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E DELL'INFORMAZIONE

Real-Time Monitoring of SCOBY-Derived Bacterial Cellulose Production for Sustainable Material Development

Tesi di Laurea Magistrale in
Telecommunication Engineering - Ingegneria delle Telecomunicazioni

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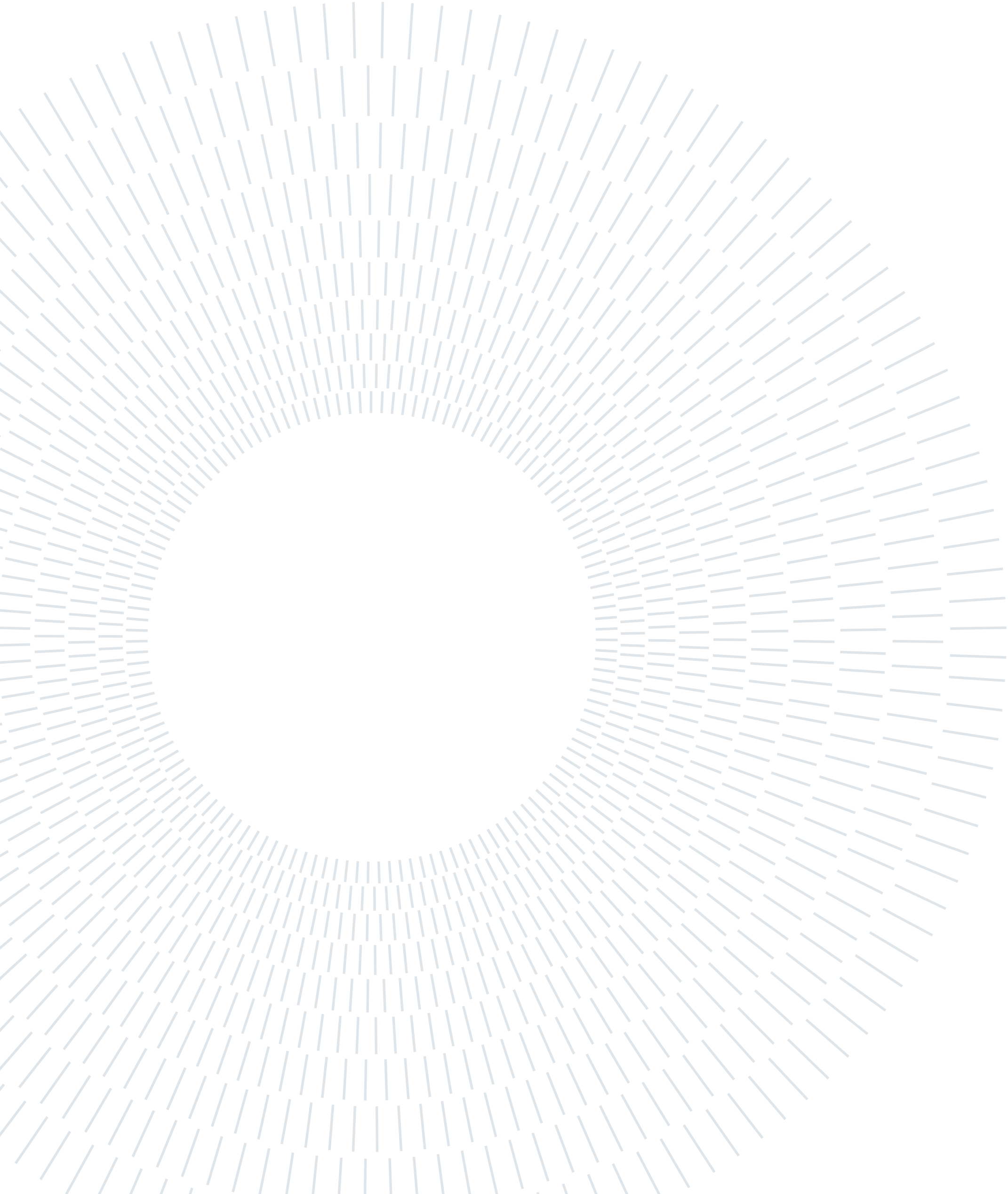


Abstract

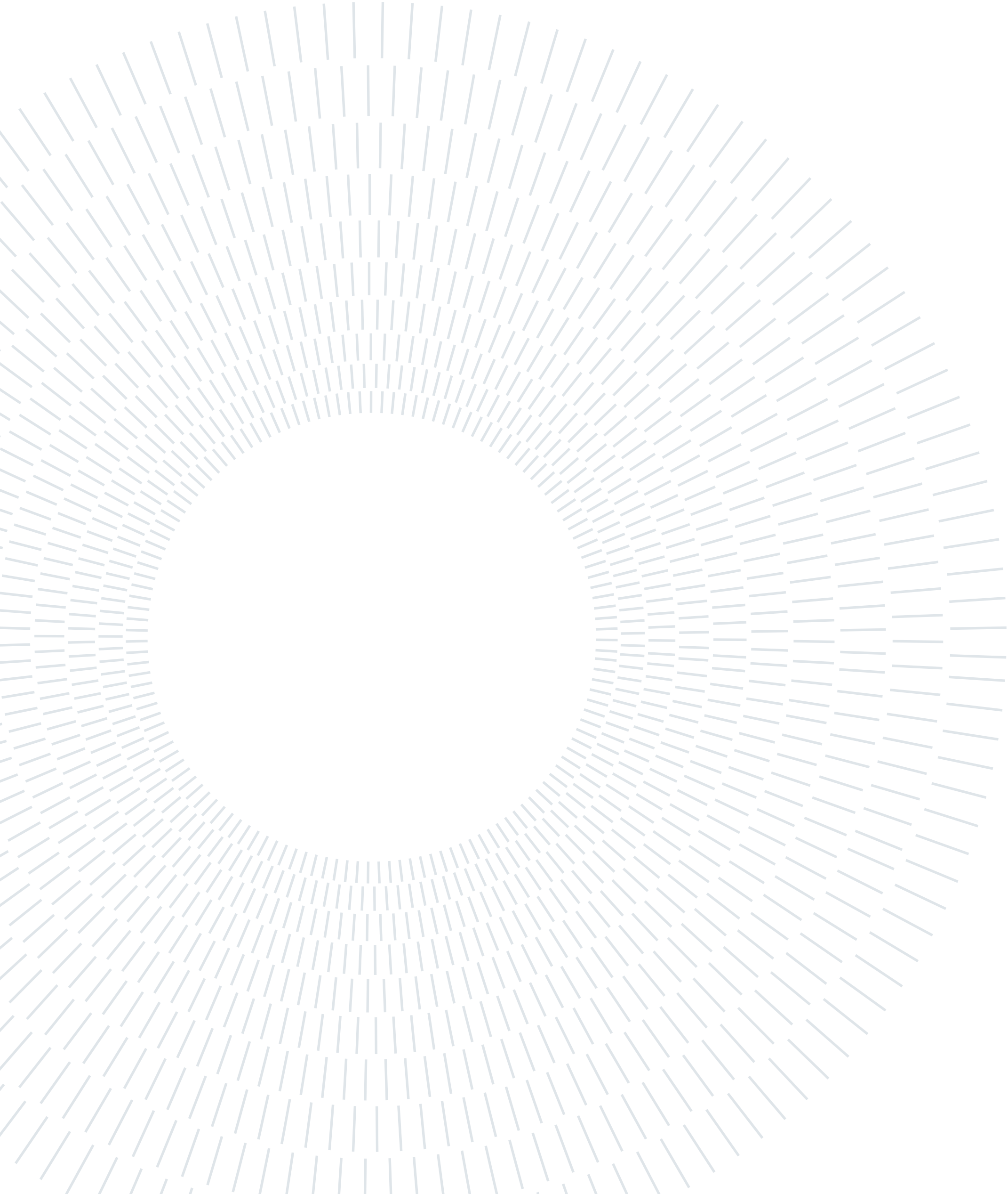
The production of Bacterial Cellulose (BC) through a Symbiotic Culture of Bacteria and Yeast (SCOBY) and tea fermentation has recently gained attention not only for its health benefits but also for its potential applications in various industries. This research project explores the feasibility of real-time monitoring in SCOBY-derived material production through low-cost sensing devices, using an indirect approach and with a focus on its potential use in various industries.

The primary objective of this study is to examine the data collected from sensors during the SCOBY growth. This analysis aims to understand the dynamics of the fermentation process, including temperature variations, pH levels, and other relevant parameters, such as glucose regulation. These insights will serve as a foundation for potential future developments in the use of SCOBY in various applications. This research adopts a pragmatic approach, focusing on the use of low-cost sensors and simple data acquisition techniques. It does not aim to create a fully automated system but instead provides a preliminary understanding of the information that can be gathered from the fermentation process.

Moreover, this study highlights the potential for resource efficiency and waste reduction in the context of BC production. By adopting a heuristic approach that is mindful of overproduction, it aligns with the principles of a circular economy and sustainable resource management.

In conclusion, this research project offers an initial exploration of real-time monitoring in BC production and tea fermentation, emphasizing the insights gained from sensor data. While not a complete system, it sheds light on the possibilities and the value of data analysis in this context. The findings and insights from this study can pave the way for further research and development in this field , while promoting resource efficiency and sustainable practices.

Keywords: Real-Time monitoring, Sensing devices, SCOBY, Sensor data, Heuristic, Sustainability, Fermentation, Circular Economy, Bacterial Cellulose.



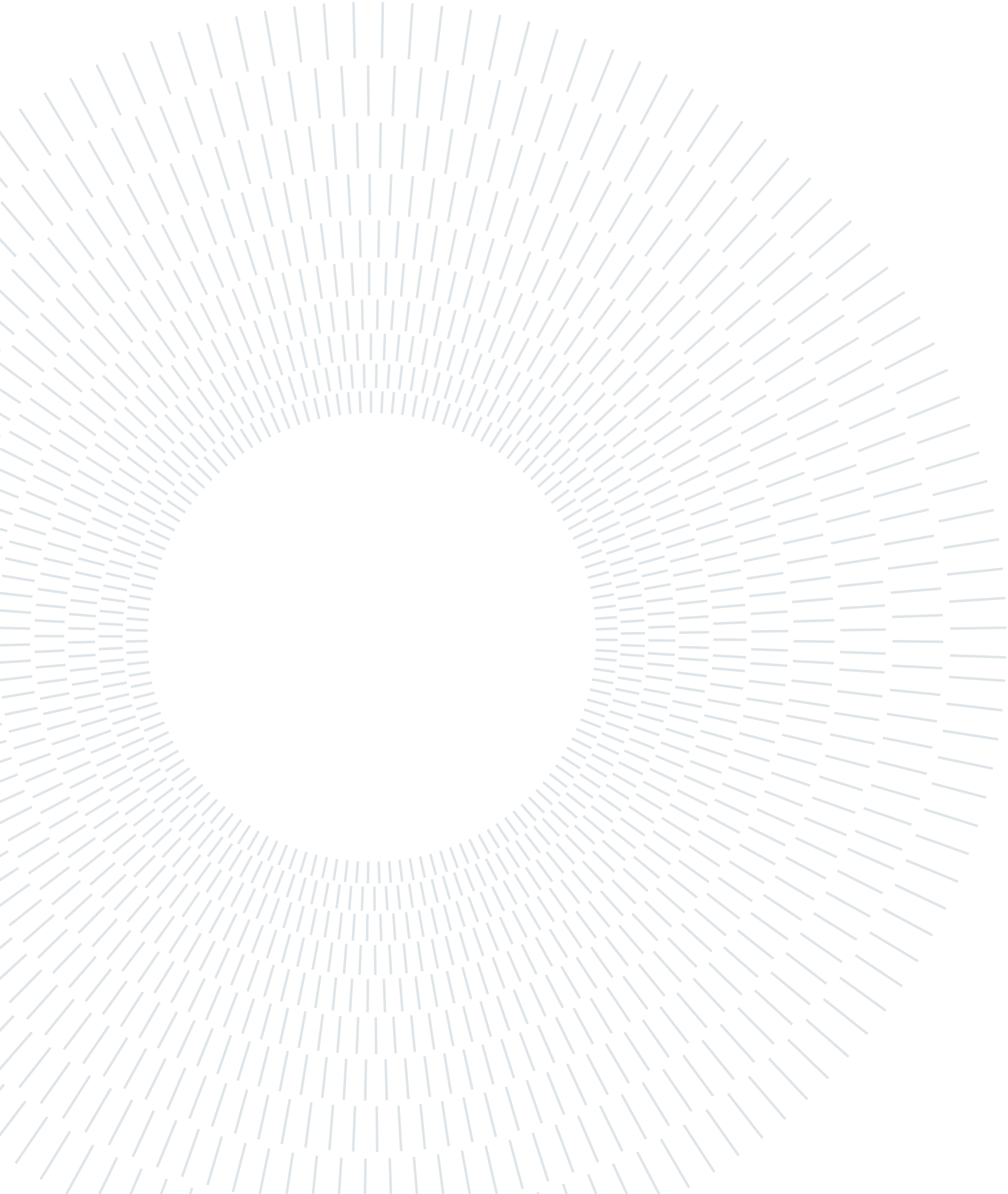
Sommario

La produzione di cellulosa batterica (BC) attraverso una coltura simbiotica di batteri e lieviti (SCOBY) e la fermentazione del tè ha recentemente guadagnato attenzione non solo per i suoi benefici per la salute, ma anche per le sue potenziali applicazioni in vari settori. Questo progetto di ricerca esplora la fattibilità del monitoraggio in tempo reale della produzione di materiale derivato dallo SCOBY attraverso dispositivi di rilevamento a basso costo, utilizzando un approccio indiretto e concentrandosi sul suo potenziale utilizzo in vari settori industriali.

L'obiettivo primario di questo studio è esaminare i dati raccolti dai sensori durante la crescita dello SCOBY. L'analisi mira a comprendere le dinamiche del processo di fermentazione, comprese le variazioni di temperatura, i livelli di pH e altri parametri rilevanti, come la regolazione del glucosio. Queste conoscenze serviranno come base per potenziali sviluppi futuri nell'uso dello SCOBY in varie applicazioni. Questa ricerca adotta un approccio pragmatico, concentrandosi sull'uso di sensori a basso costo e di semplici tecniche di acquisizione dei dati. Non mira a creare un sistema completamente automatizzato, ma fornisce invece una comprensione preliminare delle informazioni che possono essere raccolte dal processo di fermentazione. Inoltre, questo studio evidenzia il potenziale di efficienza delle risorse e di riduzione dei rifiuti nel contesto della produzione di BC. Adottando un approccio euristico attento alla sovrapproduzione, si allinea ai principi dell'economia circolare e della gestione sostenibile delle risorse.

In conclusione, questo progetto di ricerca offre un'esplorazione iniziale del monitoraggio in tempo reale nella produzione di BC e nella fermentazione del tè, sottolineando le intuizioni ottenute dai dati dei sensori. Pur non essendo un sistema completo, fa luce sulle possibilità e sul valore dell'analisi dei dati in questo contesto. I risultati e le intuizioni di questo studio possono aprire la strada a ulteriori ricerche e sviluppi in questo campo, promuovendo al contempo l'efficienza delle risorse e le pratiche sostenibili.

Parole chiave: Monitoraggio in tempo reale, dispositivi di rilevamento, SCOBY, dati dei sensori, euristica, sostenibilità, fermentazione, economia circolare, cellulosa batterica.



