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Design and Implementation of a Microstrip Patch Antenna–Based Sensing System for pH Estimation of Aqueous Solutions Using Machine Learning

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An undergraduate senior project submitted by

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in consideration of the partial fulfillment of the requirements for the degree of

BACHELOR OF SCIENCE

in

ELECTRICAL AND ELECTRONIC ENGINEERING

Department of Electrical and Electronic Engineering

Summer 2025

DECLARATION

I do hereby solemnly declare that the research work presented in this undergraduate thesis has been carried out by me and has not been previously submitted to any other University / Institute / Organization for an academic qualification / certificate / diploma or degree.

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The Authors
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ABSTRACT

This paper presents the design and implementation of a microstrip patch antenna-based sensing system for pH estimation of aqueous solutions using machine learning. Conventional pH sensors are widely used, such as frequent calibration, easy contamination, the measurement range is limited, and the maintenance is expensive. In order to overcome these limitations, the proposed system uses rectangular microstrip patch antenna fabricated using FR4 substrate for the detection of change in the dielectric properties of liquid samples. Variations in resonant frequency, return loss (S_{11}) and bandwidth are then analyzed to provide the predict pH level. Experimental measurements were conducted for solutions with a pH value ranging from 4 to 12 by using a Vector Network Analyzer (VNA) with the results verified by simulation results of CST Studio Suite. Furthermore, Random Forest, Support Vector Regression (SVR) and k-Nearest Neighbors (kNN) machine learning models were also trained with the collected dataset in order to predict the pH with respect to the antenna response parameters. Out of them, Random Forest showed the highest accuracy (R^2 level of higher than 0.85) with the lowest MAE (Mean Absolute Error) showing also the strong predictive reliability. The obtained results validate the concept that a low-cost, wide-area and contact-less pH monitoring solution is obtained by the combination of microwave sensing and data-driven modeling. The proposed system has potential applications in environmental monitoring, industrial process control, fish farming and agricultural water management especially for resource constrained environments like that of Bangladesh.

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CHAPTER 1
INTRODUCTION

1.1 Overview

Water is indispensable for sustaining and life and its quality is of the utmost importance of public health, perspective of agriculture, industry and environmental sustainability. A cluster of water quality indicators are used to assess water quality, like Dissolved Oxygen (DO), Total Dissolved Solid (TDS), pH (potential of hydrogen) etc. Among these, pH is a logarithmic scale that finds out whether a given solution is basicist, acidic or neutral. The reason why pH is so important is that the environment, flora and fauna of a specific area is susceptible to pH changes. Even slight deviations from the optimal pH range can lead to cascading and catastrophic consequences. For example, we get optimal harvest in the pH range 6.5-7.0. However, reduced crop harvest can be seen in both alkaline and acidic soils. On the other hand, corrosion of metals and degradation of industrial instruments happen much faster in sub-optimal pH conditions. In water, marine life is greatly affected if pH levels vary. This can lead to massive increases in fish deaths in aquatic ecosystems. Consequently, we desperately need an accurate and reliable pH monitoring system. Our agriculture, manufacturing, marine life and environment sectors would benefit tremendously with such systems [1].

Based on our experience, currently used methods of pH sensing are typically based on electrochemically based pH-sensing probes such as glass electrodes and ion sensitive field-effect transistors (ISFETs). In real-life applications, in those methods, mix advantages and disadvantages can be noticed. The main advantage is that older methods give precise measurements. But they also have drawbacks. Those are a short range of application for detection, need for frequent calibration, electrode fouling, fragility in inclement weather phenomena, and high operational and maintenance costs. Many of these sensors give only point-based measurements. Which are insufficient for large-scale environments such as extensive water reservoirs, industrial pipeline networks, or agricultural irrigation systems [2]. Thus, old ways of working quickly become obsolete, and new technology replaces them.

Microwave sensing technology is now offering many new solutions. In my view by utilizing the relationship between the properties of materials and electromagnetic waves, microstrip patch antenna sensors have been developed, which are compact in size, low-cost to manufacture, easy to use, and capable of hassle-free measurements. Placement of a liquid sample in the vicinity of the antenna results in variation of effective permittivity of the surrounding medium. This indicates measurable shifts in resonant frequency, return loss (S_{11}) and bandwidth. Due to the shifts being sensitive to changes in pH levels, it becomes possible to develop a pH sensing system without contacting the surface or chemical reactions.

The present project is dedicated towards the employment of such a microstrip patch antenna-based microwave sensor for the wide-ranging pH measurement with the in-depth analysis of the design, fabrication and experimental measure validation of such a system [16]. To achieve an antenna working under a multitude of liquid dielectric condition CST Studio Suite was harnessed in the design and simulation phase. Furthermore, an experimental paradigm of a standard FR4 substrate had to be used in order to guarantee cost-effectiveness and ease of production. In order to cover the entire range of pH range (pH 4-12), the experimental validation was done by hydrochloric acid (HCL) and sodium hydroxide (NaOH) solutions at controlled temperatures (20°C–30°C) To keep track of some key antenna response parameters some measurements were taken using a Vector Network Analyzer (VNA) [3].

Machine learning algorithms were used in the analysis framework, attention was given to enhance interpretability and prediction capability. In present research work, the various Machine learning models have been developed using experimentally obtained data sets respectively. From the results obtained it is clear enough that from resonant frequency, S_{11} and bandwidth's parameters it is possible to obtain sufficiently accurate pH estimation. This degree of accuracy further indicates the presence of a strong and consistent relationship between the response characteristics of the antennas and the solution pH which further indicates the feasibility of the proposed approach.

Overall, the proposed system is a combination of electromagnetic sensing with data-driven modelling in creation of a low-cost, non-invasive and scalable pH measurement solution. In my view such a system has special relevance for a developing country such as Bangladesh where the cheap and wide-area monitoring of water quality is still an issue. Some of the potential uses include environmental monitoring, industrial process control, precision agriculture and public health surveillance. By reducing the dependence on expensive conventional sensors, this approach could assist in facilitating more accessible as well as sustainable water quality evaluation in the direction of supporting long-term environmental in addition to developmental goals.

1.2 Background & Motivation

pH is one of the most important parameters of water quality. The changes of pH, even if small, can cause serious environmental and economical problems. When the pH is shifted away from neutral, aquatic ecosystems are quite frequently influenced. In ponds and in aquaculture systems this can even lead to death of fish. Abnormal pH levels also destroy soil and water quality. As a result, there can be a falling agricultural productivity.

Most of industries have dependency on the strict pH control. Textile processing is one such process. Food and beverage production such as soft drink production also involves strict pH control in the process. Without proper control, the quality and safety of a product can be at risk. That is why systems of accurate and reliable pH monitoring are so important. Cost-effective solutions are especially important in the long-term protection of the environment and the sustainability of industries [4].

(a) (b) (c)

Fig. 1.1. Impact of pH (a) Environment (b) Health and (c)Fish farming.

The pH level is an important water quality measurement. Changes in pH levels from neutrality can have a negative effect on aquatic ecosystems. In ponds as well as aquaculture environment, this may even lead to the death of fish as depicted as shown in Fig 1.1.

Widely used pH sensing technologies usually use glass electrodes or ion-sensitive field-effect transistors (ISFETs). However, those suffer from the following technical and operational problems:

- Limited measuring range, which can make them unsuitable measuring devices for highly concentrated for highly acidic or alkaline environments.
- Small-interval maintenance and calibration frequency in the field in particular, field service measurements are becoming more demanding on calibration of blood and urine specimens.
- Fragility and prone to breakage resulting into shorter life span with continuously increasing operational costs
- Point based measurement Declining accuracy with higher spatial coverage in larger systems (pond, tanks, pipelines)

Recent studies have shown that the use of microwave sensors as a good alternative in pH measurements. We believe that microstrip patch antenna-based sensors are especially promising ones. They are small in size and are relatively inexpensive. Another advantage is that they are easy to fabricate using standard PCB techniques [24].

Microwave sensor is feasible to detect the variation of dielectric property of materials without any physical contact. When we put a liquid sample with a specified pH is put near the antenna and the effective permittivity of the surrounding medium changes. This change induces changes in the resonant frequency and the S_{11} response. By analyzing these variations pH of the solution is able to be accurately estimated [5].

