteins, which are known to emit a characteristic fluorescent signal when exposed to a specific light. FACS uses those fluorescent characteristics to separate various species and/or physiological condition of the microalgae. Individual cells are first encapsulated in small droplets or flowed through micro channels, when combined with microfluidic devices. As the cells pass through a laser detection region, the pigments are absorbed by the laser and the signals generated are detected by the fluorescence detectors. The identified target cells can be distinguished by level of fluorescence and the cells of the spectral characteristics can be selected for further analysis. The big advantage of FACS-integrated microfluidics is the use of high throughput single cell screening. Manual observation and cell isolation is time consuming and labor intensive and the traditional screening methods. Otherwise, microfluidic-FACS systems have the ability to analyze thousands to millions of cells within a short period of time. Strands that are very rare in the environmental sample can be very useful in microalgae studies, as can be very high diversity in the samples. The use of high throughput sorting greatly improves the chances of finding rare species that possess desirable properties. This technology has particular application to screening the lipid-rich microalgae, which is essential for biofuel production. Intracellular lipids can be stained with fluorescent dyes, e.g. Nile Red or BODIPY. As cells pass through the microfluidic-FACS platform, the brighter the fluorescence signals from the cells, the more lipid that the cells contain, and the brighter cells can be automatically sorted into separate collections. This will help in faster identification of the improved biodiesel producing strains. The second one is selection of high growth strains, which is important. Chlorophyll fluorescence is closely linked to the activity of photosynthesis and the health of the cells. The efficiency of photosynthetic cells and growth can be obtained by measuring the intensity of the fluorescence. The selected strains can be cultured further for biomass production, carbon sequestration, aquaculture feed production etc. The FACS-integrated microfludics also can be used for single-cell physiological analysis. Single microalgal species can have a very wide range of cell variability within the culture. Some cells may have a higher lipid content, higher pigment production or different responses to stress factors in the environment. These differences between cells are not reflected in bulk measurements which are an average of these. However, the capacity to characterize the metabolism in single cells and the capacity to measure stress resistance and adaptive mechanisms are possible features of the microfluidic-FACS systems. This will enable researchers to gain a deeper insight into the biology of microalgae and to find the best conditions for microalgae cultivation. FACS is even more accurate when used in conjunction with droplet microfluidics. In droplet based systems each microalgal cell is surrounded by a single droplet which serves as a microreactor. Fluorescence measurements made on the whole droplet and not on free flowing cells. A directing mechanism, such as an electric, pneumatic or valve sorting device, will direct a droplet into a collection channel when a cell that has a desired fluorescence property is within the droplet. By this process can be reduced the contamination, and can be maintained the selected cells as isolated cells during cultivation and further downstream analysis. FACS-microfluidic systems can be valuable for the recovery of rare/uncultivable microalgae from natural

samples in biodiversity studies. These unique fluorescent markers can then be employed to isolate a single cell within a mixed population and subsequently utilized for the culture of that specific cell, the sequencing of the cell's genome and/or transcriptome. This capability allows for the exploitation of an enormous new untapped diversity of microalgae and will improve the chances of discovering new species of microalgae with interesting biochemical properties. There are advantages to FACS technology, but it needs a considerable amount of instrumentation and it is a costly technology. Microfluidic integration allows to decrease the amount of reagents, sample volume and cost of operation, improving sorting precision. Cell encapsulation, fluorescence detection, cell sorting, cell cultivation and molecular analysis can be carried out in a single microfluidic platform, allowing to develop a compact and efficient "lab-on-a-chip.

Microfluidics assisted microalgae research has great environmental significance as it offers efficient and sustainable net-zero emission technology by reducing carbon dioxide (CO_2) in the atmosphere, which is a major greenhouse gas responsible for global warming and climate change. CO_2 is naturally absorbed by microalgae during the photosynthesis process and turns into biomass with O_2 released. Microfluidic-based screening and identification of microalgae with high potential for carbon fixation is a fast method. These are very efficient strains, selected and developed on a large scale to be able to remove carbon dioxide from the atmosphere in greater quantities, thus slowing down the build-up of greenhouse gases in the global climate. Climate change is one of the greatest environment challenges facing mankind and leads to the increase in global temperature, melting of glaciers, sea level rise, extreme weather events, drought and floods. Microfluidics helps to mitigate the effects of climate change by shortening the time required to discover and evaluate microalgal strains that can more efficiently capture and utilize CO_2 than did traditional strains. The optimised microalgae can be grown on a large scale and their cultivation would remove a considerable amount of CO2 from the atmosphere, slowing global warming and the resulting impacts on ecosystems and human societies. There is also a significant environmental benefit, in the form of improved air quality. Major sources such as industrial processes, power generation facilities and transportation systems emit large amounts of CO2 and other pollutants into the atmosphere. Microfluidic technology is used to identify cheaper microalgae for efficient use of industrial emissions as a carbon source. The microalgae can be grown in proximity to emission sources so as to remove pollutants before they are released to the atmosphere. This means reduced air pollution, better environmental quality and lower risk of pollution-associated diseases such as respiratory diseases. Microfluidics also helps to foster the creation of eco-friendly carbon-capture methods. Traditional carbon capture technologies are energy-intensive and expensive to implement. Contrary, the carbon sequestration by micro algae is a natural and renewable process. Microfluidic systems enable the high throughput screening of microalgal strains and single cell analysis to identify highly productive strains in a timely and efficient manner. This makes the use of biological CCS more feasible and effective, and reduces impacts on the environment caused by traditional carbon management methods. The technology also helps the conservation of biodiversity. Climate change poses a risk to many species of flora and fauna, through changes to habitats and the ecological balance. Research on the microalgae using microfluidics contributes to the conservation of ecosystems and biodiversity by reducing green house gas emissions and the concentration level of carbon dioxide in the atmosphere. Furthermore, microfluidic devices enable the separation and investigation of rare species of microalgae that could have distinct ecological roles and novel carbon capture efficiencies, thus maintaining valuable bio-diversity for future uses. Microfluidics is an important enabling technology for renewable energy generation. Fossil fuel dependency has continued to be one of the highest sources of GHGs. Microalgal strains with high lipid content for biofuel production can be easily identified using microfluidic platforms with fast time. These lipids can be converted to biodiesel and other renewable fuels which can be used as alternative fuels to fossil fuels. Biofuels from microalgae will offer substantial reductions in net GHGs and cleaner energy systems since they do not release fossil carbon but rather sequester carbon from the atmosphere. Further environmental benefit is the decrease of resources used for research and development. They use very small volume of fluids, nutrients and reagents in microfluidic systems. They use less water, less chemicals and less energy compared with traditional