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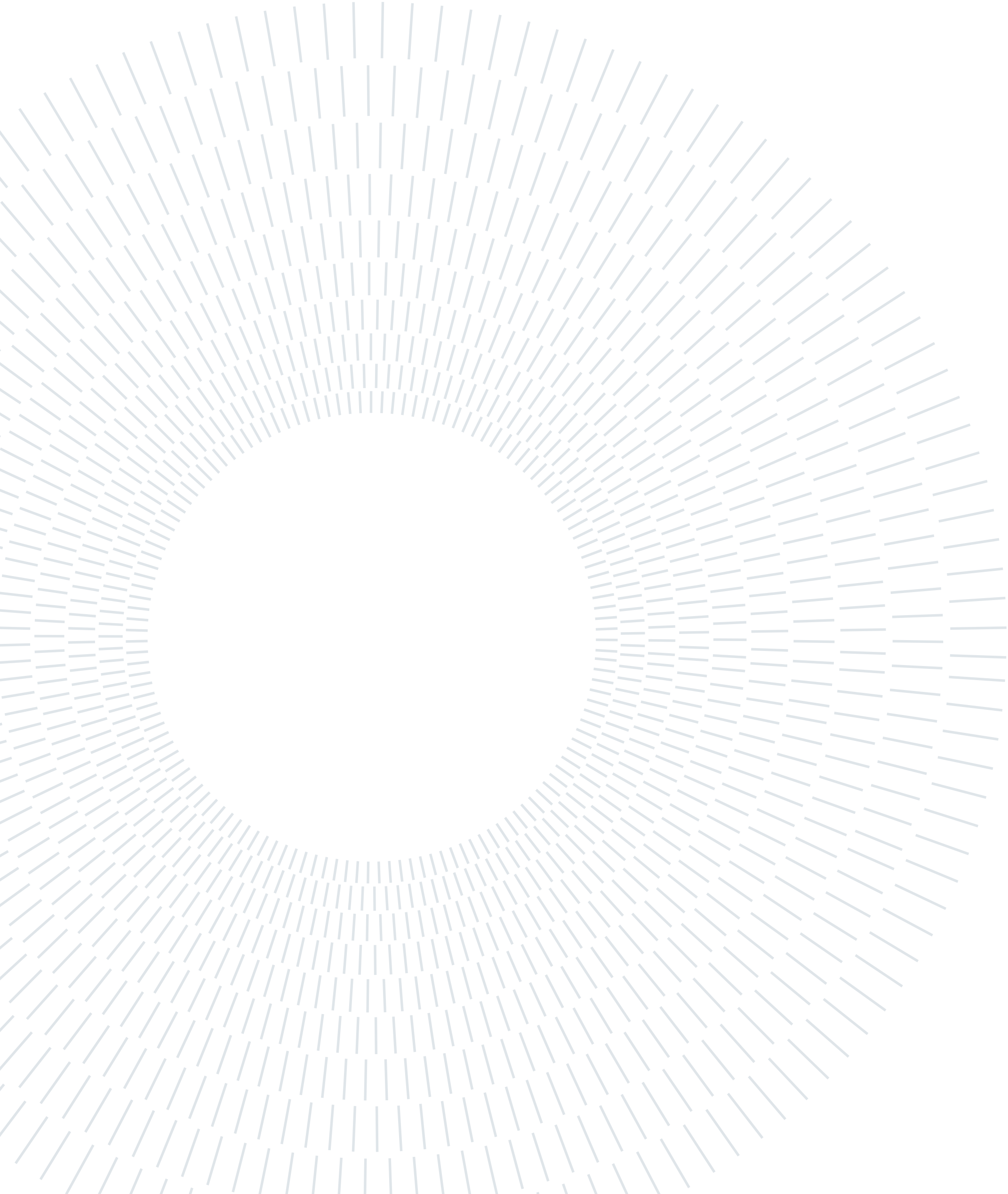

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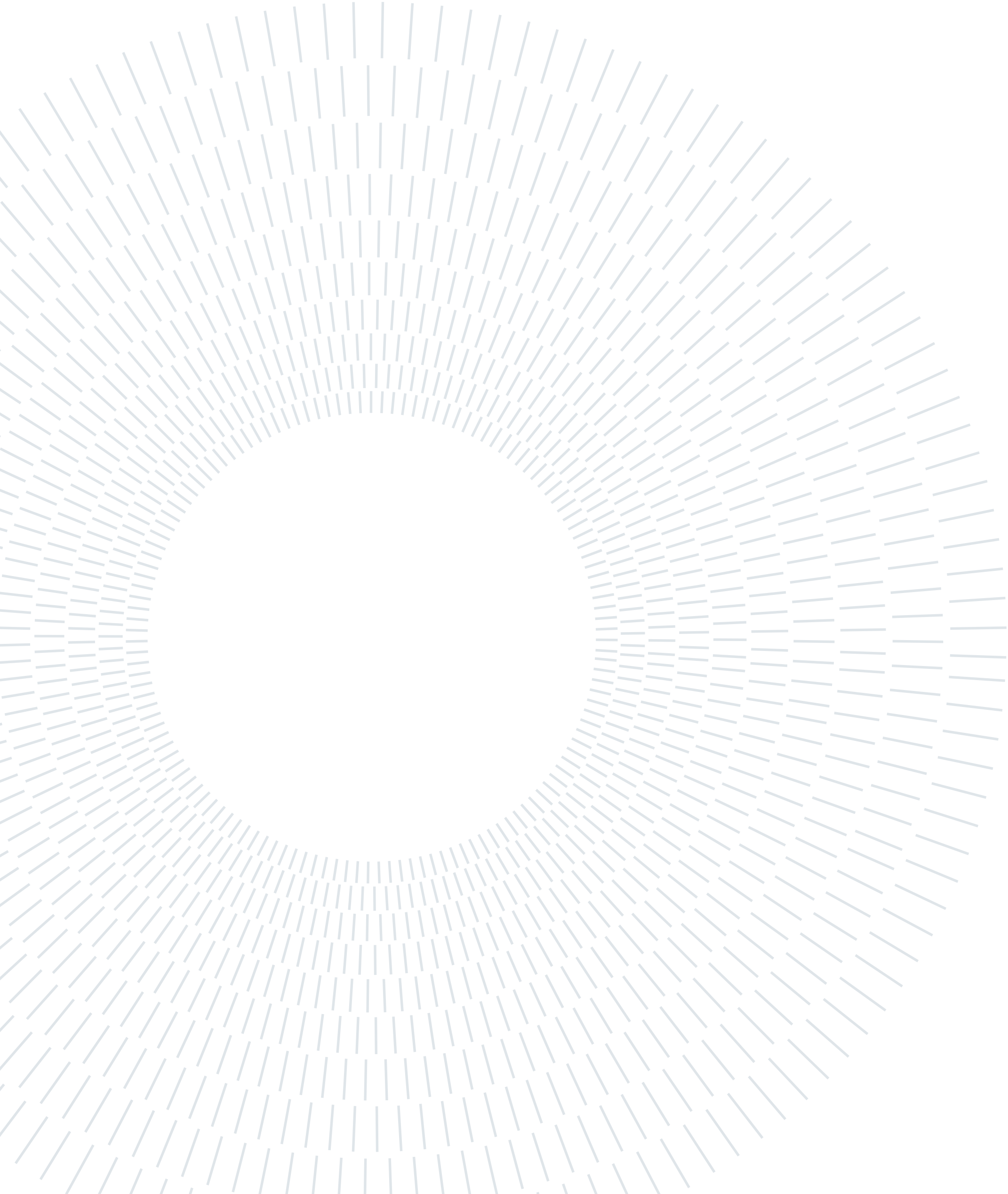

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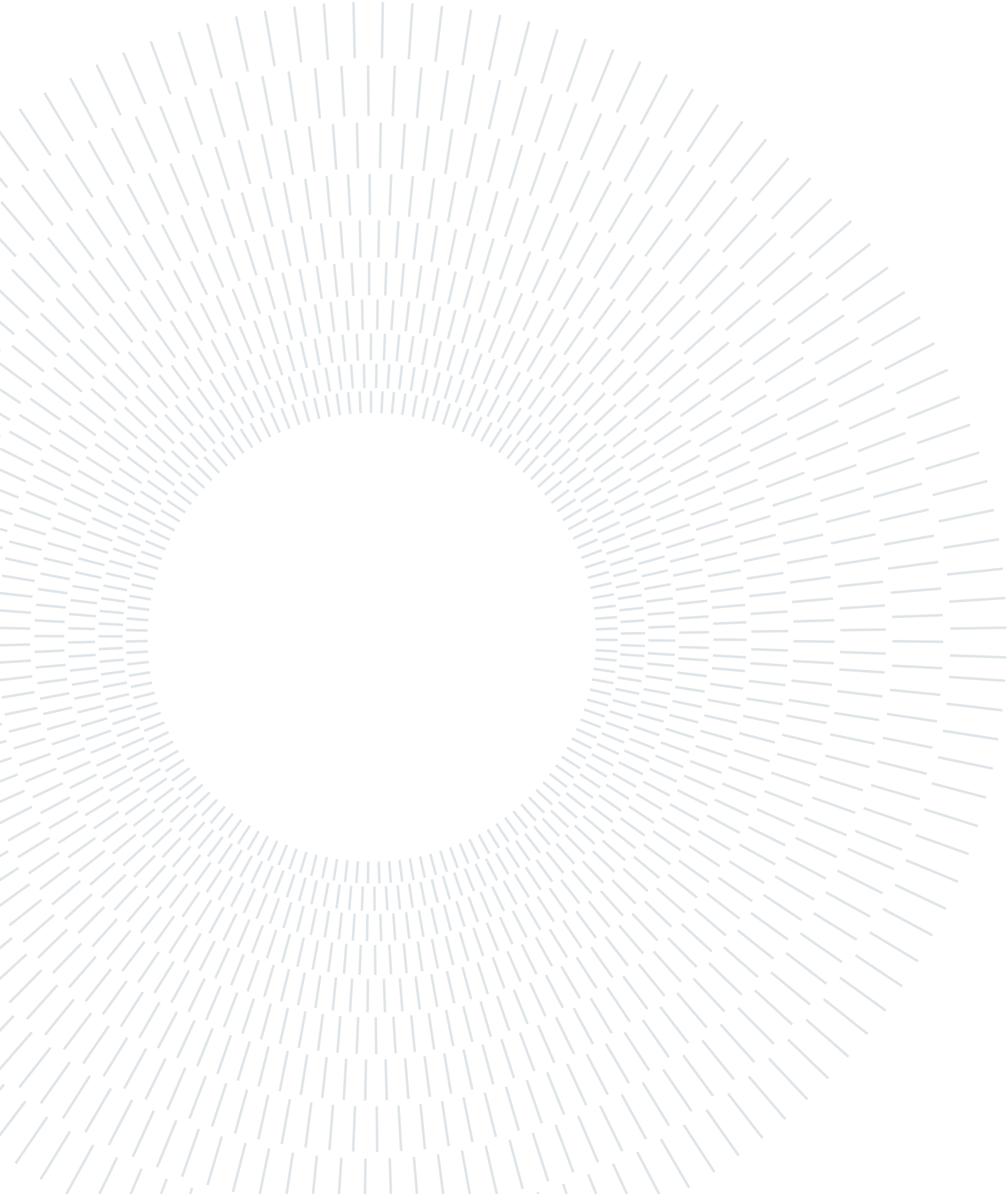
Per i miei carissimi amici, sia di vecchia data che nuovi, non mi dilungheró piú di tanto.
Ognuno in cuor suo sa quanto ha contribuito a rendermi la persona che sono oggi.
Nominarvi tutti sarebbe eccessivamente complicato, quindi semplicemente non lo faró :)
Grazie di cuore!



Introduction

In the modern world, many of the objects we use are made of chemically produced, non-biodegradable plastic materials such as acrylic, nylon, and polyester.
However, a shift is occurring towards bioengineering materials produced by living organisms like bacteria, algae, yeast, or fungi.
One such organism is the Symbiotic Culture of Bacteria and Yeast (SCOBY), which is used in the production of Kombucha tea, a fermented tea known for its health benefits.

Kombucha is a lightly effervescent, sweetened black tea drink, fermented with a SCOBY. The SCOBY is a gelatinous, cellulose-based biofilm that floats at the air-liquid interface of the fermentation container, and can vary greatly in density within the biofilm due to fermentation conditions, leading to possible variations in the end product.

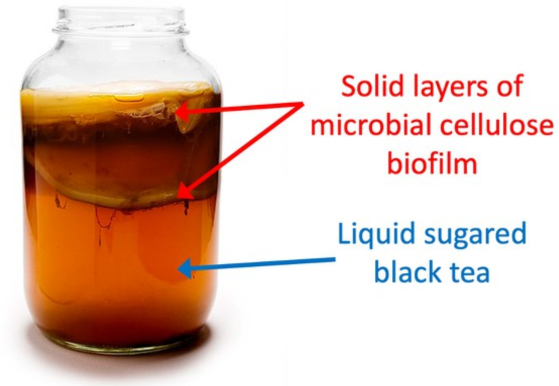


Figure 1: SCOBY growth in black tea

The aim of this research is to monitor the fermentation process of tea in conjunction with the SCOBY for the production of a bacterial cellulose, using low-budget sensing devices. The data obtained from the monitoring should mitigate potential errors or anomalies that may occur when working with a "living" material, paving the way for automated processes in an industrial setup.

The growth system for optimal kombucha fermentation involves several critical factors. Firstly, maintaining precise temperature control within the range of 18°C to 26°C is crucial

for an optimal growth. This temperature range fosters the ideal environment for fermentation. Additionally, pH control is essential, as the kombucha brew should consistently maintain a pH level between 2 and 3 throughout the fermentation process.
A fundamental factor is the regulation of glucose levels. Glucose serves as a vital component in the fermentation process, significantly influencing the growth and vitality of the SCOBY (Symbiotic Culture of Bacteria and Yeast). To ensure favorable conditions, it's imperative to maintain initial glucose levels between 8 to a maximum of 10 Brix (a measure of the dissolved solids in a liquid).
Furthermore, comprehensive data collection on temperature, pH, and glucose levels is essential. This data serves a dual purpose: enabling the replication of successful growth conditions and facilitating a continuous refinement of the fermentation process over time. By recording and analyzing these factors, a consistent quality and growth of the SCOBY can be achieved.

In the following sections, we will delve into the motivations of this research, as well as the possible applications in the market as of today.

0.1. The Need for Sustainability

In recent years, our global practices in production and disposal have significantly affected the environment, resulting in the depletion of vital resources and a surge in environmental degradation. This dangerous trajectory has been marked by an alarming increase in waste generation, necessitating an urgent shift in our resource management paradigm. To combat these challenges, a fundamental re-evaluation of our approach is imperative. We must embrace resourcefulness, minimize waste generation, and favour sustainable methodologies.

A critical concern within our existing production model is the phenomenon of overproduction, which perpetuates an incessant cycle of surplus goods, leading to waste, amplified resource consumption, and detrimental environmental repercussions. Addressing this challenge necessitates a pivot towards a circular economy. This transition promotes the preservation, reutilization, and recycling of resources, thereby mitigating the adverse impacts of production practices.

This transformative shift not only conserves valuable resources but also diminishes the ecological footprint engendered by industrial processes. In this context, leveraging bacterial cellulose sourced from SCOBY cultures, emerges as a promising avenue toward sustainability. The adaptability and biodegradability of bacterial cellulose position it as a viable substitute for environmentally deleterious materials. Embracing this material presents an opportunity to foster sustainability and align with the principles of a circular economy. However, its effective integration necessitates the development of efficient and controlled production methodologies.