We are Design and optimize rectangular Microstrip patch antenna using CST Studio Suite. Impedance matching and resonant frequency behavior for suitable liquid sensing applications are taken in consideration. Make length antenna prototype in FR4 substrate using the popular techniques of PCB fabrication. Here we can do focus is affordability, repeatability and optimized performance.

Combining microwave sensing and machine learning helps to improve the system performance even more. We get multiple parameters like temperature, bandwidth and S_{11} can be considered at the same time. In this way the results would more robust prediction model with increase in its accuracy and generalization. In our eyes, what motivates this particular project is not just the technical advance. The proposed approach is aimed to provide an accessible, easy to maintain and broad solution to the pH sensing. It also aligns with environmental sustainability goals including the UN Sustainable Development Goal 6 (Clean Water and Sanitation) which is suitable for the practical implementation of a local context such as Bangladesh.

1.3 Objectives

The general goal of this project is design and experimental validation of low cost and wide-ranging and non- invasive microwave-based pH sensing system. The proposed system is based on microstrip patch antenna and machine learning techniques of data analyzing for the prediction of pH. This set up is record S_{11}, resonant frequency and bandwidth information for solution over a large pH range (pH 4 - 12) at controlled temperature conditions (20°C – 30°C) [6]. To achieve this goal, the following specific objectives are defined.

- To train and evaluate machine learning models to predict pH from antenna response parameters.
- To design and implement an experimental setup that consists of liquid container, co-axial cable connections and a Vector Network Analyzer (VNA).

The goals are focused on affordability, scalability and practicality. Together, they support development of a pH sensing platform, which can be used in sustainable water management applications, agricultural optimization and environmental monitoring or, most relevantly in developing regions, in Bangladesh. Systematically record and archive the experimental data such as pH value, temperature, resounding frequency, S_{11} return loss and bandwidth. This dataset can also be used for possible future research and analysis.

1.4 Research Methodology

The steps or methodology of our experiment can be demonstrated by using flowchart which as shown in Fig 1.2 Extensive literature review regarding electromagnetic simulation, hardware prototyping, experimental measurement and machine learning based data analysis procedure. After that we ensued a structured step-by-step workflow to ensure accuracy, repeatability and align between what's measured in the real-life applications and what's simulated by the use of computers. This methodology allows to ensure a systematic way from the theoretical study to the simulation, hardware, data collection, machine learning modelling and finally the analysis of the result.

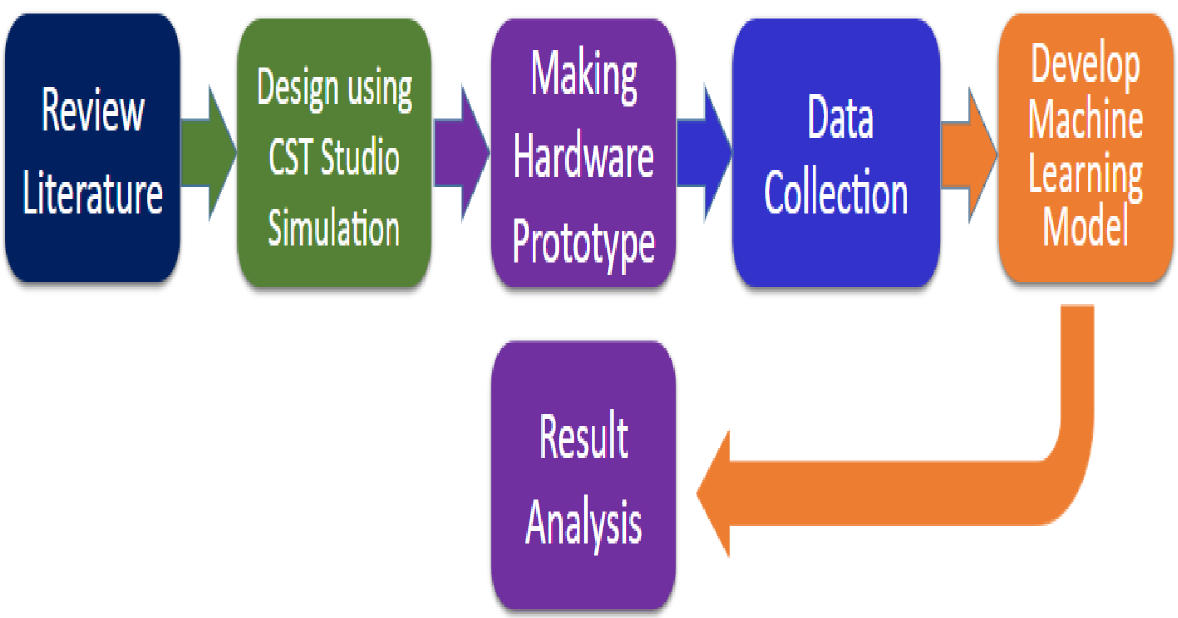


Fig. 1.2. Research Methodology

Step 1: Literature Review and Problem Identification

A literature review of current methods for pH sensing, microwave sensing techniques, and antenna-based methods for liquid characterization was conducted in this study. We found several limitations of conventional pH sensors were identified, such as limited operating range, the need of frequent calibration and structural fragility. Insights from past studies on antenna-based dielectric sensing were applied to make suitable design parameters and operational frequency ranges for the proposed system.

Step 2: Antenna Design and Simulation

A rectangular microstrip patch antenna was designed in CST Studio Suite using FR4 as substrate material ($\varepsilon_r \approx 4.3$). Design equations for patch width, effective dielectric constant, and length extension were found to be sufficient to obtain resonance in the frequency band of interest. To detect variations in S_{11}, curves, bandwidth, and resonant frequency [7], simulations were conducted under different sample conditions (air, container only, water, and solutions of varying pH).

Step 3: Antenna Fabrication

Taking the optimized CST design as model, the antenna was fabricated on an FR4 copper-clad board using standard PCB etching techniques. Soldering SMA connectors enabled coaxial feed connections. As good impedance matching of the simulated and the fabricated structures is indispensable, particular care was taken to keep precise dimensions [8].

Step 4: Experimental Setup and Data Acquisition

Our experimental set-up was made with a custom-made measurement set-up. A plastic container was used to retain 10 mL of the solution sample while the fabricated microstrip patch antenna was placed directly under or near the container. The antenna was attached to a Vector Network Analyzer (VNA) using SMA cables to measure the response of the antenna.

Experiments were conducted using acidic, neutral and basic solutions. The pH of the samples varied from 4 to 12, and the aqueous solutions were prepared from HCl and NaOH. During the performed measurements the temperature was varied in the range (20°C – 30°C) to observe its influence on sensor performance. At each measurement stage, some important parameters such as S_{11} (dB), resonant frequency (GHz) and bandwidth (GHz) were measured.

Step 5: Data Compilation and Pre-Processing

The collected experimental data were organized into Excel spreadsheets, with separate files created for each pH level (pH4.xlsx to pH12.xlsx). For comparison of different conditions, the measurements recorded at 26°C were chosen as the reference data set. Additional temperature-based filtering and data cleaning steps were performed to remove inconsistencies and outliers. During analysis, the marker-3 resonant frequency, return loss (S_{11}) and bandwidth were identified as the most relevant features and were therefore extracted for further processing and model training.

Step 6: Machine Learning Modeling and Analysis

Our prime concern of the project is to set up a connect in among the antenna parameters and pH. To achieve this objective, multiple regression models were built on the data set using the Python programming language. The models used were Random Forest, Support Vector Regression (SVR), k-Nearest Neighbors. We used R^2, MSE, RMSE, and MAE to evaluate the Performance. For easy visualization and to facilitate the interpretation of the model's features, importance analysis, predicted vs actual plots, scatter plots, and heatmaps were created.