lab procedures. This is an efficient use of the resource and minimizes waste production and the environmental impact of scientific investigations, making microfluidics an environmentally friendly technology. Microfluidics also contributes to the development of a circular bioeconomy. Selected microalgal strains can be used for biofuels, bioplastics, fertilizers, animal feed, aquaculture feed, pharmaceuticals and nutraceuticals production. These products can be used in place of petroleum-based products and can help save the use of non-renewable resources. Sustainable production and use of microalgal biomass help reduce waste generation and ensure efficient resource recycling for environmental sustainability(Gomez, 2010; Wang et al., n.d.). Moreover, the microalgae are screened in the microfluidic system and can be applied in the wastewater treatment and nutrient recycling. A large number of micro algal species can have the ability to take up excess nitrogen, phosphorus and other pollutants from wastewater and also capture the carbon dioxide. Microfluidics is used to identify strains that are better at removing nutrients, which enables the development of integrated systems for treating wastewater, recycling the nutrients, and generating valuable biomass. This has a dual benefit for environment which in turn means better health for the environment and better water resources. An additional significant achievement is the creation of microalgae that are climate resistant. Microalgal growth and productivity can be affected by environmental factors like temperature changes, salinity changes, and high level of carbon dioxide. Microfluidic platforms allow individual cells to be subjected to different environmental stresses and the ability to determine which strains can continue to have a high carbon fixation rate under a challenging environment. These climate-resilient varieties can help to sustain stable carbon capture in future climate scenario, thus enabling more reliable and sustainable net zero emission strategies. Finally, microfluidics-assisted microalgae research can provide a number of environmental benefits towards achieving “Net Zero”. It can lower atmospheric levels of CO_2, help reduce climate change, help improve air quality, support sustainable CCS technologies, conserve biodiversity, aid in the production of renewable energy, reduce resource use, develop bioeconomy, improve wastewater treatment, and develop climate resilient strains of microalgae. When taken together, all these advantages highlight the potential of microfluidics in improving sustainable environmental management and contributing to global efforts for a cleaner, healthier, and more sustainable world.

VI. CONCLUSION

The incorporation of microalgae biotechnology, carbon dioxide sequestration, and droplet and digital microfluidic technologies is a promising and innovative pathway towards global net zero emission targets. With the levels of CO2 in the atmosphere on the rise as a consequence of industrialization, fossil fuel use and human activity, the need for sustainable solutions to capture carbon has never been more urgent. The use of microalgae for carbon sequestration is considered to be a very efficient biological system due to their high growth rates, high photosynthesis efficiency and possibility to produce valuable biomass and bio-based products in a carbon dioxide utilization process. Precise manipulation, cultivation, monitoring, and analysis of individual microalgal cells at the microscale have been revolutionized by droplet microfluidics and digital microfluidics. These technologies can be used to carry out high throughput screening, single cell isolation, fluorescence-based sorting, and real-time monitoring of cellular performance, thus enabling researchers to quickly identify strains that have higher carbon fixation capacity, higher biomass productivity, better photosynthetic efficiency, and more lipid accumulation. Microfluidic devices make it far more efficient to discover better microalgal strains for environmental and industrial purposes by cutting down on reagent use, the cost of experiments and the error of analysis. Droplet and digital microfluidics further improve the potential of discovery of rare and stress-tolerant microalgae that will survive industrial microalgal cultivation, such as high carbon dioxide concentration and variable environmental parameters. These advanced screening technologies can help optimize carbon capture and utilization systems, allowing for better capture of greenhouse gases from industrial emissions and the atmosphere. Furthermore, the sequestered biomass can be converted into renewable biofuels, bio-plastics, bio-fertilizers, medicinal products, nutraceutics and animal feed; thus, contributing to a sustainable circular

bioeconomy. In addition to carbon capture, the synergy between microfluidics and microalgae biotechnology holds numerous advantages from an environmental perspective, such as climate change mitigation, air quality improvement, wastewater treatment, biodiversity conservation, resource efficiency and the production of renewable energy. Microfluidic technologies are essential tools for next generation carbon management strategies, as they enable precise, high-throughput and automated analysis at the single cell level. To summarize, droplet and digital microfluidics are revolutionary technologies that enable the full potential of microalgae to be harnessed in CO_2 sequestration and net-zero emission programs. Their coupling to microalgae biotechnology offers a sustainable, efficient and scalable solution to solve global climate challenges, while also offering valuable bio-based products. With the evolution of research and technological developments, the use of microfluidic assisted microalgae systems is expected to be a cornerstone of future carbon neutral economies and to make a significant contribution to a cleaner, greener and more sustainable world.

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