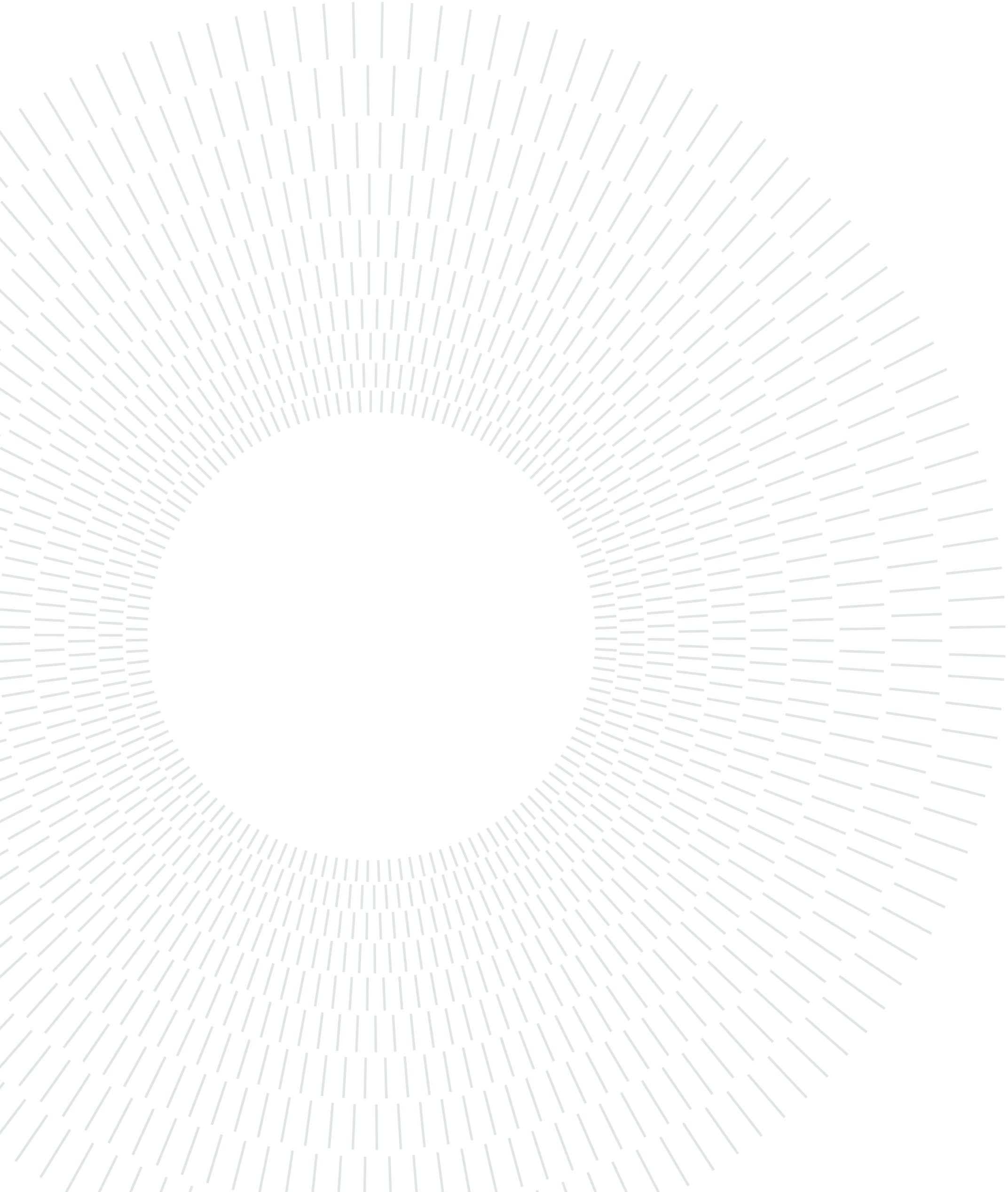
In the next chapter, we will further explore the applications of Bacterial Cellulose in industrial scenarios, elucidating its potential to revolutionize various sectors and contribute significantly to sustainable and eco-friendly practices.

0.2. Research Goal

This research project seeks to monitor the BC growth, paving the way to automate its cultivation while optimizing the production processes, thereby controlling resource wastage and mitigating environmental impact. Central to this attempt is the utilization of low-cost sensing devices, representing a significant innovation that facilitates real-time monitoring and control throughout the monitoring and production processes.

It seeks to demonstrate that integrating low-cost sensing devices can empower precise regulation of SCOBY-derived material growth. This level of control is instrumental in reducing overproduction, resource consumption, and resonating with the tenets of a circular economy. By aiming to automate and refine BC production through data-driven insights, we contribute to a more sustainable future.

Subsequent chapters will delve into the methodologies employed for this research and the discoveries made during this research, offering invaluable insights into the capacity of low-cost sensing devices within the realm of biomaterial production. Through the adoption of this approach, the goal is to inspire the widespread adoption of automated production processes in BC cultivation, underscoring the criticality of resource preservation and the circular economy within contemporary industrial landscapes.



1 | State of the Art

The production of Bacterial Cellulose through different approaches has gained substantial traction due to its distinct material characteristics and the progress made in automating its production. Bacterial Cellulose (BC) extracted from SCOBY and Kombucha tea constitutes a biofilm that manifests during the fermentation phase, exhibiting unique properties that position it as a promising supply for bioengineered materials. The pursuit of automating this process represents a swiftly evolving domain, with numerous steps and innovative developments which are going toward simplifying and enhancing the production cycle.

The intrigue surrounding SCOBY and its derivative, Bacterial Cellulose, arises from their multifaceted utility and remarkable attributes. Notably, the BC generated through the fermentation process demonstrates exceptional mechanical strength, high water retention capacity, and biocompatibility, rendering it a potential candidate for various applications spanning medical, textile, and industrial sectors. This rapidly growing interest in leveraging SCOBY-derived materials has propelled research and innovation in automating the growth and extraction processes.

The realm of automation in SCOBY and BC production has undergone considerable evolution in recent years, propelled by advancements in sensor data affidability and simplicity, as well as data analysis enhancements. These developments aim to not only reinforce efficiency but also ensure consistent quality, standardization, and scalability in the generation of bioengineered materials. Integrating automation into this domain holds promise for precise control over key parameters, leading to enhanced reproducibility, reduced resource consumption, and minimized production variability.

This chapter aims to delve into the contemporary landscape of SCOBY growth and BC extraction, tracing the trajectory of advancements in process automation. By examining current trends, innovations, and emerging technologies, it seeks to provide a comprehensive overview of the state of the art in this rapidly growing field.

1.1. SCOBY and Tea Fermentation

Kombucha tea is obtained from a symbiotic culture of various acid bacteria and yeasts in a sweet medium, generally black tea. Its fermentation process also leads to the formation of a floating biofilm on the surface of the growth medium [14].
There are several types of fermentation and obtained products depending on the metabolic pathway followed. Kombucha fermentation is a combination of three of them: alcoholic, lactic, and acetic one, this because of the presence of several yeasts and bacteria coexisting in the medium [14]. The fermentation process involves a Symbiotic Culture of Bacteria and Yeasts (SCOBY) metabolizing the sugars present in the tea solution.
This metabolic activity facilitates the growth of bacterial cellulose, a vital component formed during the fermentation process. Bacterial cellulose production occurs as a result of the SCOBY's interaction with the tea components, leading to the synthesis of various organic acids, ethanol, and gas [14].

Understanding the intricate dynamics governing bacterial cellulose growth within the SCOBY-mediated fermentation process stands as a fundamental gateway to find an answer to the basic mechanisms guiding not only the beverage production but also the formation of bioactive compounds with subsequent biological activities [10].
The selection of the growth medium for bacterial cellulose assumes a fundamental role in shaping the composition of bioactive compounds and the consequent biological responses observed in the final product [10].

An illustrative study conducted by Bolzan et al. [3] meticulously analyzed six distinct BC samples, revealing a diverse spectrum of characteristics in the final product, ranging from color to sensory attributes. These observed traits encompassed a wide array of qualities such as roughness, warmth, stickiness, and flexibility. The properties observed in the final material finds its direct core with the types of medium employed in the cultivation process. Varying tea constitutions with the incorporation of additives such as karkade, vinegar, honey, glycerine, textile fibers, pepper powder, among others, wield substantial influence over the resultant BC. This influence translates into a rich tapestry of textures, appearances, and sensory traits.

Figure 1.1: BC samples in Bolzan et al. research

1.2. Bacterial Cellulose Applications

This section delves into the diverse applications of bacterial cellulose (BC) across various industries. It presents compelling studies, highlighting BC's adaptability and transformative potential in fields like environmental sustainability, fashion, and food packaging. The research showcases how BC fosters sustainability, optimizes resources, and introduces innovative materials. This exploration aims to uncover the versatility and wide-ranging impacts of BC's applications.

A fascinating field of application set for exploration involves the potential application of bacterial cellulose (BC) in the fast fashion industry. The study conducted by Bolzan et al. [2] illuminates the multifaceted impact BC can wield across environmental, social, and cultural spheres. A comprehensive analysis of BC's manufacturing processes unveils its important role in minimizing water purification needs, thereby promoting water reuse from diverse sources. This strategic move not only encourages a sustainable bioeconomy but also promotes the utilization of renewable resources and diminishes waste, aligning smoothly with zero-waste practices.

Integral to BC's transformative prowess is its integration with metal and plastic components, revolutionizing disassembly processes. This integration not only forecasts the simplification of recycling methods, but holds the promise of significantly reducing manual labor associated with recycling efforts. Such innovation not only augurs well for environmental sustainability but also encourages the development of local, waste-free production systems. The implications are countless, painting a picture of a fashion industry that navigates towards a more conscious resource utilization while significantly reducing its carbon footprint and promoting circularity within its production cycles.

The extensive experimentation detailed by Bolzan et al. [2] underscores the complexi-

ties and potentials of BC within the realm of fashion sustainability. The investigation of controlled growth, waste integration, and recyclability open the door for new insights. Notably, the proposed methodology for sustainable BC utilization from its growth phase to final product fruition stands as a testament to the intricate balance sought between innovation and ecological consciousness. As the study delves into the fundamental nature of BC's behavior during the drying phase, a strategic methodology emerges —BC tartare— a novel means of repurposing excess BC and rectifying production defects while minimizing environmental impact. Moreover, the incorporation of textile waste within BC layers or BC tartare opens unforeseen avenues in material design, offering diverse aesthetic and structural possibilities.
The integration of waste materials from disparate sectors —wood and brick powders— into BC composites further expands the horizons for sustainable material production, notably in fashion accessory creation. Equally noteworthy is the innovative incorporation of accessories within BC during growth, signaling a paradigm shift in assembly and disassembly processes, potentially revolutionizing clothes recycling methods.

Figure 1.2: Different BC tartares in Bolzan et al. research

In a similar fashion, this study by Kamiński et al. [6] presents an innovative approach in harnessing kombucha-derived bacterial cellulose to revolutionize textile production. The focus lies in synthesizing and modifying this material to achieve specific physicochemical and mechanical attributes essential for textile applications.

Through a meticulous procedure yielding stable hydrogel bacterial cellulose (HGBC), the paper highlights the tailored properties vital for the textile industry's demands. The sourcing from a yeast/bacteria kombucha culture, known as SCOBY, underscores the accessibility and cost-effectiveness of this technique. The paper notably emphasizes the versatility of the HGBC materials, showcasing their adaptability in the fabrication of diverse clothing articles. This versatility extends to employing conventional sewing techniques, previously unsuitable for non-modified cellulose-based materials.

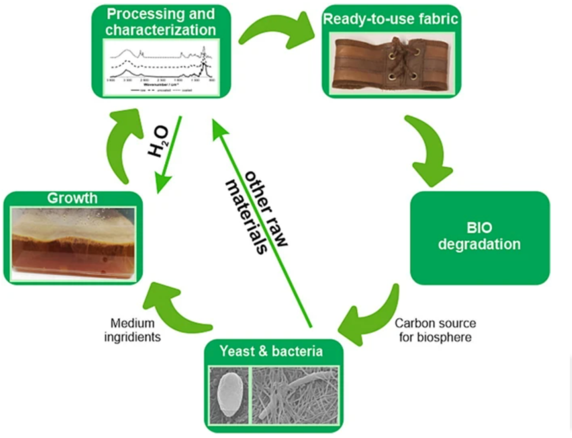


Figure 1.3: Production cycle in Kamiński et al. research

In this article by Lin et al. [9], we explore BC's multifaceted roles. Bacterial cellulose (BC) has the potential to revolutionize food packaging practices. The emergence of BC-based films promises enhanced control over moisture and gas permeability in packaged foods. These films, adapted to exhibit specific properties, display augmented strength and have inherent antimicrobial effects, thus significantly extending the shelf life of perishable goods. BC's remarkable versatility further extends to facilitating enzyme and cell immobilization, thereby bolstering their stability and functionality in various facets of food production. Its influence permeates the fermentation processes essential in wine and beer production, contributing to heightened ethanol yields and aiding in the synthesis of critical food components.

The extensive applications of bacterial cellulose (BC) transcend conventional boundaries, showcasing its transformative potential across diverse fields. Its versatility and unique properties position BC as a revolutionary material with far-reaching impacts, extending beyond specific industries. From its role in fast fashion, to the enhancement of food packaging, to its contributions in food production through enzyme immobilization and fermentation process optimization, BC emerges as a catalyst for innovation and advancement.

BC's multifaceted nature opens pathways for innovation, offering solutions that extend beyond current limitations. Its transformative influence promises an era characterized by elevated standards, pioneering advancements, and a paradigm shift towards sustainable, quality-driven practices across industries.

1.3. Automation in Bacterial Cellulose Production

The automation of the BC production from Kombucha tea fermentation is a relatively new field, with several advancements being made to optimize and simplify the process. While the studies I'll reference center their intererests on various fermentation processes and the usage of other types of yeasts rather than SCOBY, their methods hold potential for our research. The techniques they employ in monitoring and data analysis could be adapted seamlessly for studying SCOBY and bacterial cellulose growth.

One such example is the implementation of a Sensor Network used to monitor the fermentation process. Studies by Saikia et al. [12] have delved into monitoring relative humidity (RH) and temperature during fermentation using innovative sensor systems integrated with microcontrollers for real-time data analysis. While initial systems lacked networking capabilities and central monitoring, they introduced a cost-effective monitoring system using thermistors, although without networking capabilities.
This innovative system, comprising smart sensor nodes with network interfaces, allows for real-time monitoring and data logging of ambient humidity (RH) and temperature, facilitating quality control and process optimization. Integration of such advanced monitoring and logging systems into BC fermentation not only ensures precise control over parameters but also sets the stage for enhanced scalability and quality improvement within BC production processes

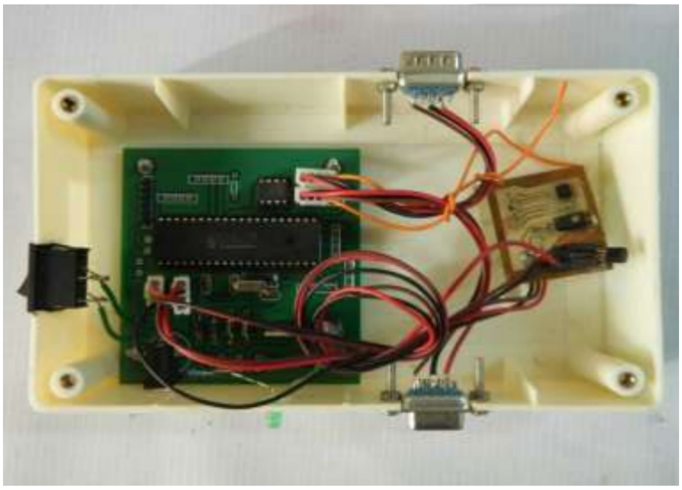


Figure 1.4: Sensor node in Saikia et al. research

Other studies, like Adeleke et al. [1] present compelling insights collected from water quality monitoring studies. The use of machine learning and Internet of Things (IoT) technologies in assessing water quality underscores their potential application in optimizing BC fermentation.