Step 7: Results Interpretation and Validation

Our experimental and ML prediction results provided the datapoints which provide the way to evaluate the sensor sensitivity and robustness. It was discovered that the Random Forest Regression models had better performance than other models with R^2 values close to 0.85 - 0.88. It confirms that resonant frequency and S_{11}, can be effectively used for the inference of solution pH. In our experiment experimental results were compared with simulation outputs in order to evaluate the reliability of the proposed approach of microwave-based pH sensing. We were interested in prominent antenna response characteristics, namely resonant frequency and return loss (S_{11}), since these response characteristics directly indicate the modification of the surficial dielectric environment. Simulation data acquired with CST Studio Suite was examined together with experimentally acquired data under similar operating conditions.

To quantify the amount of agreement, percentage error and overall trend consistency were investigated amongst different pH levels. Our experimental results showed good agreement with the simulated responses with only small deviations observed in some cases. These differences are to some degrees explained by practicalities (fabrication tolerances, cable losses, small differences in the positioning of the liquid container while making the measurements). Overall, there is a good agreement of simulation and experimental data which confirms the proposed sensing approach for reliable recording of pH-dependent variations of liquid phase medium.

Step 8: Conclusions and Future Work

The main findings of this study are summarized along with the observed limitations, including temperature sensitivity and overlapping bandwidth responses at certain pH levels. These limitations indicate areas where further refinement is required. Based on the experimental observations, future improvements may focus on optimizing the antenna geometry to enhance sensitivity and reduce overlap. In addition, integrating the sensing system with wireless IoT platforms could enable continuous and real-time monitoring, making the system more suitable for practical field applications.

1.5 Project planning

The key conclusions of this study are summarized together with the limitations that were observed, such as temperature sensitivity and overlapping bandwidth responses for some pH values. These restrictions indicate places that need more improvement. Based on the experimentally obtained, the improvements in the future will be possibly addressing the antenna geometry to optimize sensitivity and reduce overlap. In addition, integration of the sensing system with wireless IoT platforms could facilitate continuous and real-time monitoring for the system to be more suitable for practical application in the field.

Since it was important to complete the experiment in the academic timeframe, a work plan that was both clear and practical was prepared at the start of the study. Since the experiment had several components. Such as design of antenna, electromagnetic simulation, hardware fabrication, experiment measurements, machine learning analysis. There had to be proper coordination between these activities. Organized plan helped the team manage these different tasks without any overlap and unnecessary delays. The planning process concentrated on how the work would be done in terms of sequence of work, responsibilities of team members in consultation with the supervisor and setting reasonable time frames for each stage of the work. Particular attention was given to the maintenance of a coordinated interaction between the simulation work, experimental measurements and subsequent data analysis since progress in one stage often depended on completion of another. This approach helped to reduce confusion during execution and enabled the team to track more effectively progress throughout the duration of the project.

Based on this scheme, the total workflow was divided into six major phases:

1. Literature Review and Problem Identification
2. Antenna design and simulation
3. Hardware fabrication
4. Data collection and experimental set up
5. Analyzing data & Modelling machine learning
6. Documentation and presentation

Following this phased structure made it easier to distribute technical tasks and monitor the deadlines. It also supported clear communication within the team in terms of responsibilities. Also progress contributing to timely and organized completions of the project.

1.5.1 Work plan - RACI Matrix

To define individual responsibilities, an RACI matrix was prepared based on the major project activities. This helped differentiate who was responsible for carrying out specific tasks and who was accountable for their completion. The progress was kept to the supervisor with regular updates and review meetings. This enabled on-time feedback where needed. As a result, important tasks were done without any problems. Also, potential coordination issues were addressed early in the project, as shown in Table 1.1

Table 1.1. Work plane RACI Matrix

Period	Assignments	Prof.Dr. Feroz Ahmed	Md. Mishurul Islam	Nafish Kabir Nirob	Start	End	Days	Status
1st Term	Prepare Plan	C	R	R	01.05.2024	30.05.2024	30	✓
	Review Literature	I	R	A	16.05.2024	30.08.2024	105	✓
	Problem Identification	C	A	R	16.06.2024	30.08.2024	75	✓
	Prepare Draft Budget	I	R	R	01.08.2024	30.08.2024	30	✓
	Prepare, Submit &Present (Proposal, Progress Presentation & Progress Report)	I	A	A	18.08.2024	07.10.2024	50	✓
2nd Term	Project Design (specify the work)	C	R	R	01.10.2024	30.11.2024	60	✓
	Simulation / Hardware (specify the work)	C	R	R	01.11.2024	30.12.2024	60	✓
	Prepare, Submit & Present (Presentation & Progress Report)	I	A	A	01.12.2024	15.01.2025	45	✓
Final Term	Testing prototype	C	R	R	01.01.2025	25.02.2025	31	✓
	Result & Analysis	C	R	R	01.03.2025	30.05.2025	91	✓
	Prepare, Submit & Present (Final Report & Presentation)	I	A	A	10.04.2025	17.09.2025	20	✓
	Prepare Poster & Present Group Demonstration	I	A	A	01.09.2025	18.09.2025	17	✓

Legend:

- **R – Responsible:** Performs the work
- **A – Accountable:** monitors task completion as well as quality control
- **C – Consulted:** Gives input and advice
- **I – Informed:** Up to date on Developments

As a result, the responsibilities of the team in the tasks became well-defined. One student was mainly responsible for data analysis and report preparation. The other one was responsible about simulation work, antenna fabrication and making the experimental measurements. The supervisor led to the progress of the project and was responsible for the regular guidance and feedback. Further technical assistance was secured during fabrication and measurement stages from the laboratory staff as needed that as shown in Table 1.1

1.5.2 Work Plan - Gantt Chart

Since the project activities were spread throughout the semester, a Gantt chart was developed to help carry out the organization of and control over the workflow. Tasks were ordered according to their logical order. We had given particular attention to dependencies such as getting simulation work done before fabrication. The chart was updated on a regular basis and used to monitor progress against planned deadlines. It helped the team to identify any delayed at early stage and to adjust the schedule when necessary.

Several key milestones were set to track progress during the experiment:

1. The literature review was completed and the problem statement was finalized
2. The antenna design was finalized using CST simulations
3. The prototype antenna was fabricated on an FR4 substrate
4. Experimental data were then collected for solutions with pH values from 4 to 12
5. Machine learning models were trained and evaluated based on the collected data
6. The report was completed and the final presentation was prepared

Table 1.2. Work Plan - Gantt Chart

Task Name	May-24	Jun-24	Jul-24	Aug-24	Sep-24	Oct-24	Nov-24	Dec-24	Jan-25	Feb-25	Mar-25	Apr-25	May-25
Prepare Plan	✓												
Review Literature	✓	✓	✓	✓									
Problem Identification		✓	✓	✓									
Prepare Draft Budget				✓									
Prepare, Submit & Present (Proposal, Progress Presentation & Progress Report)				✓	✓	✓							
Project Design (specify the work)						✓	✓						
Simulation / Hardware (specify the work)							✓	✓					
Prepare, Submit & Present (Presentation & Progress Report)								✓	✓				
Testing prototype									✓	✓			
Result & Analysis											✓	✓	✓
Prepare, Submit & Present (Final Report & Presentation)												✓	✓
Prepare Poster & Present Group Demonstration													✓

A Gantt chart was used throughout the semester to monitor progress and check whether tasks were moving as planned. It helped the team to identify if any delays at an early stage. Made it easier to adjust the schedule and ensure that the work was completed on time, as shown in Table 1.2.

1.6 Project budget

To work the thesis within a limited budget, we made careful plans of the expenses at an early stage. A simple cost breakdown was prepared to cover the main phases of the work which included the fabrication of the antenna, the experimental measurements, collection of data, and finally the reporting of the results. The effort was to use simple, easily available materials and still achieve the technical requirements of the project.

- Antennas: The major costs were on antenna fabrication including FR4 substrate sheets, SMA connectors and PCB etching materials.
- Additional costs were plastic containers to hold liquid samples, chemical reagents (HCl and NaOH) for samples preparation for pH analysis and a digital pH meter that was used during experiments.
- Some expenses were also required for documentation purpose (printing, stationery etc. for preparation of reports and posters to submit and present them).

Overall, the proposed budget was adequate for supporting all the necessary activities without exceeding the financial constraints.

Some quite expensive equipment, the Vector Network Analyzer VNA that is available via the University laboratory. We utilized those facilities to the maximum and saved on our overall expenditure. All of the critical tasks were allocated sufficient money. Ultimately, we were able to find a balance between our needs and limited financial resources.

1.6.1 Overall budget

Table 1.3. Overall budget

No	Item	Justification	Quantity	Unit Price (BDT)	Price (BDT)	Remark
1	CST Studio Suite Software	To simulate the proposed design and analyze the outcome	1	–	–	Available in the Laboratory
2	CNC Machine	For cutting and making the antenna	1	–	–	Available in the Laboratory
3	Personal Computer	To install and run the CST Studio Suite Software	1	–	–	Available in the Laboratory
4	Vector Network Analyzer	To analyze different frequency	1	–	–	Available in the Laboratory
5	FR4 substrate	For create Antenna	1	1,000	1,000	Purchased
5	240 GB Solid State Drive	To provide extra storage space and improve overall performance of the computer, in order to harbor the large simulated data files	1	3,000	3,000	Purchased
6	Computer Accessories & Essential	To aid in conducting the computational work	1	1,200	1,200	Purchased
7	Digital pH meter and solutions	To evaluate the accuracy of our pH measurements, we will compare them with those obtained using a conventional pH meter	1	4,700	4,700	Purchased
				Total: 9,900		
In words: Nine Thousand Nine Hundred Taka Only						

The overall project budget reached approximately BDT 9,900. The sum is inclusive of all essential materials and activities performed. Major defrayments are listed, as shown in Table 1.3.

i. FR4 substrate (BDT 1,000)
ii. SMA connectors and RF cables (BDT 400)
iii. PCB fabrication chemicals (BDT 1,500)
iv. plastic containers (BDT 800)
v. pH meter and solutions (BDT 4,700)
vi. stationery and printing (BDT 1,500)

The VNA was provided by the university, which otherwise would increase equipment expenses significantly. Thus, we could limit expenses within our expectations.

1.6.2 Component

Both hardware components and software tools are used in design, fabrication, testing, and analysis for the project.

Hardware Components:

FR4 substrate board, SMA connectors, Coaxial cables, PCB etching chemicals, Plastic container, HCl and NaOH (for the range of pH from 4-12), Digital pH meter, thermometer, Vector Network Analyzer (VNA), and soldering tools.

Software Tools:

CST Studio Suite (antenna design & simulation), Python (Machine learning & Data Analysis), Excel (Data processing) and MS Word/PowerPoint (Documentation and presentation). Therefore, the entire process from antenna results to experimental validation to data driven analysis benefited from these resources.

1.7 Organization of This Report

This undergraduate thesis report consists of eight chapters. Each chapter addresses a specific component of the research work in a logical and structured manner. The organization is as follows:

Chapter 1 — Introduction

This chapter appraises the readers of the overall context of the research. Additionally, the project overview, background and motivation, objectives, and research methodology of this research paper are presented. It provides a rundown of the overall organization of the report.

Chapter 2 — Literature Review

This chapter provides the theoretical background necessary for understanding the study. We begin by reviewing previous research and existing technologies. Which are related to pH sensing and microwave antenna-based sensors. The review includes conventional electrochemical sensors as well as dielectric sensing methods. Those papers highlight their advantages and limitations. We also discuss the basic principles of microstrip patch antennas. Which show how electromagnetic fields interact with the dielectric properties of liquids.

Based on this review, we identify key research gaps. Those gaps are the lack of cost-effective, wide-range pH sensing platforms that combine microwave antennas with data-driven modeling. Addressing these gaps forms the basis of our research objectives. By relating the theoretical concepts to practical challenges in this chapter helps to guide the design and experimental approach presented in the later sections.

Chapter 3 — Theory, Design, and Simulation

This chapter describes the theoretical background and the steps to go through to design the antenna and perform the simulations in CST Studio Suite. We also explain in detail how the antenna dimensions, effective dielectric constant, and the resonant frequency were obtained from the perimeters. These parameters are significant for the simulations as well as for the later experiments.

To test the design for practical applicability we examined the results of the simulation. We focused on S_{11}, curves, changes in resonant frequency and change in bandwidth. These types of indicators helped us to check how the antenna would react to different dielectric conditions before moving on to the experimental testing. By comparing the results of the simulations and model outputs with the expected trends we could identify potential design issues in advance and modify the model accordingly.

Chapter 4 — Fabrication and Experimental Setup

The fabrication of the microstrip patch antenna with a network of FR4 substrate and conventional PCB etching methods is addressed in this chapter. FR4 was used because it is affordable, readily available and microwave frequency suitable. The experimental setup was ready after manufacture. This included placing the antenna under the liquid container, and connecting it to a Vector Network Analyzer (VNA) to make measurements.

To consider the effects of background, we obtained background measurements using only air and the empty container. Next, distilled water was tested, followed by solutions of different pH values. These steps enabled us to see how the antenna response varied as a function of the different liquids that we used, and take into account that the measurements would be reliable enough to be used for further analysis.

Chapter 5 — Data Analysis and Machine Learning Modeling

This chapter is dedicated to analyzing the experimental dataset and making it ready for machine learning. A number of regression models were used to predict the pH from antenna response parameters. These models were Random Forest, Support Vector Regression (SVR), k-Nearest Neighbors, Support Vector Regression (SVR) and k-Nearest Neighbors (kNN). We generated heatmaps, feature importance graphs, scatter plots and much other visualizations as well as performance measurements.

Chapter 6 — Results and Discussion

This chapter reveals the results from simulation and experiment. We investigated the variation of resonant frequency, S_{11} and bandwidth with varying pH and temperature. The machine learning models were compared to actual measurements of sampled pH to evaluate their accuracy compared to the predicted values. We were also able to find possible sources of error, such as temperature fluctuations, measurement noise, or sample inconsistencies, in order to understand the accuracy of the system and with the future improvement of the system.

Chapter 7 — Societal, Environmental, and Engineering Considerations

This chapter covers the larger effect of the project. We are able to highlight the usefulness of the system in monitoring the environment, sustainable agriculture, and industrial process control. The chapter also reviews some difficulties we encountered with the temperature sensitivity, material selection and data set limitations. Addressing these issues assisted in ensuring that the project fulfilled the requirements of the EEE400 course.

Chapter 8 — Conclusions and Future Work

This last chapter discusses the key achievements of the project. It also tells us about the important conclusions we have made from the research. Finally, we propose some ideas of future work. These include improving the antenna design to get more sensitivity with it, testing it with real environmental samples, connecting the system to IoT devices and also trying out the system in real field conditions.

CHAPTER 2

LITERATURE REVIEW AND METHODOLOGY

2.1 Traditional methods of pH Sensing

Accurate and efficient measurement of pH is important in many fields. For example, environmental controls, agriculture, Industrial processes control and water treatment all require reliable PH measurement. Here, traditional pH sensors will often employ electrochemical techniques including glass electrodes or ion sensitive field effect transistors (ISFETs). These sensors are used to measure the potential difference between a reference electrode and a sensing electrode in order to calculate the hydrogen ion concentration in a solution [9]. Those conventional systems are usually accurate and give standardized results. However, they also have some practical limitations. First, they often work in a small pH range, so very acidic or very alkaline solutions cannot be measured reliably. Secondly, glass electrodes and ISFET meters need regular calibration; otherwise, their accuracy decreases over time.

This process consumes time and is difficult to achieve in real-world applications. Thirdly, electrodes themselves are prone to be contaminated in the industrial atmosphere and natural water sources. Additionally, fragility of the glass electrodes often incurs sudden extra expense. Altogether, engineers often have to trouble themselves with maintenance when conventional methods are used. Because of these limitations, technologies that can compensate for those shortcomings are in great demand lately. The newer systems need to be low-maintenance, cost-effective, and capable of operating properly in a variety of situations [10].

2.2 Microwave Sensing and Antenna-Based Sensors

Recent advances in microwave sensing technologies have opened new possibilities for non-invasive, wide-ranging, and low-maintenance pH measurement. The electromagnetic fields and the dielectric properties of the material interact with each other, and, under test conditions, microwave sensors exploit this interaction to accurately estimate. The changes of pH in a solution also cause a commensurate variation in dielectric constant and loss tangent, which, in turn, enacts measurable shifts in the resonant frequency and return loss (S_{11}) of the sensor [15].