The study focused on evaluating water pollutants by measuring parameters like temperature, pH, turbidity, Dissolved Oxygen (DO), Total Dissolved Solids (TDS), Oxidation Reduction Potential (ORP), and electrical conductivity, factors that significantly impact BC fermentation.

The successful deployment of Artificial Neural Network (ANN) and Support Vector Machine (SVM) algorithms in predicting water impurity levels suggests a promising avenue for forecasting and regulating fermentation conditions in BC production.

Moreover, the introduction of automated corrective measures based on contamination levels in water treatment introduces a parallel for potential interventions within the fermentation process to ensure optimal growth conditions for bacteria producing BC. The efficiency demonstrated by AI and IoT in remotely monitoring water conditions speaks to their potential applicability in enhancing precision, standardization, and real-time monitoring within BC fermentation processes, setting the stage for improved efficiency and quality control within this domain.

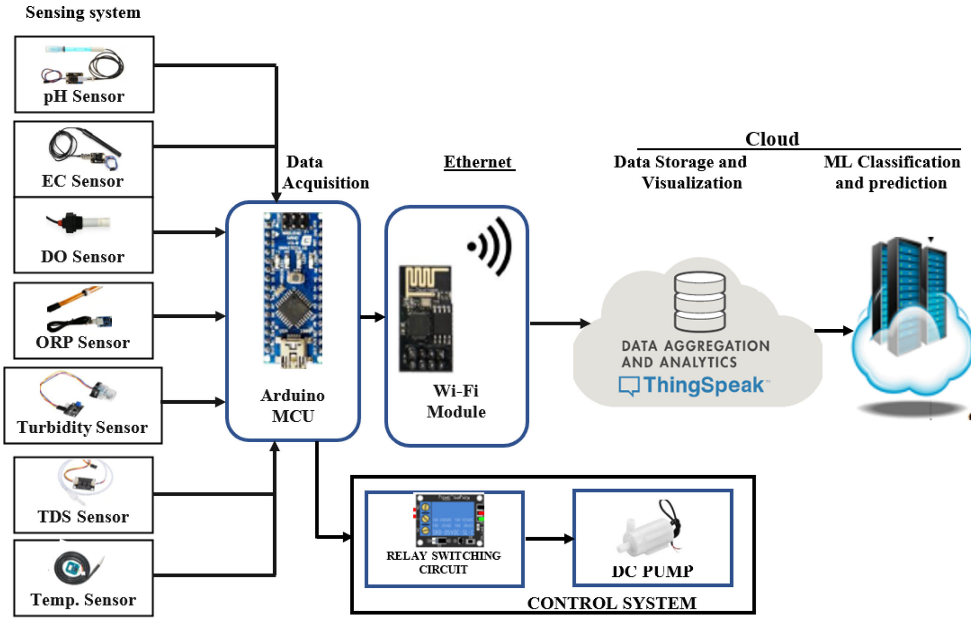


Figure 1.5: Sensing system in Adeleke et al. research

A similar approach was implemented by Sarma and Boruah [13], with the design and development of a Relative Humidity (RH) and Room Temperature (RT) monitoring system for tea factory fermentation rooms. This innovative system utilizes a capacitive RH sensor and a temperature to digital converter (TDC), orchestrated by an 8051 core microcontroller. By digitizing the RH sensor's analog output and synchronizing ambient temperature readings, this system offers real-time data logging and display capabilities, enhancing the precision and reliability of monitoring fermentation environments.
The integration of firmware within the microcontroller for RH calculation and temperature correction ensures accurate RH measurements displayed on an LCD and transmitted to PCs for data visualization and logging. The system's evaluation against standard instruments showcased its impressive accuracy, with a maximum observed error of ±3% over a continuous 12-hour run. This research signifies a pivotal step in advancing monitoring technologies for fermentation environments. Its capacity to provide real-time and accurate RH and RT measurements, coupled with continuous data logging, addresses crucial aspects of quality control and process optimization in tea factory fermentation rooms.
Additionally, the system's ability to minimize errors and negate on-site calibration requirements highlights its reliability and ease of implementation within industrial settings. Such innovations pave the way for enhanced precision and efficiency in monitoring critical parameters essential for ensuring optimal fermentation conditions, subsequently impacting the quality and consistency of final tea products.

There are other indirect methods for monitoring the fermentation: this is what is presented by Kimutai et al. [8], leveraging Internet of Things (IoT), deep convolutional neural networks, and image processing for black tea fermentation monitoring offers insights into potential technological adaptations for BC growth optimization processing images during the fermentation process. The study's use of Raspberry Pi models equipped with Pi cameras for real-time image capture during tea fermentation sets a precedent for potential monitoring solutions in BC production. the precision and accuracy demonstrated by the deep learner in real-time image evaluation indicate its adaptability for monitoring diverse fermentation processes, similar to the complexities involved in BC growth dynamics.
The successful application of majority voting techniques in decision-making processes further underscores the potential for robust and accurate monitoring mechanisms, potentially transferrable to BC fermentation evaluation. Moreover, the study's suggestion of scalability by retraining the prototype for monitoring other crops, such as coffee and cocoa, hints at the adaptability of similar technologies for optimizing BC fermentation across varying environmental and growth conditions.

This exploration opens doors for innovative adaptations of IoT and image processing techniques in BC production, potentially revolutionizing real-time monitoring and optimization strategies within this domain.

An hybrid approach presented in another study by Kimutai et al. [7] focuses on the critical role of fermentation in black tea processing and its impact on global tea consumption and economies. In this context, the manual methods used to monitor tea fermentation, reliant on subjective assessments by tea tasters, pose challenges in ensuring consistent quality. To address this, the study aims to revolutionize monitoring by utilizing IoT for capturing a comprehensive dataset comprised of temperature, humidity, and black tea fermentation images. The study's approach involves leveraging Raspberry Pi Model B+, a Pi-Camera, temperature and humidity sensors, cloud storage on Amazon Web Services (AWS), and Python programming for image capture.

Figure 1.6: Fermentation monitoring in Kimutai et al. research

This research by Saikia et al. [11] presents an instrument employing a sensor network to monitor crucial elements such as ambient temperature, relative humidity (RH) during fermentation, and the firing temperature of the drying process. Utilizing an RH to voltage converter (HIH 4000) and a temperature to voltage converter (LM 35), this setup creates monitoring nodes for RH and temperature. These nodes feed data into a PIC microcontroller, enabling analog signals from sensors to undergo digital conversion for RH and temperature measurements.

Notably, this system's simplicity lies in its focus on only two vital parameters—RH and temperature—keeping the monitoring approach straightforward and cost-effective. By employing basic yet effective components such as the RH to voltage converter (HIH 4000) and the temperature to voltage converter (LM 35), this setup ensures precise monitoring without unnecessary complexity. This streamlined system, coupled with its cost-effectiveness, stands as a promising tool for comprehensively recording these critical parameters and assessing their influence on tea quality.

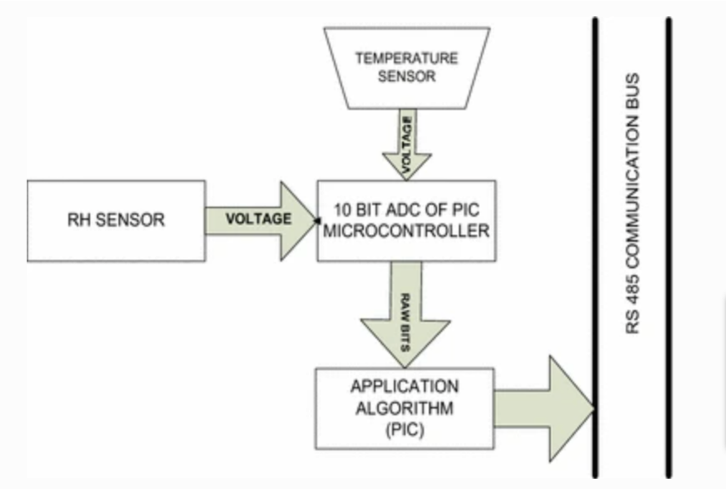


Figure 1.7: Block diagram of the monitoring system in Saikia et al. research

Buonocore et al. [4] present an innovative and cost-effective online monitoring system tailored for beer fermentation, offering a solution to the challenge faced by craft breweries that lack sophisticated sensor-equipped fermenters. Traditionally, these breweries resort to offline measurements, intermittently sampling beer from fermenters due to cost constraints. To enhance this process, the study introduces a fermentation monitoring module integrated into each fermenter and a monitoring interface responsible for collecting, processing, and storing the acquired data.

The fermentation monitoring module devised by the study is a sophisticated yet simplified system. It comprises an ESP8266 board with microcontroller capabilities and an integrated WiFi module, facilitating seamless communication. This board is complemented by an MCP9808 temperature sensor with an I2C interface, ensuring continuous monitoring of the fermentation temperature.

Crucially, load cells, connected to an HX711 24-bit analog-to-digital converter (ADC), are strategically employed to gauge the wort's density changes during fermentation. These load cells, situated between steel frames at the tank's base, detect fluctuations in wort weight resulting from the release of CO2 during fermentation. The system's calibration, stored in flash memory, and recalibration procedures guarantee accuracy. Notably, the MCU collects data from the ADC and temperature sensor, transmitting these readings every 9 seconds via WiFi to the monitoring interface.

Complementing the monitoring module is the monitoring interface, anchored by a Raspberry Pi 4 board. This interface incorporates a user-friendly interface facilitating command transmission and data reception. Batch-related data are systematically stored in an SQL database for reference and analysis. Employing MQTT as the communication protocol, a lightweight Machine to Machine (M2M) messaging protocol, the system ensures a smooth data exchange between devices. Utilizing a publish/subscribe mechanism, the fermentation monitoring modules publish monitoring data to the broker, while the monitoring interface subscribes to these topics, ensuring a comprehensive data collection mechanism.

This innovative system, marked by its simplicity, cost-effectiveness, and real-time capabilities, showcases a transformative approach to beer fermentation monitoring, catering to the needs of craft breweries while upholding product quality and efficiency.

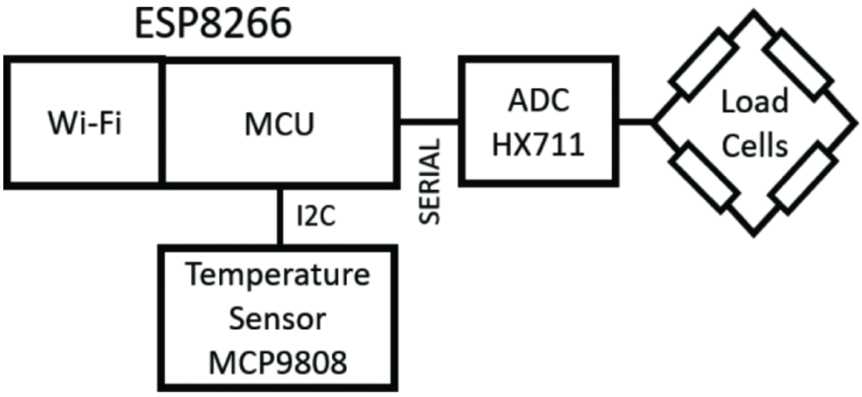


Figure 1.8: Hardware scheme in Buonocore et al. research

This study by Cañete-Carmona et al. [5] delves into monitoring alcoholic fermentation in winemaking, warranting control to mitigate potential risks throughout the process. Typically, this oversight involves time-consuming physical or chemical analyses, either on-site or in dedicated enological labs, leading to delays in decision-making for winemakers. However, leveraging technologies like the Internet of Things (IoT) and sensors for autonomous carbon dioxide (CO2) monitoring presents a transformative solution.
This system, tested at a laboratory scale, showcases its capability as a cost-effective tool for real-time tracking of alcoholic fermentation progress. The amalgamation of CO2 sensors with IoT technologies furnishes winemakers with crucial insights, enabling prompt identification of fermentation stagnation or halting, facilitating immediate action crucial for ensuring the intended quality of the wine.

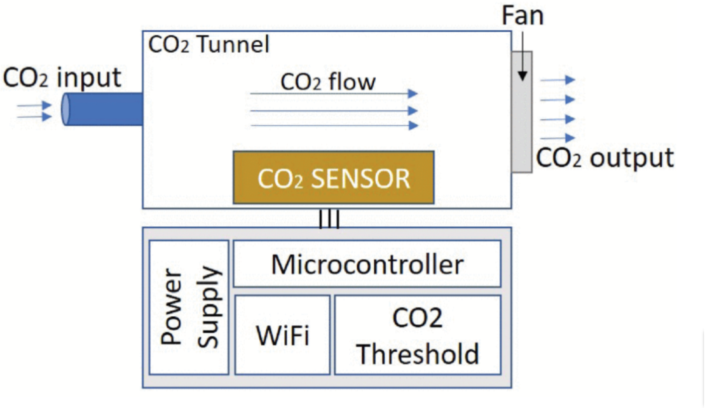


Figure 1.9: System architecture of Cañete-Carmona et al. research

1.4. Challenges and Future Directions

The exploration of diverse technologies in related fermentation processes offers invaluable insights for the automation and optimization of SCOBY-derived bacterial cellulose production. Studies examining IoT implementations, machine learning algorithms, sensor networks, and image processing techniques showcase the potential adaptability of these innovations to SCOBY fermentation dynamics [2, 3, 6, 9, 10, 14].

Harnessing these technological innovations presents an opportunity for substantial enhancements in SCOBY-mediated BC production. Such enhancements could lead to:

- Improved Monitoring and Optimization: Utilizing sensor networks and real-time data analysis could optimize critical parameters like temperature, pH, and humidity, vital for enhancing BC growth during SCOBY-mediated fermentation.
- Predictive Capabilities: Integrating machine learning algorithms and IoT technologies offers the potential for predictive modeling, facilitating precise forecasting and regulation of fermentation conditions crucial for optimal BC synthesis.