Though there is a plethora of different microwave sensor types, microstrip patch antennas have stood out due to their compact size, cost-effective fabrication, ease of integration with measurement systems and high sensitivity to dielectric variations. A liquid sample being placed in proximity to the antenna, the effective permittivity around the patch changes. The antenna then detects variations in traits like resonant frequency, bandwidth and reflection coefficient. This is immensely useful in situations where physical contact is not possible. When dielectric characterization of liquids, including pH measurement, need to be detected, these traits make patch antennas a feasible alternative to other methods [11].

Several studies highlight the potential of antenna-based microwave sensors for pH sensing. Building on this idea, Islam *et al*. (2018) improved sensitivity by using an ultrawideband hexagonal split-ring resonator antenna for pH measurement [12]. Two HSRRs are connected with a strip line and a split on one of the HSRR is added to increase the electrical length and coupling effect. The presented UWB antenna consists of three-unit cells on the top on the radiating patch element. This combination of UWB antenna and HSRR give double negative characteristics increase the sensitivity of UWB antenna for pH sensor. The operating frequency of this antenna sensor comes to bandwidth of 17 GHz that starts from 3 up to 20 GHz with realized gain of 3.88 dB. The design is very complicated with the three unite cell on top of radiating patch maintenance of the sensor become difficult and would prove to be costly to fabricate and implement. Microstrip patch antenna aims to streamline production while maintaining practicality. The simple design aligns with the goal of an efficient, cost-effective sensor for practical use.

Shoaib *et al.* (2023) successfully shows good initial results in simulation, also showing sensitivity of microstrip patch antenna to water pH (6.5–9.0) [27]. In this paper used Rogers RT/Duroid 5870 substrate having dielectric constant of 2.33 which is applicable for high frequency broadband operations. They incorporated double inset fed varying the dimensions in the range of the width 0.1 to 1.0 mm & length 0.05, 0.1, 0.3 and 0.5 mm respectively. This paper has got return loss close to -60dB, VSWR close to 1 and bandwidth as 4. 65GHz.Their limitation are narrow pH range, very small frequency shifts, FR4 dielectric losses, and lack of experimental validation. Extend pH range, optimize antenna design, use low-loss substrates, fabricate and test experimentally, improve packaging, and apply advanced signal processing for better accuracy.

Bouchalkha *et al*. (2019) investigated reconfigurable slot antennas that could be tuned for more advanced pH measurements [27]. The paper successfully develops and tests a planar microstrip antenna sensor for pH monitoring using RF signals, makes practical pH monitoring applications. The sensor had good frequency shift of between 180 MHz and lowest acidic solution of pH value 3 and the highest basic solution of pH value of 10. The measured frequency shift as a function of pH values showed good second order polynomial fit with a fitting factor of 92.16 %. This paper has no information provided on its performance outside the specified range. Enhance the sensor's design to accommodate an expanded pH range for increased versatility and implement modifications to ensure scalability for larger monitoring systems.

Microwave antenna-based sensors evince a number of advantages when compared to conventional pH probes:

1. **Wider measurement range:** Health of the measurement: Suitable for strongly acids and alkaline solutions.
2. **non-contact operation:** decreasing the possibility of contaminations and maintenance.
3. **Compatibility with wireless/IoT systems:** allows the systems to monitor in real-time.
4. **Low fabrication cost:** utilizing the standard techniques for fabricating PCB.

2.3 Identified Research Limitation and Project Contribution

The reviewed literature has shown a strong potential for microwave antenna-based sensors for liquid characterization and pH measurement. At the same time, there are a number of challenges that require further attention:

- Earlier study shows report of inconsistent performance when testing with different liquid samples. This indicates that antenna geometry plays an important role and sensitivity may be improved with proper design optimization [17].
- FR4 is so popular for its low cost. It can present substrate losses that affect the quality of the antenna and also decreases the difference in the detection accuracy [18].
- Another important issue is the impact of environmental conditions. In particular, temperature variations can change the dielectric properties of liquids and responses of the sensor. This impacts on the reliability of a measurement [19].

- The relation between antenna parameters such as the resonant frequency, bandwidth, the return loss and pH is often nonlinear. As a result, advanced data modeling and machine learning techniques are required to accurately model antenna responses in terms of pH values [20].

To solve those gaps and limitations. The following steps are taken:

- Making and designing of rectangular microstrip patch antenna.
- Experimenting the antenna response across pH 4–12 at changing temperatures (20 °C–30 °C).
- Collecting a dataset of resonant frequency, return loss, and bandwidth for different pH values.
- Applying machine learning algorithms (Random Forest Regression) to build predictive models to estimate pH from the collected set of data.
- Among Random Forest achieved the highest accuracy with R^2 values exceeding 0.85, demonstrating strong predictive reliability

This approach represents a combination of microwave sensing at a low cost with data-driven modeling to produce a complete solution. It is a reasonable advance towards pH monitoring systems that is scalable. This experiment can be used in case of environmental monitoring, agriculture and industrial uses.

CHAPTER 3

DESIGN OF THE MICROSTRIP PATCH ANTENNA

3.1 Proposed System

The proposed system is used for measuring the pH of liquid solution. It works by observing the change in the electrical response of a microstrip patch antenna, as caused by the surrounding medium changes. When we placed liquid sample with specific pH on the antenna, the dielectric properties around the antenna has changed. For this reason, the antenna exhibits appreciable changes in resonant frequency, return loss (S_{11}) and bandwidth. These changes are stored with a Vector Network Analyzer (VNA) and subsequently analyzed to determine the pH of the solution [21].

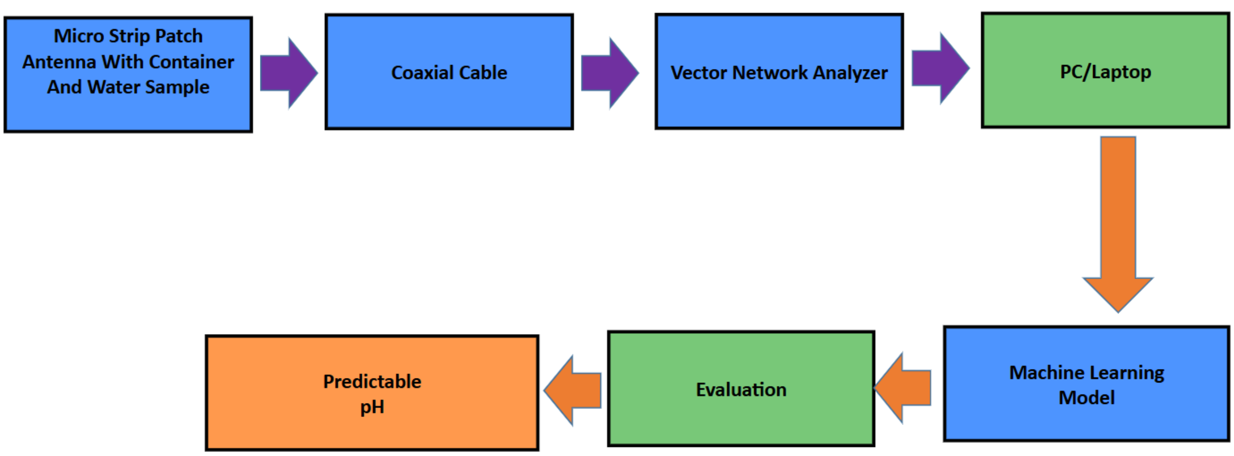


Fig. 3.1. Proposed System of microstrip patch Antenna

In Fig 3.1 shown in how can detect pH in patch Antenna The data from the antenna are then analyzed to understand how they relate to the pH value of the liquid. In this system:

- The antenna is used as the main sensor.
- The plastic container contains the water then the solution samples.

- S_{11} response is measured by the VNA for every sample.
- Machine learning models are fed with the collected data. Those data used to analyze to predict pH accurately.

This method provides a low cost and non-invasive method of measuring pH over a broad range. While also decreasing the common problems of calibration and maintenance of traditional electrochemical sensors. [22].