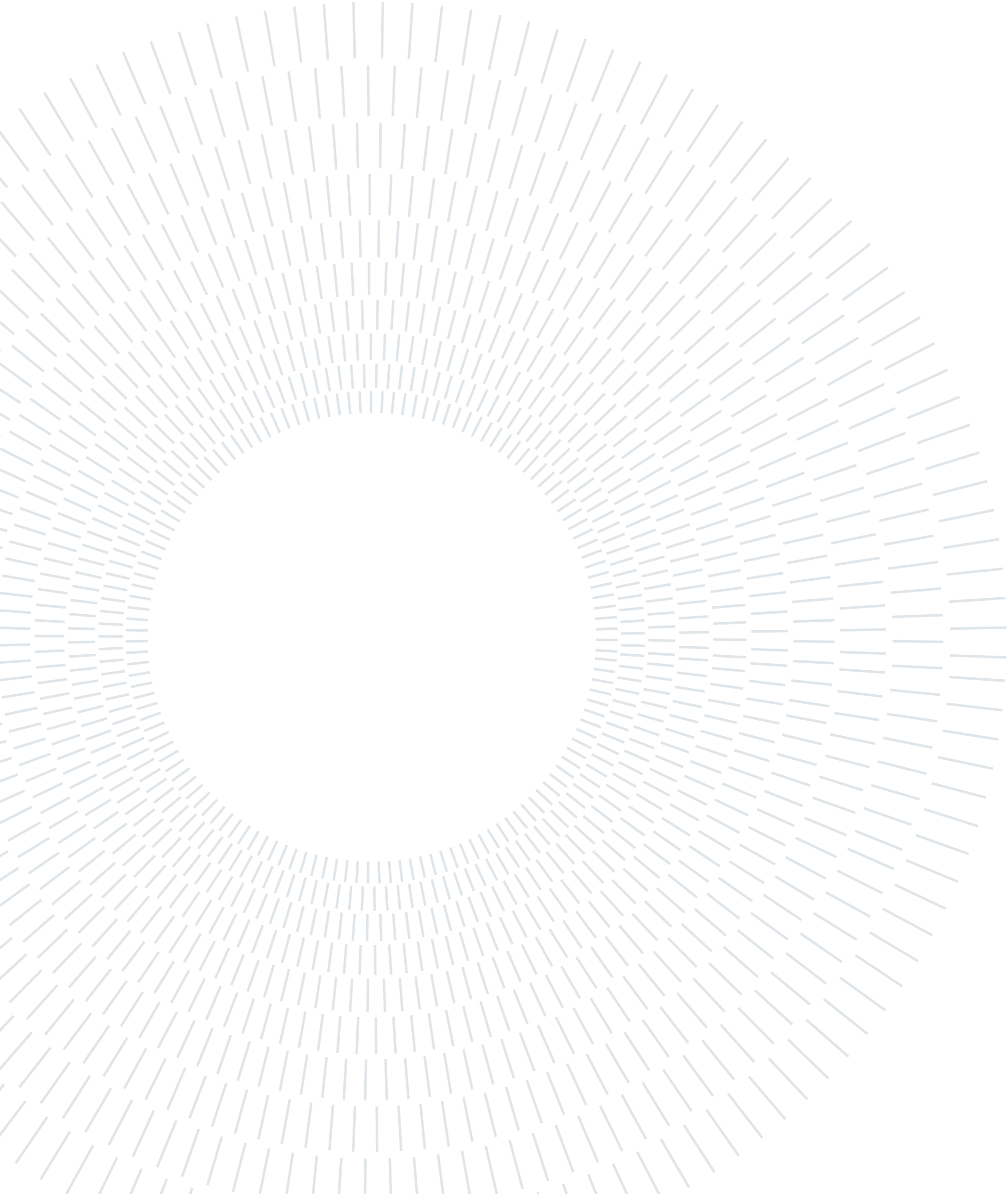
Diverse Applications of SCOBY-derived BC SCOBY-derived BC exhibits versatile applications across various industries:

- Fast Fashion and Textiles: Its potential in fast fashion aligns with sustainability efforts, offering materials for eco-friendly textiles [6].
- Food Packaging: BC-based films showcase enhanced control over moisture and gas permeability, prolonging the shelf life of packaged foods while ensuring safety and quality [9].

- Environmental Sustainability: BC's impact on environmental sustainability reflects its potential in promoting water reuse and aligning with zero-waste practices [2].

These potential applications illustrate the versatility and far-reaching impact of SCOBY-derived BC, extending from enhancing product quality to fostering sustainable practices across industries. Leveraging technological advancements in tandem with these applications paves the way for innovation and efficiency in SCOBY-mediated BC production.

In conclusion, the automation of BC production is a promising field with several advancements being made to optimize and streamline the process. However, further research is needed to address the challenges associated with this process and to further improve the quality and efficiency in this field.



2 Hardware Setup

This chapter offers insights into the methodologies used to select the hardware and sensors for this research. It begins by comparing the MicroController Units (MCUs) Arduino and Raspberry Pi, highlighting their respective traits and explaining the specific relevance within this research, ultimately justifying the final selection.

Following this, it explores the various sensors considered for monitoring the fermentation process and SCOBY growth. Each sensor's utility, advantages, and limitations in the context of the research are discussed, providing reasons behind the decision to acquire or discard them.

Subsequently, it delves into the setup specifics of each acquired sensor. This section elucidates the required wiring and connections necessary for optimal functionality of these sensing devices within the research environment.

This comprehensive overview sheds light on the thought process behind the hardware and sensor selection, providing a holistic understanding of their roles and implications in this research.

2.1. MCU Selection

Expanding the discussion on the choice between Arduino and Raspberry Pi for monitoring the fermentation process in SCOBY tea production involves diving deeper into their distinctive features and functionalities. Both microcontrollers, while suitable for IoT projects, present unique characteristics that needs to be looked at for an aware choice.

2.1.1. Arduino's Characteristics

Arduino stands out for its simplicity, versatility, and efficiency in managing nodes within IoT setups. Its architecture, often based on microcontrollers such as the Atmel AVR series, delivers real-time control capabilities. The platform's user-friendly Integrated Development Environment (IDE) streamlines code development, making it accessible for beginners and seasoned experts alike. Furthermore, Arduino's extensive community support and diverse libraries enhance its adaptability across various projects.

One of Arduino's notable strengths lies in its connectivity options, facilitating seamless interfacing with a wide range of sensors and actuators. This feature greatly enhances its suitability for diverse applications. Its low power consumption and robustness make it an excellent choice for projects requiring extended operational periods, especially in remote or resource-limited environments.
An inherent advantage of Arduino is its integrated Analog to Digital Converters (ADCs), enabling effortless incorporation of both analog and digital inputs for sensor integration. This capability significantly reduces the need for extra components in most scenarios.
Despite Arduino's strengths in simplicity and low power consumption, integrating wireless connectivity features such as Bluetooth and WiFi requires external components. Various options exist to equip Arduino with these capabilities. Shields like the *Arduino WiFi Shield* or *Arduino Bluetooth Module* provide direct connectivity but may increase overall hardware complexity.

An alternative option, the *ESP8266* series, renowned for cost-effectiveness and robust WiFi capabilities, offers modules like the *ESP8266 ESP-01*. These modules can interface with Arduino, providing WiFi functionality while being relatively straightforward to set up. For IoT applications, the *Arduino MKR1000* stands out with its tailored design, combining Arduino's programming ease with built-in WiFi connectivity. This integration significantly simplifies the setup process, making the MKR1000 a compelling choice for streamlined IoT projects.

2.1.2. Raspberry Pi's Characteristics

Raspberry Pi stands as a formidable computing platform renowned for its robust processing capabilities and versatile applications. Operating on an ARM architecture, it mimics a miniature computer, supporting potent operating systems like Linux or Raspbian. This feature-rich framework enables multitasking and handling computationally intensive tasks, opening doors to diverse project scenarios.

Connectivity forms a cornerstone of Raspberry Pi's functionality. Equipped with built-in networking capabilities encompassing WiFi and Ethernet, it effortlessly facilitates connectivity, empowering remote access and swift data transfer. This intrinsic feature not only fosters IoT applications but also extends its utility to server setups and remote data management systems.

While Raspberry Pi excels in digital capabilities through its GPIO (General Purpose

Input/Output) pins, it poses limitations regarding analog inputs. Integrating analog sensors necessitate external components like Analog to Digital Converters (ADCs) to extend its compatibility with a wider array of sensors.

An advantage inherent to Raspberry Pi is its operating system. With the ability to support full-fledged operating systems like Linux or Raspbian, it elevates its functionality beyond conventional microcontrollers. This affords flexibility in software configurations, allowing the utilization of various programming languages like Python, C++, and Java, making it a versatile platform for diverse coding preferences and complex software setups.

The inclusion of HDMI outputs and USB ports amplifies its versatility, enabling diverse applications beyond IoT, including media centers, educational tools for programming and computing, servers, and more.

Community support significantly bolsters the Raspberry Pi ecosystem, offering a wealth of resources, tutorials, and an active user base. This robust community fosters collaborative learning and troubleshooting, making it an attractive choice for both beginners and experienced developers.

2.1.3. Deciding Factors

The choice between Arduino and Raspberry Pi for monitoring the fermentation process in SCOBY tea production involves a thorough evaluation of their distinctive features and functionalities, each catering to specific project requirements.

Arduino's versatility lies in its simplicity and efficiency in managing IoT nodes. Based on microcontrollers like the Atmel AVR series, it ensures real-time control capabilities and boasts a user-friendly Integrated Development Environment (IDE), suitable for both beginners and experts. Arduino's extensive connectivity options and low power consumption make it an excellent choice for projects requiring extended operational periods, especially in resource-constrained environments. Its integrated Analog to Digital Converters (ADCs) streamline sensor integration, although it requires external components for wireless connectivity features like Bluetooth and WiFi. The Arduino MKR1000, designed specifically for IoT applications, offers integrated WiFi, simplifying setup for streamlined projects.

On the other hand, Raspberry Pi stands as a powerful computing platform operating on ARM architecture. Its robust processing capabilities and support for operating systems like Linux or Raspbian enable multitasking and handling computationally intensive tasks. The Raspberry Pi's built-in networking capabilities, including WiFi and Ethernet, facilitate remote access and swift data transfer, enhancing its utility across diverse applications.

However, its limitations with analog inputs require external components for integrating analog sensors, despite its support for a broader range of programming languages and versatile applications beyond IoT.

Deciding between these platforms often hinges on project-specific requirements. Arduino's simplicity, real-time control, and low power consumption suit scenarios demanding precise control and minimal power usage. Conversely, Raspberry Pi's superior processing power, multitasking capabilities, and broader functionalities cater to projects needing higher computational capabilities and extensive connectivity.

For this research project focused on indirect sensing in bacterial cellulose-based growth materials, Arduino's simplicity aligns well with the project's needs. While Raspberry Pi offers compelling features, its higher processing power and embedded WiFi and Bluetooth capabilities aren't imperative within this scope, reaffirming Arduino as the most fitting microcontroller for this study.

2.2. Sensors Scouting

The sensor scouting phase is pivotal in selecting appropriate sensors for monitoring the SCOBY tea fermentation process. This selection process involved meticulous evaluation of various sensors, considering specific parameters and their compatibility with the project's objectives.

2.2.1. Criteria for Sensor Selection

The process of selecting sensors crucial for monitoring the fermentation process and bacterial cellulose (BC) growth was guided by essential criteria, each decisive in facilitating efficient data acquisition and analysis:

1. **Fundamental Measurement Parameters**: The chosen sensors prioritize the measurement of crucial solution parameters and fermentation-related metrics. Parameters such as pH, temperature, humidity, dissolved oxygen, and other indicators significantly influencing the fermentation process and BC growth were central to the selection criteria.
2. **Affordability and Scalability**: Ensuring cost-effectiveness without compromising data accuracy remained a top priority. Affordable sensor options allowed for scalability, enabling large-scale production while maintaining data precision and quality.
3. **Waterproof Design**: In the liquid environment inherent to fermentation, the selected sensors possess waterproof capabilities, ensuring accuracy and reliability within the solution. Their robust design ensures durability and consistent performance during deployment.
4. **Microcontroller Compatibility**: Sensors were chosen based on seamless integration with prevalent microcontrollers like Arduino and Raspberry Pi. Compatibility with these platforms streamlines deployment and data acquisition, optimizing the monitoring process.
5. **Minimalist Approach**: The pursuit was to limit the number of sensors within the system, opting for a minimalist approach to avoid sensor redundancy. This strategic selection aimed to achieve comprehensive data capture while minimizing system complexity.

The scouting process aimed to identify sensors capable of tracking evolving data during fermentation. Direct parameters such as pH and temperature were targeted for real-time monitoring, while indirect metrics like glucose levels in the solution were considered for their substantial impact on the fermentation process and the properties of the final product. Despite endeavors to source sensors directly measuring critical parameters like glucose levels (e.g., a Digital Refractometer), suitable options were not readily available. Consequently, an indirect approach was adopted, focusing on amalgamating potentially useful sensors identified through extensive online scouting. This deliberate sensor selection process, emphasizing accuracy, efficiency, and a minimalist approach, aims to provide a comprehensive understanding of the dynamic changes occurring during SCOBY fermentation and BC growth. Despite challenges in directly measuring certain critical parameters, the strategic selection of sensors promises a holistic overview while optimizing system simplicity.

2.2.2. Chosen Sensors

After the scouting process, the following sensors were selected, each serving a specific role in monitoring the fermentation process:

Temperature Sensor The temperature sensor was a pivotal selection due to its crucial role in monitoring the fermentation temperature. Maintaining the optimal temperature is fundamental as it directly impacts yeast activity and the rate of fermentation in SCOBY. Furthermore, certain measurements, including Total Dissolved Solids (TDS), are temperature-dependent, emphasizing the necessity for precise temperature monitoring during fermentation. This sensor ensures real-time temperature data acquisition, enabling precise temperature control critical for SCOBY health and optimal fermentation outcomes.

pH Sensor The pH sensor plays a vital role in maintaining the acidity level within the optimal range of 2-3pH during SCOBY fermentation. pH levels significantly influence yeast activity, bacterial growth, and the overall quality of the final tea product. By providing real-time pH measurements, this sensor facilitates continuous monitoring and control, ensuring the fermentation environment remains conducive for SCOBY growth and fermentation progress. Precise pH monitoring mitigates the risk of undesirable pH fluctuations that could hinder SCOBY activity and compromise the quality of the final product.

Total Dissolved Solids Sensor The Total Dissolved Solids (TDS) sensor serves a crucial role in measuring the concentration of dissolved solids in the fermentation mixture, including glucose. Glucose serves as the primary food source for SCOBY during fermentation. Monitoring TDS allows for precise control over the glucose content, ensuring an adequate nutrient supply for SCOBY without leading to imbalances that might hinder fermentation or impact the tea's final properties. This sensor's capability to measure dissolved solids provides insights into the solution's overall composition and aids in maintaining optimal conditions for SCOBY growth and fermentation, by checking the ranges in which it can grow properly.

Turbidity Sensor The turbidity sensor emerges as a potentially useful component for monitoring the cloudiness or haziness of the liquid solution during SCOBY fermentation. This sensor detects changes in solution clarity caused by numerous particles, aiding in understanding and controlling solution characteristics. Maintaining consistent turbidity levels is vital as it indicates the presence of suspended particles or microbial growth. Monitoring turbidity provides insights into SCOBY health, fermentation progression, and the overall solution's quality, ensuring an environment conducive to optimal SCOBY growth and fermentation outcomes.

Each selected sensor serves a unique and critical purpose in monitoring specific parameters essential for SCOBY health and tea fermentation. This comprehensive sensor array enables real-time data acquisition, precise control over fermentation parameters, and the creation of an optimal environment for SCOBY growth.
Balancing cost-effectiveness with sensor utility was fundamental. While O2 and CO2 sensors offer detailed fermentation insights, their individual costs surpass the combined expense of temperature, pH, Total Dissolved Solids, and turbidity sensors.
To ensure affordability without compromising valuable fermentation data, the decision was made to forgo O2 and CO2 sensors. Focusing on data from the retained sensors was deemed more cost-effective.

Finally, the chosen sensors for this project include:

- Temperature Sensor DS18B20
- pH Sensor PH4502C
- Total Dissolved Solids Meter Sensor CQRSENTDS01
- Turbidity Sensor SEN0189

These sensors, selected for their suitability, affordability, and ability to provide essential fermentation insights, will be extensively detailed in subsequent sections, covering both hardware and software aspects. This balance between cost and data quality ensures the project remains cost-effective while offering valuable fermentation insights.

2.3. Sensors Setup

This section presents a detailed overview of each sensing device used in this research, explaining their operational principles, configurations, and usage.

2.3.1. Temperature Sensor DS18B20

Figure 2.1: Temperature sensor DS18B20

The DS18B20 temperature sensor serves a fundamental role in measuring the solution's temperature. First of all, it serves the basic purpose of checking that the solution stays in range of the required temperatures for a good SCOBY growth and fermentation process. Second, there are other sensors which have a dependance on temperature variations, such as the Total Dissolved Solids (TDS) meter sensor, and so having a temperature reference measurement improves the quality of the overall collected data.