3.2 Design Requirements

The design requirements were carefully specified. The dichotomy between the efficacy of antenna operation as a sensing element, and cost-efficiency and ease of fabrication was treated conscientiously. The following are the primary design requirements:

- Operating Frequency: The operating frequency of our antenna is of about 2.2GHz. In this range out antenna give a good balance between compact antenna size and sensitivity to change in dielectrics.
- Substrate Material: The substrate martial we selected the FR4 epoxy with relative permittivity (εr) = 4.3 and thickness (h) = 1.6mm. This material is selected because it is available and low cost.
- Antenna Geometry: A rectangular patch was chosen due to the advantages which it has simple structure, well-known design equations and stable performance.
- Feed Type: Coaxial Cable feeding to get good impedance matching At least fabrication complexity.
- S_{11}, Response: Minimum return loss of -10 dB at resonance Also target of less than -20 dB to good matching.
- Size: Being compact in size, the antenna can be placed easily under a plastic container without causing any major disturbance to the electromagnetic field distribution.

Meeting these requirements is important. Strict compliance ensures reliable detection of dielectric changes caused by issues formed of solutions with different pH values. This allows the system to deliver proper operation within a desired measurement.

3.3 Theory and Mathematical Design

The antenna was designed using the transmission-line model for rectangular microstrip patch antennas. The design equations were used to calculate the patch dimensions for the target resonant frequency (f_r) of approximately 2.2 GHz**.**

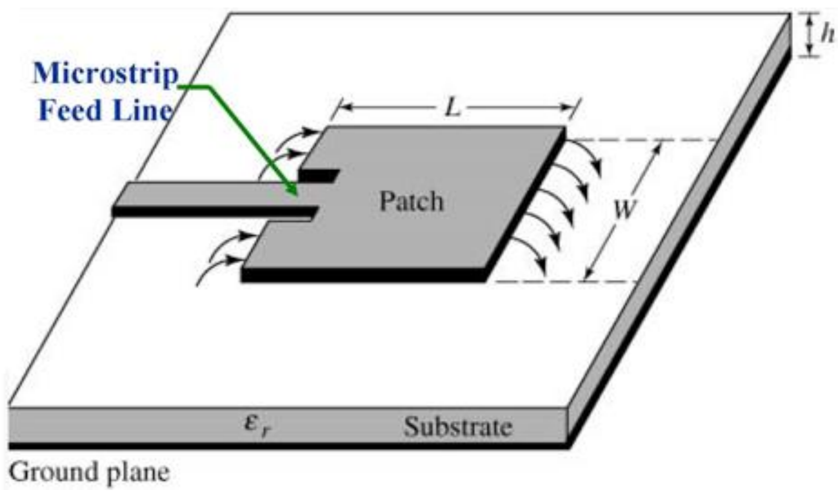


Fig. 3.2. Design of Microstrip Patch Antenna.

Key parameters and formulas used, where fr = is the resonant frequency of the antenna, C = is the speed of light and εr is the dielectric constant, as shown in Fig 3.2

Width of Patch (W):

The width of the patch is given by [23]:

$$W = (c / 2fr) * sqrt (2 / (\varepsilon r + 1)) \quad (3.1)$$

where c= the speed of light, fr = the resonant frequency, and εr = the dielectric constant of the substrate.

Effective Dielectric Constant (εeff):

Due to fringing fields, the effective dielectric constant is expressed as [24].

$$\varepsilon eff = (\varepsilon r + 1)/2 + (\varepsilon r - 1)/2 * (1 + 12h/W) \wedge (-1/2) \quad (3.2)$$

where h = the thickness of the substrate, W= width of patch, εr = the dielectric constant of the substrate

Effective Length (Leff):

The effective length of the patch corresponding to the resonant frequency is calculated as [25].

$$Leff = c / (2fr * \mathrm{sqrt}(\varepsilon eff)) \tag{3.3}$$

where c= the speed of light, fr = the resonant frequency, εeff = effective dielectric constant

Length Extension (ΔL):

The length extension due to fringing fields is given by [26].

$$\Delta L = 0.412h * ((\varepsilon eff + 0.3) (W/h + 0.264)) / ((\varepsilon eff - 0.258) (W/h + 0.8)) \tag{3.4}$$

where h = the thickness of the substrate, W= width of patch, εeff = effective dielectric constant

Actual Length of Patch (L):

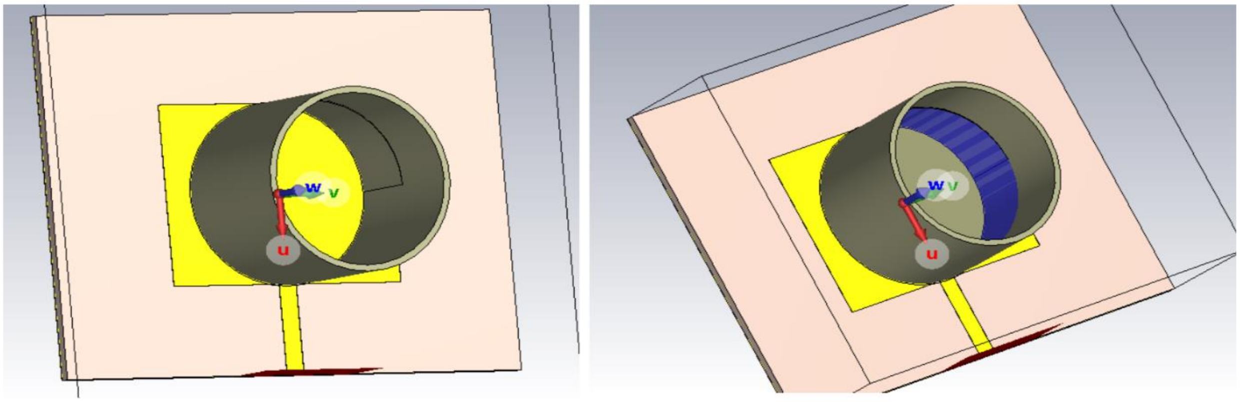
The actual physical length of the patch is obtained by [27].

$$L = Leff - 2\Delta L \tag{3.5}$$

where Leff = effective length, ΔL = length extension

3.4 3D Design

CST Studio Suite was used to model the antenna utilizing the calculated patch dimensions and feeding configuration. In Fig 3.3 shows the 3D view of the final antenna model, where a plastic cylindrical container is positioned on top of the rectangular copper patch. Experimental sensing configuration is accurately portrayed in the setup. Also, Liquid samples of different pH values are placed inside the container. The antenna is mounted on an FR4 substrate. A separate coaxial probe feed extends through the ground plane. The container and the water volume were designed as dielectric cylinders that facilitated analysis of their impact on the electromagnetic fields and resonant properties.



(a) (b)

Fig. 3.3. 3D model construction of the patch antenna (a) without water and (b) with water

Thus, a proper evaluation of frequency shifts, return loss variations, and field distribution under different sensing conditions could be performed via this realistic 3D modeling.

3.5 Design parameter

Table 3.1. Dimensional Parameter of the Designed Patch Antenna

Name	Expression	Value(mm)
SL	80	80
SW	84	84
SH	1.5	1.5
Mt	0.035	0.035
PL	34.2	34.2
PW	51	51
ML	23.9	23.9
MW	2.98	2.98
InL	9	9
InW	0.74	0.74
k	5.62	5.62

The design parameters and physical dimensions for a microstrip patch antenna (in mm) as shown in Table 3.1.