The DS18B20 temperature sensor has the following characteristics:

- Temperature range: from -55°C to +125°C.
- Power supply: 3.0V to 5.5V DC with an operating current of approximately 1mA.
- Accuracy: ±0.5°C within the range of -10°C to +85°C.
- Communication: Utilizes the 1-Wire protocol, enabling multiple sensors to be connected to a single microcontroller pin.
- Water-proof probe: Ensures functionality even in wet or humid environments, critical for fermentation processes.
- Resolution: Adjustable resolution, with options for 9, 10, 11, or 12-bit conversions, offering flexibility in precision vs. speed trade-offs.

Wiring and Connections

The DS18B20 temperature sensor comprises three pins:

- VCC – 5V DC
- GND – Ground for Arduino board
- DATA – DS18B20 analog output

For proper connection, the following components are required:

- Arduino Uno
- Breadboard
- DS18B20 Temperature sensor
- $4.7K\Omega$ resistor

Being a digital sensor, it bypasses the need for analog-to-digital conversion. The crucial consideration lies in incorporating a $4.7K\Omega$ resistor to prevent excessive current flow through the sensor.

Referencing figure 2.2 illustrates the wiring setup of the DS18B20 with the Arduino:

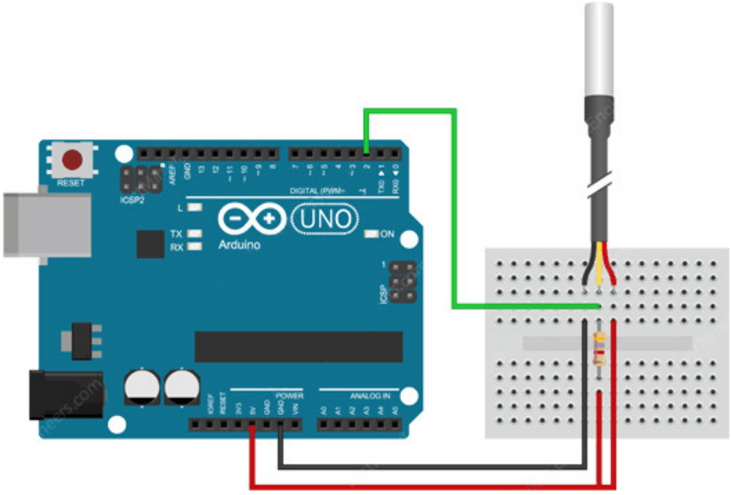


Figure 2.2: Temperature sensor DS18B20 wiring and connection

2.3.2. PH Sensor PH4502C

(a) PH sensor (b) PH probe

Figure 2.3: PH sensor PH4502C

The PH4502C pH sensor is dedicated to directly measuring solution pH, a critical parameter during fermentation. The probe, interfaced with the sensor through the BNC connector, gauges voltage output based on the immersed pH probe, which is then converted into a pH value via software.

The PH4502C PH sensor has the following characteristics:

- Working current: 5-10mA.
- Detection concentration range: PH 0-14.
- Detection range of temperature: 0-80°C.
- Response time: <= 5s.
- Stability time: <= 60s.
- Power consumption: <= 0.5W.
- Working temperature: -10-50°C (nominal temperature 20°C).
- Output: analog voltage signal output.

Wiring and Connections

The PH4502C pH sensor entails various pins for operation:

- VCC – 5V DC
- GND1 – Ground for Arduino board
- GND2 – Ground for PH probe
- PO – PH analog output
- DO – 3.3V pH limit trigger
- TO – Temperature output
- POT 1 – Analog reading offset (Nearest to BNC connector)
- POT 2 – PH limit setting

To correctly connect the PH4502C pH sensor, the following components are necessary:

- Arduino Uno
- Breadboard (optional)
- PH4502C pH sensor

Referring to figure 2.4 illustrates the wiring configuration for the PH4502C with the Arduino:

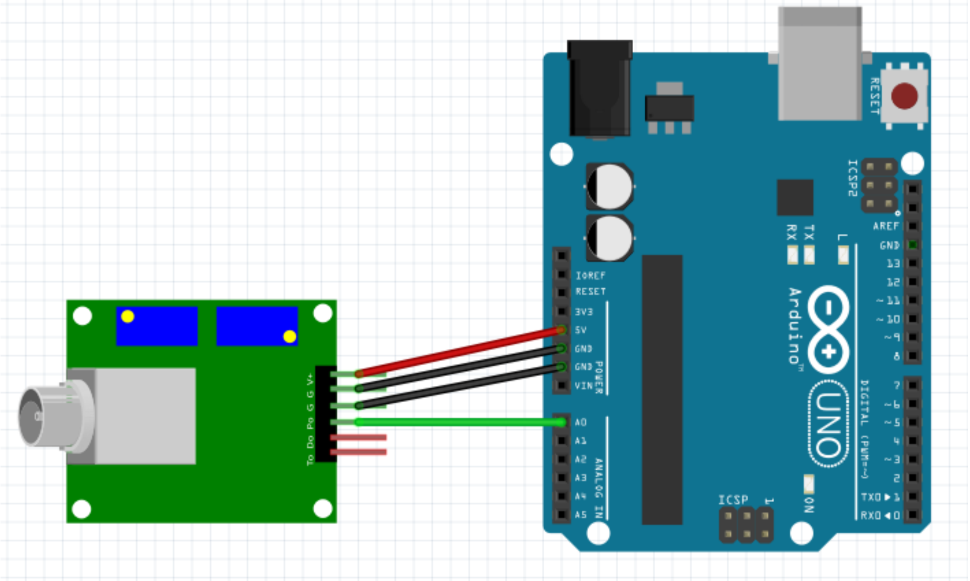


Figure 2.4: PH sensor PH4502C wiring and connection

Calibrating this sensor involves essential steps to ensure accurate readings across different conditions.

Initially, I calibrated the sensor at a short-circuit state by using an offset potentiometer (POT1) to set the voltage to 2.5V, verified with a multimeter. This baseline voltage establishes a reference point for subsequent measurements.

The second calibration employed two solutions with known pH values—4.1 pH and 6.86 pH. This calibration step fine-tuned the sensor's responsiveness to different pH levels, facilitating the conversion from voltage outputs to precise pH measurements.

These calibrations are fundamental for the sensor's accuracy, allowing it to interpret voltage fluctuations and reliably convert them into meaningful pH readings across diverse environments.

2.3.3. TDS Meter Sensor CQRSENTDS01

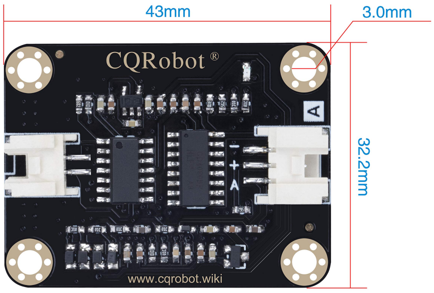


Figure 2.5: TDS sensor CQRSENTDS01

The CQRSENTDS01 TDS sensor gauges the quantity of dissolved solids in a solution, making it potentially useful for the project. For our purposes, it operates like a conductivity sensor, correlating glucose concentration with solution conductivity.

The CQRSENTDS01 TDS meter sensor has the following characteristics:

- TDS measurement accuracy: ±10% F.S. (25°C).
- Input voltage: 3.3V to 5.5V.
- Output voltage: 0 to 2.3V.

- Working current: 3mA to 6mA.
- Module size: 43mm x 32.2mm.
- Module interface: JST 2.0mm 3-pin.
- Electrode interface: JST 2.54mm 2-pin.
- Operating temperature: 5°C to 90°C.
- Storage temperature: -10°C to 90°C.

Wiring and Connections

The CQRSENTDS01 TDS sensor encompasses three pins:

- VCC – 5V DC
- GND – Ground for Arduino board
- DATA – CQRSENTDS01 analog output

To correctly connect the CQRSENTDS01 TDS sensor, the following components are required:

- Arduino Uno
- Breadboard (optional)
- CQRSENTDS01 TDS sensor

The hardware setup, depicted in figure 2.6, demonstrates the straightforward connection setup for the TDS sensor:

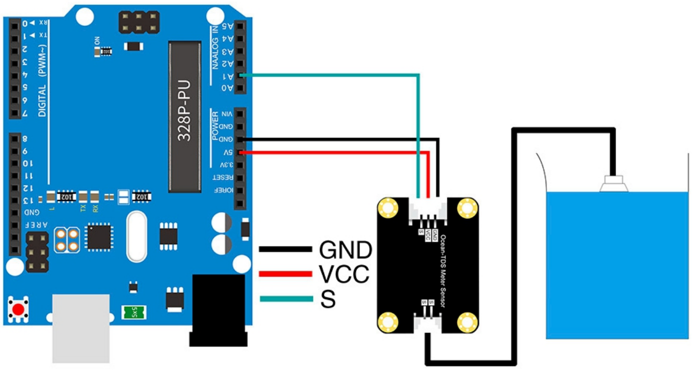


Figure 2.6: TDS sensor CQRSENTDS01 wiring and connection

2.3.4. Turbidity Sensor SEN0189

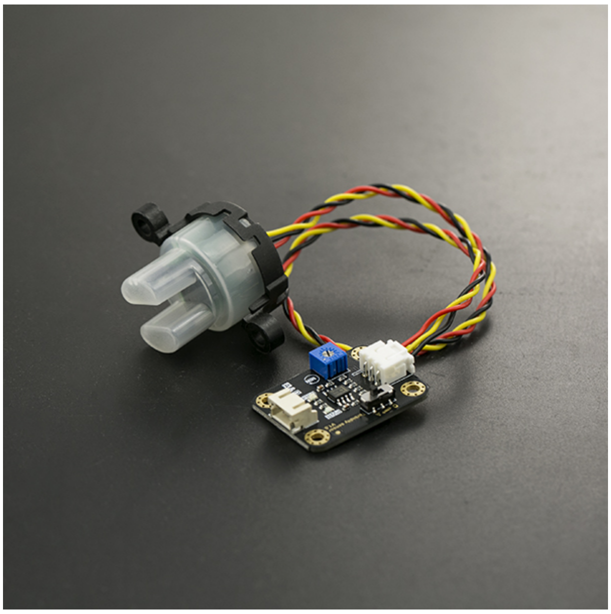


Figure 2.7: Turbidity sensor SEN0189

The SEN0189 turbidity sensor assesses water quality by gauging turbidity, utilizing light to detect suspended particles and measure light transmittance and scattering rates.

The SEN0189 turbidity sensor has the following characteristics:

- Operating voltage: 5V DC.
- Operating current: 40mA (max).
- Response time: <500ms.
- Insulation resistance: 100 $M\Omega$ (min).
- Output method:
  - Analog output: 0-4.5V.
  - Digital output: High/Low level signal (you can adjust the threshold value by adjusting the potentiometer).
- Operating temperature: 5°C to 90°C.
- Storage temperature: -10°C to 90°C.
- Weight: 30g.

Wiring and Connections

The SEN0189 turbidity sensor involves three pins:

- VCC – 5V DC
- GND – Ground for Arduino board
- DATA – SEN0189 analog output

For proper connection, the following components are needed:

- Arduino Uno
- Breadboard (optional)
- SEN0189 turbidity sensor

Similar to the CQRSENTDS01, this sensor operates without external components or calibration, as illustrated in figure 2.8:

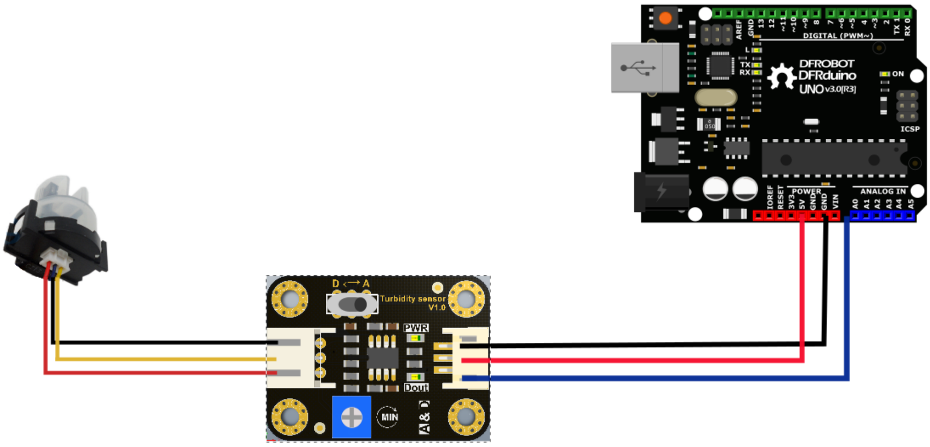


Figure 2.8: Turbidity sensor SEN0189 wiring and connection

While initially considered for its potential in gauging glucose concentrations during fermentation, regrettably did not yield significant data variations. Despite efforts to utilize its readings for insights into the fermentation process, the sensor's data did not meaningfully correlate with glucose concentrations or fermentation progress. As the variations in its data remained negligible, this sensor was consequently excluded from the data collection process.

This exhaustive setup and description of the sensors elucidate their functionality, wiring, and connections for effective integration into the research project.

Each sensor's characteristics and operational intricacies are vital for accurate data collection and analysis during the fermentation process.

Finally, figure 2.9 illustrates the hardware setup utilized for this research:

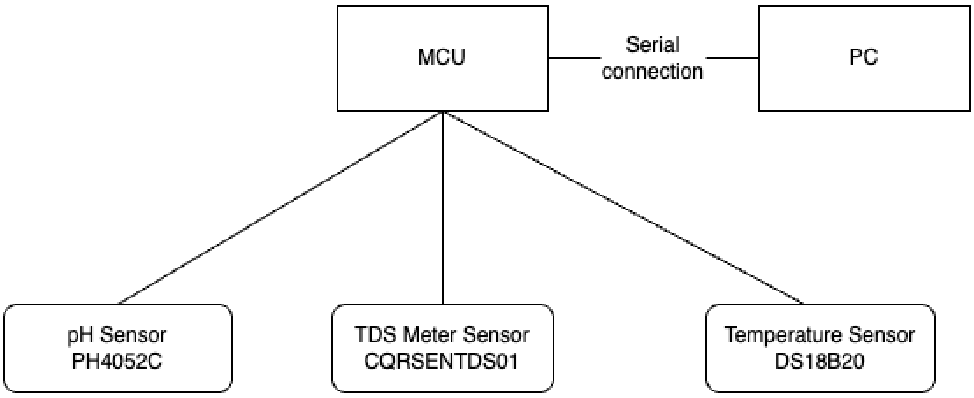


Figure 2.9: Hardware setup

3 | Data Acquisition

This chapter provides a comprehensive overview of the dataset used in this study. It delves into the structure of the dataset, elucidating the significance and interpretation of its values.

Understanding the structure of the dataset is crucial for unraveling the insights it encapsulates. By exploring the meanings and intricacies behind the recorded values, we gain deeper insights into the variables and their implications within the context of our study.

In parallel to the sensor-based data collection, manual data acquisition played a pivotal role in benchmarking and tracking additional parameters. This manual collection process involved meticulous recording and documentation of specific correlations not captured by the sensing devices, such as the glucose values measured in Brix.
These manually acquired data points serve as crucial benchmarks, complementing the sensor-derived information and enhancing the comprehensiveness of our dataset. Integrating these manually collected parameters adds depth and context to our analysis, contributing to our study's findings.

3.1. Dataset Creation

This section delineates the process involved in creating the dataset. It describes the transformation of raw data received from Arduino into a structured dataset, as well as the steps from the initial data transmission to its preprocessing using dedicated Python scripts. The data acquisition involves the Arduino retrieving voltage values from the sensors. These voltage readings are subsequently converted into corresponding values for temperature, pH, and total dissolved solids (TDS) measured in parts per million (ppm). Following this conversion, the acquired data is formatted in a manner conducive to easy readability and manipulation by the Python scripts responsible for subsequent data processing and visualization. The methodical formatting ensures the data is readily accessible and conducive to effective analytical and visualization processes.
The data collection process is performed periodically, with each cycle collecting a certain

number of samples for a certain amount of time. In my data acquisition I chose to collect 50 samples every 15 minutes. This carefully chosen interval and sample count were instrumental in ensuring comprehensive coverage and granularity in the dataset. Such periodic planning allowed for a nice understanding of the temporal dynamics and fluctuations within the dataset.

Moreover, for most sensors, I averaged the data every 10 samples to obtain more stable values. This averaging process contributed to smoothing out abrupt fluctuations, providing more reliable and consistent readings. Additionally, to enhance the data quality I removed duplicates and out-of-range values resulting from voltage drops or serial errors. This step ensured that the dataset maintained accuracy and coherence, free from anomalous readings that could compromise the analysis.
This systematic approach facilitated a more detailed analysis of the data, providing a robust foundation for subsequent interpretations and insights derived from the collected information.

Finally, the dataset's structure, as depicted in Table 3.1, provides a comprehensive record of sensor readings captured over the course of the experiment. Each row represents a timestamped entry showcasing environmental variables, crucial for understanding the experimental conditions.

timestamp	temperature (°C)	pH	TDS (ppm)
2023-10-31 18:35:47	23.69	2.57	483
2023-10-31 18:35:50	23.75	2.68	482
...	...	...	...
2023-11-06 12:00:06	18.50	2.51	646
2023-11-06 12:00:09	18.56	2.41	648
...	...	...	...
2023-11-09 03:18:53	19.75	2.73	831
2023-11-09 03:18:56	19.69	2.69	837

Table 3.1: Dataset structure

3.2. Manual Data Collection

This section serves as an exhaustive exploration of the process involved in the manual data collection procedures. The methodology employed in gathering data from diverse measurement devices is outlined here, providing an in-depth understanding of the meticulous manual data acquisition process.

The data collection mechanism involves a comprehensive array of measurement tools utilized to capture essential parameters crucial for understanding the fermentation process. These tools encompass various devices and instruments employed to capture critical metrics pivotal to comprehending the intricacies of the fermentation process. The collected data is then organized, ensuring accuracy and precision, serving as a benchmark against which the data obtained from the sensing devices is juxtaposed and evaluated. This manual data acquisition process is instrumental in providing a comprehensive ground truth, essential for validating and assessing the reliability and accuracy of the sensed data.

Throughout this section, an exhaustive account of the methodology, instruments utilized, and intricacies involved in manual data collection is delineated. This comprehensive exposition aims to elucidate the stringent procedures and methodologies implemented in acquiring ground truth data, essential for a rigorous evaluation and comparison with sensor-derived data.

3.2.1. Benchmark Tracking

Prior to engaging in automated periodic data collection facilitated by our sensing devices, it is imperative to establish a meticulous baseline by gathering precise data regarding our solution. The initial experiment involved the utilization of the Mother solution, constituting a blend of green tea and SCOBY, without any supplementary sugar. To ensure accuracy in each measurement, 1 gram of sugar was methodically introduced to the solution at each step of the experiment.

Various critical parameters were measured at each interval, including temperature recorded via the DS18B20 sensor, pH readings from both a pH-meter and PH4502C sensor, Brix values obtained from a analog refractometer, and the total dissolved solids captured by the CQRSENTDS01 sensor. Brix is a measure of the sugar content in a solution and is critical in understanding the fermentation process. It indicates the sugar concentration in a solution, which influences SCOBY growth and fermentation.

Throughout the data collection process, a consistent observation emerged: with the addition of each gram of sugar to the solution, the total dissolved solids, measured in parts per million (ppm) by the sensor, exhibited a linear decrease. This trend was closely linked not only to the quantity of sugar incorporated into the solution but also to the volume of the solution itself. Consequently, the experiment was iterated with varying quantities of the Mother solution to ascertain these interdependencies.

Tables 3.2, 3.3 and 3.4 outline the measurements garnered from solutions with distinct volumes, specifically from solutions measuring 0.5, 0.25, and 0.1 liters:

Sugar [gr]	TDS [ppm]
0	643
1	635
2	627
3	622
4	614
5	609
6	602
7	598
8	592
9	587
10	580
11	576
12	569
13	565
14	559
15	553

Table 3.2: TDS trend in a 0.5 Liter Mother solution

Sugar [gr]	TDS [ppm]
0	621
1	609
2	597
3	585
4	573
5	561
6	551
7	545
8	535
9	524
10	515
11	506
12	497
13	487
14	479
15	470

Table 3.3: TDS trend in a 0.25 Liter Mother solution

Sugar [gr]	TDS [ppm]
0	515
1	498
2	472
3	444
4	426
5	413
6	394
7	379
8	362
9	348
10	336
11	324
12	311
13	298
14	284
15	272

Table 3.4: TDS trend in a 0.1 Liter Mother solution

Table 3.5: Measurements with different volumes of Mother solution

These results indicate that the ppm measurements decrease at a faster rate as the volume of the solution decreases. This suggests a linear relation between the volume of the solution and the ppm measurements. These results indicate that the average rate loss of the ppms increases as the volume of the solution decreases, so we can conclude that the variations in the slope are inversely proportional to the volume, following a non-linear trend, as we can see from figures 3.1 and 3.2:

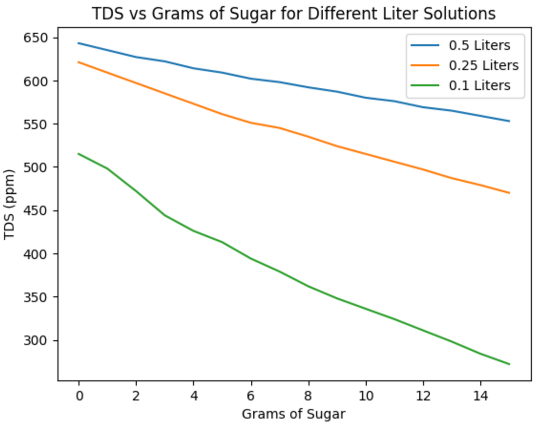


Figure 3.1: TDS slopes for different volumes of Mother solution

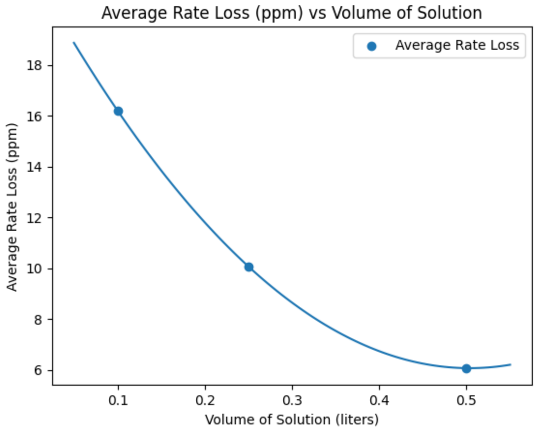


Figure 3.2: TDS values for different volumes of Mother solution

Another interesting observation to make is that the mere addition of sugar did not influence the pH measurements, as recorded by both the pH-meter and the PH4502C sensor, as we can see in Table 3.6:

Sugar [gr.]	pH (pH-meter)	pH (PH4502C)
0	2.2	2.30
1	2.2	2.33
2	2.2	2.33
3	2.2	2.37
4	2.17	2.35
5	2.17	2.35
6	2.19	2.36
7	2.19	2.32
8	2.15	2.38
9	2.18	2.38
10	2.19	2.38
11	2.2	2.38
12	2.19	2.36
13	2.16	2.37
14	2.19	2.38
15	2.19	2.35

Table 3.6: Manual measurements of pH values

This suggests that the fluctuations in pH occur during the fermentation process, rather than being directly influenced by the addition of sugar.

In conclusion, our data suggests a linear relation between the amount of sugar added to the solution and the total dissolved solids (TDS) measurements.
This relation is influenced by the volume of the solution, and we saw that the change in the slope of the ppms measurements is correlated to the change in volume.
The addition of sugar did not directly influence the pH measurements, suggesting that pH does not change when sugar is added, but only during the fermentation process.
This information is crucial for understanding the dynamics of the fermentation process and can be used to optimize the production of our solution.

4 | Results

This chapter aims to comprehensively analyze the data acquired from automated periodic data acquisitions. The primary objective is to attain a more profound understanding of the fermentation process dynamics by juxtaposing and comparing the manual data collection - regarded as ground truth - with the data obtained through sensors.

The examination of the fermentation process in this chapter entails a meticulous portrayal of its results through a comprehensive analysis of the data obtained from various sensors. This analysis intends to shed light on the intricate details and patterns within the fermentation process, highlighting essential trends, variations, and correlations.

The analysis of the sensed data in comparison to the manually collected data during the same period of time will provide crucial insights into the accuracy, reliability, and interpretability of sensor data in the context of the fermentation process. This juxtaposition will not only validate the efficacy of sensor-based data but also elucidate discrepancies or variances between sensed data and actual fermentation dynamics.

Throughout this chapter, an in-depth exploration and discussion of the fermentation process will be conducted based on the extensive data gathered from both manual and sensor-driven acquisitions. This detailed analysis aims to yield comprehensive insights into the nuances and intricacies of the fermentation process, thereby enriching our understanding and contributing to the broader discourse on this subject.

4.1. Successful Fermentation

4.1.1. Manual Monitoring

This section provides an analysis of data collected from a successful fermentation process, emphasizing key parameters tracked manually. The initial setup involved a mixture of a mother solution, green tea, and sugar, aiming to achieve specific ideal conditions: a Brix level between 8 and 10, a pH range of 2 to 3, and a temperature maintained between 18 to 26 degrees Celsius.

As the fermentation progressed, an almost flat trend emerged in the monitored parameters, as expected. Initially, the pH stood at 2.35, and the Brix value marked 8, aligning within the targeted parameters. Following this, minimal variations were observed in the subsequent days. There was a slight shift in pH to 2.43, coupled with a decrease in the Brix value to 7.5, indicating marginal sugar utilization by the SCOBY within the solution. In the following days, negligible fluctuations were noticed, hinting at possible minor changes in sugar content. Throughout these observations, changes remained minimal, indicating that both pH and Brix values remained almost stable, showcasing a consistent fermentation process.

4.1.2. Periodic Monitoring

Here we analyze the data acquired through periodic monitoring for a successful fermentation batch, aiming to compare it with previously collected manual data. The parameters measured during the fermentation process include temperature from the DS18B20 sensor, pH from the PH4502C sensor, and Total Dissolved Solids (TDS) from the CQRSENTDS01 sensor.

n	timestamp	temperature	ph	tds
0	2023-10-31 18:16:18	23.69	2.44	359
...	...	...	...	...
18332	2023-11-05 05:56:22	19.0	2.57	588
...	...	...	...	...
36664	2023-11-09 17:20:50	19.37	2.63	820

Table 4.1: Data collected from a successful fermenting batch

From the dataset we can extract some useful information for determining upper and lower bounds for a good or bad SCOBY growth for each sensed data, and particular behaviours during the fermentation process.

The temperature data consistently reveals a favorable range maintained between 18 to 26 degrees Celsius, aligning perfectly with the optimal conditions for the fermentation process. This stable temperature range fosters an environment ideal for the required biochemical reactions to occur efficiently. The consistent temperature profile signifies an optimal condition, contributing significantly to the successful fermentation process, enabling the necessary reactions to progress effectively.
Throughout the fermentation process, the pH levels remained within the desired range of 2 to 3, showcasing an environment highly suitable for ideal fermentation conditions. With pH levels consistently maintained within this optimal range, the fermentation process remains undisturbed, ensuring the essential biochemical reactions proceed without hindrance. The stable pH profile stands as a positive factor, crucial for maintaining an environment conducive to successful fermentation outcomes.
The Total Dissolved Solids (TDS) data exhibits a steady, almost linear increase within the range of 400 to 900 ppm, indicating a stable growth inside the batch. This gradual rise in TDS values reflects the desired microbial activity, including the growth and interaction of the Bacterial Cellulose. Such a trend represents a positive indicator, signifying a healthy fermentation process. The observed increase in TDS within this range remains integral to maintaining the solution's integrity, contributing positively to the desired fermentation outcomes.

In summary, the consistent temperature range, stable pH within the ideal parameters, and the gradual, controlled increase in TDS values denote highly favorable conditions for an efficient and successful fermentation process. These positive indicators collectively support the desired biochemical processes essential for quality fermentation, ensuring optimal outcomes and maintaining the overall integrity of the process.

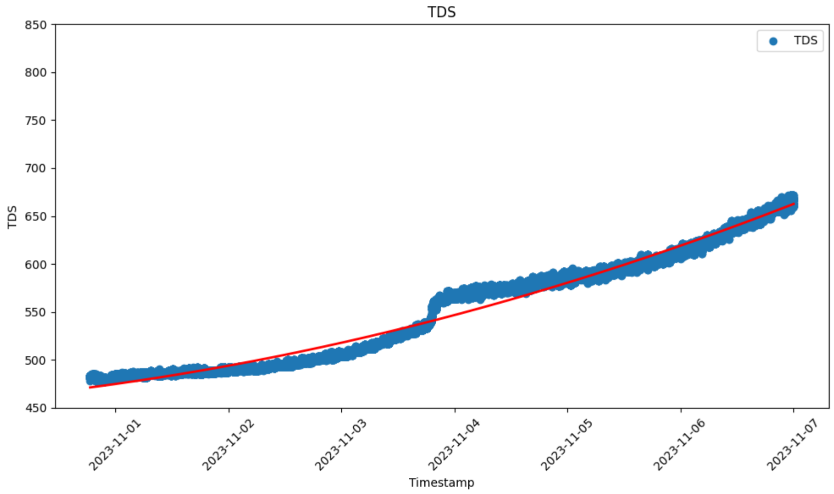


Figure 4.1: TDS data in the successful fermentation process

The depicted figure 4.1 illustrates the evolution of Total Dissolved Solids (TDS) data throughout the successful fermentation process. The observed trend showcases a consistent and linear increase in TDS values, attributed to the ongoing generation of the SCOBY. The collected TDS values consistently fall within the range of 400-900 ppm, a crucial range indicating successful SCOBY growth. It's noteworthy that this TDS sensor doesn't directly estimate Brix levels due to the SCOBY's impact on increasing dissolved solids, deviating from the expected linear relation between TDS and sugar content. The linear growth curve, in this context, represents the steady accumulation of SCOBY biomass over time, influencing the TDS values.

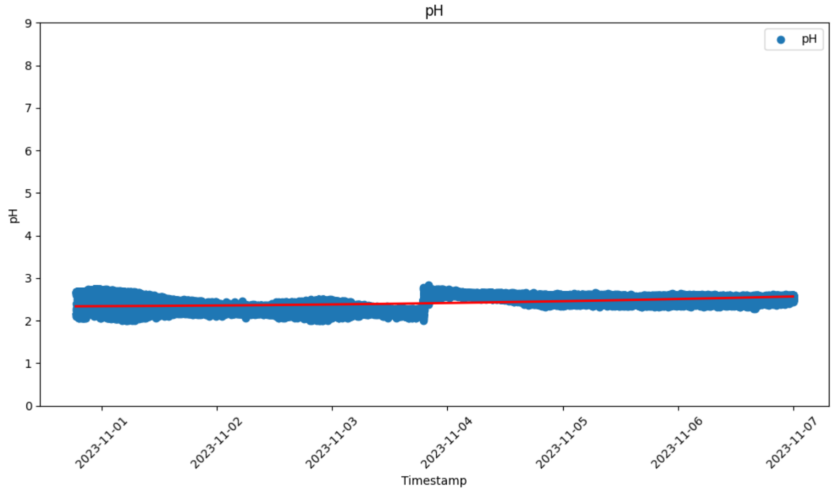


Figure 4.2: pH data in the successful fermentation process

The presented figure 4.2 depicts the pH variations observed during the successful fermentation process. The stability in pH levels throughout the process signifies a consistent and conducive environment for the fermentation process. The sustained pH levels within the optimal range of 2-3 further affirm the successful progression of the fermentation process.