CHAPTER 4

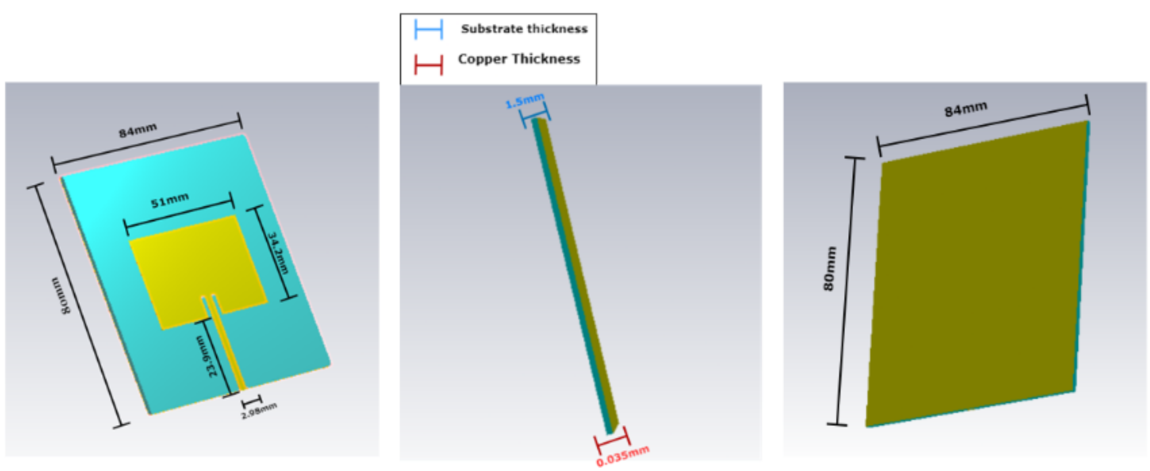
PROJECT IMPLEMENTATION

4.1 Overview

We finalized and validated the antenna design through CST simulations. The next step forward was the physical fabrication process and the development of a controlled experimental setup. Our goal was to attain parallel performance. With that goal in mind, the fabrication process aimed to reproduce the simulated design as accurately as possible. We mainly concerned ourselves with the task that the design should focus with accurate collection of S_{11}, resonant frequency, and bandwidth data for different solutions. This chapter presents the step-by-step fabrication procedure with details of the experimental setup used for the measurement campaign.

4.2 Design Simulation

After the completion of the initial step of 3D modeling, frequency-domain simulations were carried out in CST Studio Suite that investigated the antennas' electromagnetic performance and validated the mathematical design.



(a) (b) (c)

Fig. 4.1. 3D modeling of the microstrip patch antenna at CST Studio (a)Front view (b)Side view (c)Back view

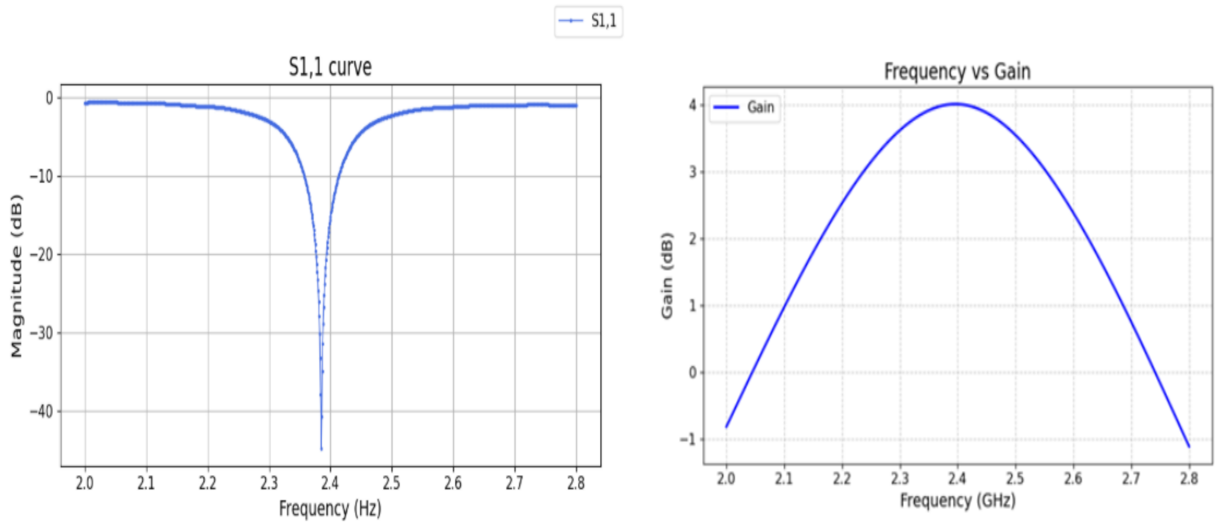
The frequency range was bounded between 1-3 GHz, which also covered the targeted resonant frequency of approximately 2.2 GHz. The primary goal of the S_{11} parameter (return loss) simulation was to examine the antenna's impedance matching characteristics. It was observed that a clear resonance subsisted near 2.2 GHz, with a minimum S_{11} of below −20 dB. Thus, it suggests excellent impedance matching between the antenna and the feed line. The bandwidth was determined at the −10 dB reference level. Additionally, the simulated value satisfied the criteria for sensitive dielectric detection, as shown in Fig 4.1.

Evaluation of the antenna's sensing capabilities appropriate for simulations that were performed with a cylindrical container and different dielectric materials placed on top of the patch. It represented distilled water and various pH solutions [13]. When we introduce the dielectric samples, the resonant frequency level moved to lower frequencies and also the return loss curve changed in magnitude and shape. This result supports the observation that the antenna response is strongly affected. The changes in the effective permittivity of the material placed above the patch. This behavior forms the basic working principle of the proposed microwave pH sensing system [23].

Since maintaining stable performance is essential for reliable operation the radiation characteristics of the antenna were also analyzed. The simulated gain results show broadside radiation with consistent directivity indicating stable antenna behavior over the operating conditions [14]. Therefore, it confirms that the antenna sustains its expected radiation characteristics even in the presence of a sensing container.

4.3 Simulation Results

With the objective of analyzing electromagnetic performance before the fabrication process, the proposed rectangular microstrip patch antenna was simulated using CST Studio Suite to analyze. To cover the targeted operating frequency band, the simulation was performed over a frequency range of 2.0 GHz to 2.8 GHz.



(a) (b)

Fig 4.2. The simulated curve (a) S_{11} (b) gain vs frequency

The simulated S_{11} curve the graph showed deep resonance drop and the minimum S_{11} value reaches around −42dB.Additionally shows the gain vs. frequency plot the peak gains approximately 4 dB at the resonant frequency.

The simulation resulted in excellent impedance matching between the antenna and the feed line. Our decision to continue with the given dimensions was thus justified. The test also ensured the feed point location for the desired frequency band.

The gain curve is in line with the typical behavior of a patch antenna. The typical behavior stipulates steady rising toward resonance and decreases afterward in a smooth parabolic shape, as shown in Fig 4.2

Via these simulation results, it can be verified that the antenna design fulfills performance prerequisites in terms of return loss, operating frequency, and radiation gain, making it well-suited for pH sensing applications. Thus, the sharp resonance and stable gain behavior indicate that, at liquid samples' introduction into the system, the antenna could be assumed to respond sensitively to variations in the dielectric environment.

4.4 Antenna Fabrication

(a) (b)

Fig 4.3. Fabricated assembled patch antenna (a) upward side and (b) downward side

The rectangular microstrip patch antenna was fabricated on an FR4 copper-clad PCB sheet with a thickness of 1.6 mm and relative dielectric constant of $\varepsilon_r \approx 4.3$. The fabrication steps were as follows in Fig 4.3:

1. **PCB Cutting**

   The FR4 board was cut to the calculated substrate dimensions to match the simulated antenna layout. Edges were meticulously smoothed out to avoid unwanted fringing effects.

2. **Pattern Transfer**

   The rectangular patch design was printed on a transparent sheet and transferred onto the copper surface of the PCB using a thermal method. This ensured accurate transfer of dimensions for the patch geometry.

3. **Etching**

   The surfeit copper areas were pruned using a PCB etching solution (ferric chloride). The rectangular patch on the top surface and the full ground plane on the bottom side were divulged through the etching process.