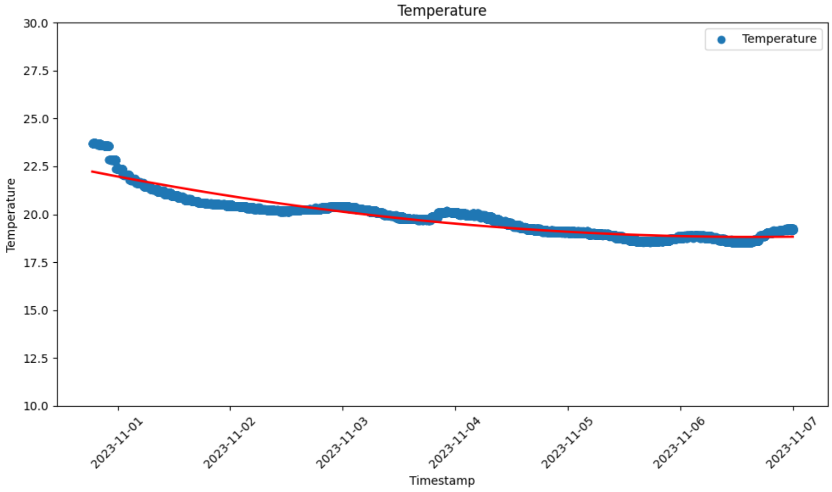


Figure 4.3: Temperature data in the successful fermentation process

The final figure 4.3 showcases the recorded temperature data during the fermentation process. Consistently maintained within the optimal range of 18-26 degrees Celsius, these temperature readings reinforce the successful nature of the fermentation process. The adherence to the recommended temperature range contributes significantly to the favorable conditions supporting SCOBY growth and fermentation.

4.2. Unsuccessful Fermentation

4.2.1. Manual Monitoring

In contrast to a successful fermentation, an examination was conducted on an unsuccessful fermentation process initiated with a mother solution combined with green tea and metal screws, without additional sugar introduced. The introduction of metal screws aimed to hinder the growth of the SCOBY, intentionally influencing the fermentation dynamics.

The data collected over the course of this process revealed a distinct progression in comparison to successful fermentation: The initiation showcased a notable deviation from the anticipated starting parameters, with a pH level recorded at 2.53 and a Brix value at 4.5. As the process progressed, there was a significant increase in pH levels to 4 while maintaining a consistent Brix value of 4.5, signifying substantial deviation from the anticipated fermentation trends. Further along, there was a continued rise in pH to 4.25, emphasizing the ongoing deviation from the ideal parameters for successful fermentation.

Throughout this monitoring, a noticeable and consistent trend emerged where the pH levels consistently increased, steadily moving out of the optimal 2-3 pH range crucial for successful fermentation. In contrast, the Brix values exhibited a flat trend, underlining the lack of growth of the SCOBY withing the tea batch.

4.2.2. Periodic Monitoring

Here we analyze the data acquired through periodic monitoring for an unsuccessful fermentation batch, aiming to compare it with previously collected manual data. The parameters measured during the fermentation process include temperature from the DS18B20 sensor, pH from the PH4502C sensor, and Total Dissolved Solids (TDS) from the CQRSENTDS01 sensor.

n	timestamp	temperature	ph	tds
0	2023-10-31 18:16:23	23.62	2.52	583
...	...	...	...	...
18330	2023-11-05 05:56:12	18.94	3.54	1849
...	...	...	...	...
36663	2023-11-09 17:20:56	19.19	4.29	2219

Table 4.2: Data from an unsuccessful fermentation batch

The temperature dataset showcases a range between 18 to 26 degrees Celsius, indicating a consistent and favorable range for the fermentation process. The observed temperatures fall within the ideal range required for fermentation, ensuring an environment conducive to the desired biochemical reactions. This consistent temperature profile remains a positive factor contributing to the fermentation process, providing an optimal condition for the necessary reactions to occur efficiently.

The recorded pH values, extending beyond the optimal fermentation range of 2-3 pH, signify an environment unsuitable for ideal fermentation conditions. The moderately acidic to slightly alkaline pH levels, ranging between 2.9 and 4.4, indicate a suboptimal environment for the fermentation process. This deviation from the ideal pH range negatively impacts the fermentation efficiency, potentially hindering the required biochemical reactions essential for optimal fermentation outcomes.

The Total Dissolved Solids (TDS) data reveals a substantial increase in dissolved solids, notably deviating from the typical range observed in good fermentation batches. This drastic rise in TDS values, ranging from 570 to 2240 ppm, may serve as a significant statistical indicator. It can be attributed to the presence of microbial activity—such as the proliferation and demise of beneficial cultures like BC (Bacterial Culture). This phenomenon can lead to a detrimental impact, causing the solution to darken and potentially disrupt the desired fermentation process.

In summary, while the temperature remains within an ideal range conducive to fermentation, the pH values drifting beyond the optimal range and the significant surge in TDS values suggest unfavorable conditions for efficient fermentation. The deviation in pH levels and the remarkable increase in TDS can potentially hinder the biochemical processes essential for successful fermentation, impacting the overall quality and outcome of the process.

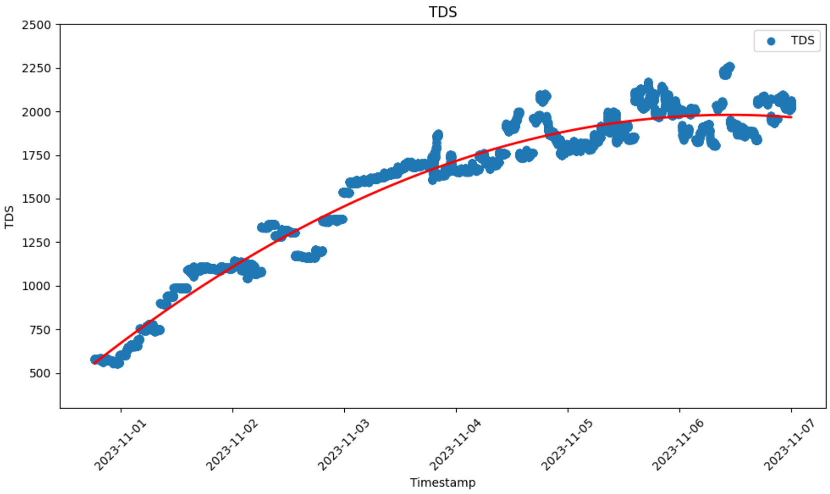


Figure 4.4: TDS data in the unsuccessful fermentation process

The provided figure 4.4 showcases the time-series trend of Total Dissolved Solids (TDS) data throughout the unsuccessful fermentation process. The data visualizes a distinctive pattern resembling a logarithmic curve. The discernible rise in TDS values is noteworthy, indicating a significant increase over time. This notable surge in TDS values could be attributed to several factors, such as the dissolution of materials within the solution or the decomposition of compounds leading to a gradual escalation of dissolved solids. Further investigation into the specific causative agents contributing to this TDS pattern would enrich our understanding of the fermentation process's failure.

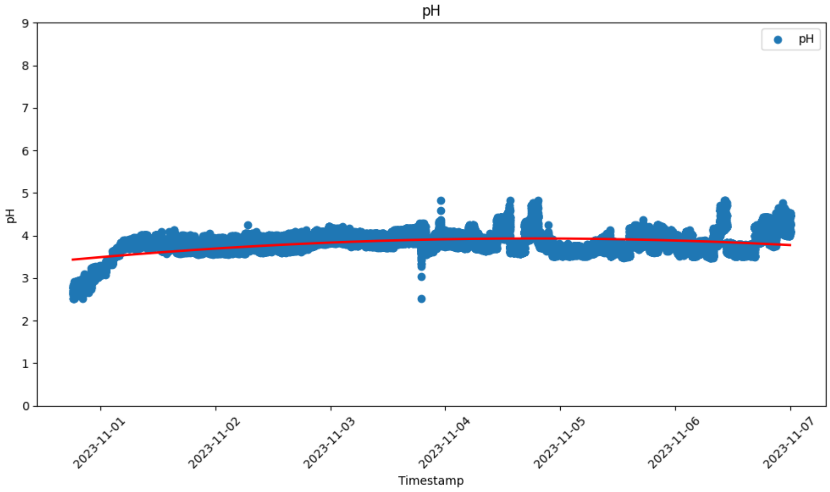


Figure 4.5: pH data in the unsuccessful fermentation process

The depicted figure 4.5 portrays the pH variations observed throughout the duration of the unsuccessful fermentation process. The initial phase witnessed a significant spike in pH levels, followed by a stabilization phase wherein the pH values remained consistently near 4. This stabilization, notably above the ideal range of 2-3, signifies an unfavorable pH environment for successful SCOBY growth. The sustained deviation from the optimum pH range highlights a critical aspect contributing to the failure of the fermentation process.

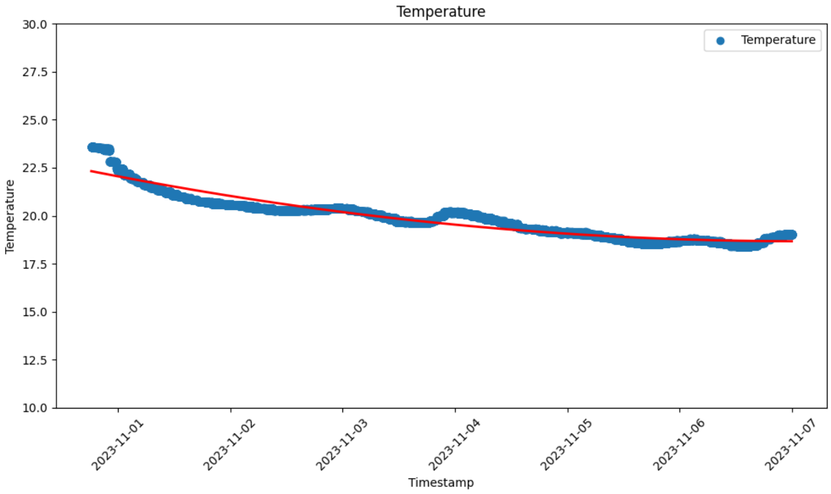


Figure 4.6: Temperature data in the unsuccessful fermentation process

The presented figure 4.6 delineates the temperature trends recorded during the unsuccessful fermentation process. Throughout the experiment, the temperature remained within the recommended range of 18-26 degrees Celsius, indicating that temperature alone did not stand as a decisive factor for the failure of the fermentation. This observation aligns with the understanding that while temperature is crucial, it works in conjunction with other parameters, such as pH and TDS, to ensure successful SCOBY growth and fermentation. Further analysis integrating these parameters' interplay would provide deeper insights into the reasons behind the fermentation's failure.

These comprehensive graphical representations offer valuable insights into the complex dynamics of the unsuccessful fermentation process, shedding light on the interplay between various parameters. By dissecting and analyzing these trends, we can unravel pivotal factors contributing to SCOBY growth failure, paving the way for informed strategies to optimize future fermentation endeavors.

The temperature data, depicted in the final figure, confirms that the temperature consistently stayed within the optimal range throughout the fermentation process. This observation implies that temperature alone did not serve as the sole determinant for the success of fermentation.

In both successful and unsuccessful fermentation processes, the Total Dissolved Solids

(TDS) values exhibited an increase. However, distinct patterns emerged: a linear growth pattern in the successful fermentation and a logarithmic-like trend in the unsuccessful one.

The differing TDS patterns suggest that while TDS values alone cannot accurately indicate sugar levels, they play a vital role in establishing an operational range conducive to successful SCOBY growth. Moreover, the distinct growth patterns (linear or logarithmic) of the TDS curve can potentially serve as an additional parameter to gauge optimal SCOBY growth conditions. This insight into the growth curve's pattern holds promise in refining future fermentation processes, possibly indicating a specific TDS curve growth indicative of optimal BC growth.

It's worth noting that maintaining pH levels between 2 and 3 and temperatures between 18 and 26 degrees Celsius, in conjunction with monitoring TDS trends, contributes significantly to fostering successful fermentation. This holistic approach aligns with the intricate dynamics of SCOBY growth, emphasizing the importance of multifaceted parameters in achieving optimal fermentation conditions.

5 | Conclusions and Future Developments

The move towards automating BC production marks an initial step, with numerous possibilities for refining and transforming this process.

Integrating extra sensors represents a crucial evolution in SCOBY cultivation. With a wider range of sensors, the system can gather a more detailed set of data, including factors like glucose levels. These sensors offer the potential to reveal detailed growth patterns, providing deeper insights into SCOBY behavior from its beginning to its maturity. For example, O2 and CO2 sensors could provide valuable insights into the fermentation process itself.
Additionally, the integration of a Raspberry Pi camera could offer fundamental visual data, providing observations and documentation of the SCOBY's physical growth and structural changes over time, further enriching the dataset for comprehensive analysis. Improved measurements and a more comprehensive dataset will pave the way for a deeper understanding of SCOBY growth. This understanding will influence the optimization of the process and enhance quality control.

Moving beyond sensing, the integration of actuators stands as a crucial milestone in achieving a fully autonomous production process. These components hold the key to dynamic adjustments within the growth environment. By regulating vital factors like glucose levels, pH, and temperature, actuators can orchestrate real-time optimization, ensuring an environment conducive to optimal SCOBY growth. This automated fine-tuning mechanism promises precise control and adaptability, minimizing manual intervention and maximizing the consistency and quality of BC production. Additionally, leveraging 3D printing for sensor and actuator supports will enable tailored and efficient hardware solutions, optimizing their integration and functionality within the growth chambers.

The heightened complexity arising from the integration of multiple sensors and actuators necessitates a robust and versatile microcontroller. The adoption of advanced microcontroller systems, like the Raspberry Pi, prefigures a more sophisticated approach in managing multiple growth chambers. Its enhanced computational power and scalability promise synchronized operation across various chambers, facilitating seamless orchestration and control throughout the entire SCOBY growth cycle.

Moreover, the incorporation of server and IoT systems, complemented by MQTT server-client configurations and Node-Red dashboard integration, promises an elevated standard of data collection and visualization. This technological fusion will not only streamline data gathering but also provide insightful real-time visualization.

Furthermore, expanding the dataset through diverse SCOBY and tea combinations will usher in a new era of adaptability. This augmentation promises a spectrum of varied data and growth curves, cultivating a deeper understanding of SCOBY behavior across diverse conditions. This enriched dataset will serve as the bedrock for a more nuanced and adaptable production process, continuously learning and adapting from diverse inputs.

Lastly, the integration of machine learning algorithms holds immense promise. These algorithms, when applied to the expansive dataset, are poised to predict and adapt to varying states of the solution throughout the growth process. As the dataset expands, these algorithms will continually refine, optimizing SCOBY growth, and amplifying the efficiency of the automated production process.

In conclusion, these proposed enhancements represent a significant leap towards an advanced, automated, and adaptive BC production system. This transformation promises an efficient, precise, and optimized growth process, propelling BC cultivation into a new era of innovation and efficiency.

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