4. **Drilling and Feed Insertion**

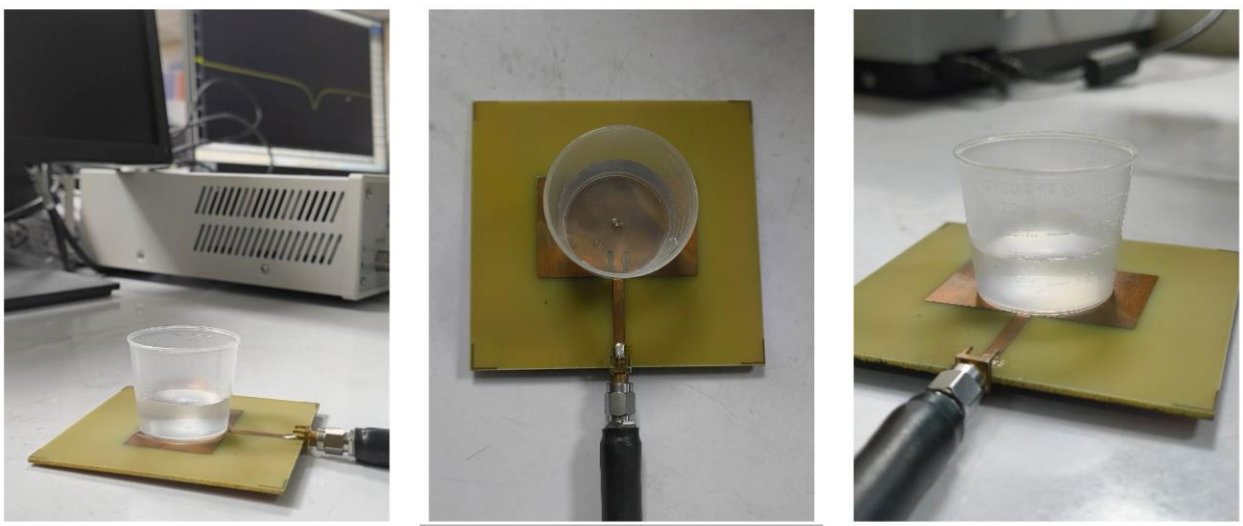
   A coaxial probe feed - at a location determined during simulation - was inserted through the substrate. The inner conductor was soldered to the patch, whereas the outer conductor was connected to the ground plane.

5. **Soldering and Finishing**

   In order to obtain minimal signal loss, SMA connectors were soldered with care. For optimized results, the antenna edges were scrubbed, and surface oxidation was removed.

The dimensional and geometric verisimilitude with the simulated design persisted in the fabricated antenna. Minimal discrepancies between simulated and measured results were ensured through dimensional accuracy.

4.5 Experimental Setup



(a) (b) (c)

Fig. 4.4 Practical measurement setup showing the VNA, coaxial connection, and container placement (a)Side view (b) Top view (c) Close view

The goal of the experimental setup was to observe and measure the antenna response to liquids with different pH values using a Vector Network Analyzer (VNA). The key components of the setup, as shown in Fig 4.4

- Fabricated microstrip patch antenna
- Plastic cylindrical container for holding liquid samples
- pH solutions (pH 4–12) prepared using hydrochloric acid (HCl), sodium hydroxide (NaOH), and distilled water
- Vector Network Analyzer (VNA) for S_{11} measurement
- Coaxial cables and SMA connectors for connection between antenna and VNA
- Thermometer and pH measuring instrument for recording the temperature pH of each sample

The preparatory phase consisted of the placement of a plastic container directly above the patch antenna so that it mimics the CST simulation environment and filling out of that container with a fixed volume of 10 mL of each solution [19]. The ambience temperature was regulated within the range of 20°C–30°C range during measurements in order to observe the effects of temperature systematically. Before each measurement, the vector network analyzer (VNA) was properly calibrated to provide accurate results.

The reflection coefficient (S_{11}) was then measured across a frequency range of 1 - 3 GHz. For each pH solution important parameters including the resonant frequency, minimum return loss and operating bandwidth were extracted and documented.

4.6 Measurement Procedure

(a) (b)

Fig. 4.5. Measurement setup to confirm repeatability (a) pH meter and solution (b) with VNA

Experimental setup using pH meter and solution Experimental setup using VNA. Cross contamination was avoided by washing down the set up well between successive tests as demonstrated as shown in Fig 4.5. A structured sequence was created and immaculately followed in order to ensure consistency between all pH measurements:

1. **Baseline Measurement**

   At the beginning we know base line antenna characteristics and measurements. Those were conducted for air (no container) and container only conditions.

2. **Distilled Water Measurement**

   a) We mix 10mL of distilled water into the container

   b) Record VNA trace

   c) Mark the liquid for reference liquid for later measurements.

4.6.1 pH Solution Measurement

Solutions with pH values from **pH 4 to pH 12** were used. Controlled mixture of HCl and NaOH were prepared for. For each pH value:

1.The temperature of the solution was recorded.

2. A total of 10 mL of solution was taken and filled into the container.

3. The S_{11} trace was recorded also the resonant frequency and bandwidth were noted

4.6.2 Repetition and Validation

Consistency and repeatability were important considerations to keep in mind during the experimental process. To check this each measurement was carried out twice. Before moving on to a different test the containers were well rinsed in distilled water. This procedure helped to reduce the risk of cross-contamination and allowed reliable and repeatable data to be obtained to be used in the subsequent machine learning analysis.

In this chapter, the patch antenna fabrication and the experimental setup were introduced. The fabricated antenna was in close agreement with the simulated antenna, and the measuring setup. This ensured precise extraction and sorting of resonant frequency and return loss data from the pH solutions.

4.7 Dataset Preparation

The effectiveness of the proposed system is based on how well the pH value can be forecast. To support these three antenna-based parameters was obtained from the measurements, which are: resonant frequency (GHz), return loss (S_{11} in dB) and bandwidth (GHz). These parameters were then used as an input feature for various machine learning regression models which were implemented and compared in terms of performance. The models were trained with experimental data that were obtained from the antenna under various pH levels between 4 and 12 and at temperatures between 20°C–30°C.

The main objective was to form a data-driven relationship between the response of the antenna and the pH of the solution. It enables us to pH estimation without having to take direct chemical sensing. All the models have been created using python's scikit-learn libraries. Prior to training, the raw VNA measurement data were carefully analyzed to be reliable. Any duplicate readings, or abnormal readings, were identified and removed from the data set.

The input features were resonant frequency (Marker 3 frequency), return loss (S_{11}), bandwidth (in the -10 dB range), and temperature (in degrees Celsius). The corresponding pH value was taken as target output. Finally, the dataset was normalized and divided into training and testing data with 80% of data allocated for training and 20% data allocated for testing.

4.8 Applied Machine Learning Algorithms

To test the predictive performance, we chose to test three supervised regression algorithms [24].

4.8.1 Random Forest Regression (RFR)

Random Forest Regression, which makes use of multiple decision trees in order to mitigate variance and enhance generalization. During the testing of this model had shown the consistent and accurate performance among all the algorithms considered with more parameters. The value of the coefficient of determination R^2 was found 0.85. These results show that there is a good correlation between the antenna response and the pH value. In addition, the model gave us a good ranking of the importance of features. Among all input parameters, the resonant frequency showed to be the major determining factor for pH estimation.

4.8.2 K-Nearest Neighbours (kNN)

K-Nearest Neighbors (KNN) is a supervised machine learning algorithm that is used for both regression and classification. The algorithm estimates what the output of a new data point is going to be based on the k nearest data points (neighbors) by identifying the k nearest data points (neighbors) from the training dataset based on some definition of a distance metric. In regression problems, the predicted value is often computed as the average or distance-weighted average of the target values of the nearest neighbors.KNN is a non-parametric and instance-based algorithm, that is, without an explicit training phase and without assuming anything about the distribution of data.

4.8.3 Support Vector Regression (SVR)

Support vector regression (SVR) is a kind of supervised learning model based on Support Vector Machines, which is frequently used to solve non-linear regression problems. In this work, SVR uses Radial Basis Function kernel to successfully model nonlinearity between antenna response parameter and pH values. The RBF kernel is used to map input data into a higher dimension for the model to learn complex data responses that could not be represented by linear functions. The performance of SVR is quite dependent upon hyperparameters such as regularization parameter (C), width of the kernel (gamma) and epsilon insensitive loss function, and proper scaling of features. The results show that SVR is sensitive to data scaling and dataset size which can be explained by the somewhat low diversity and number of samples.

4.9 Model Evaluation Metrics

The assessment format was based on the evaluation of several statistical indicators [25].

- R^2 (Coefficient of Determination) -Helps to measures how well predictions are matched with true values.
- MSE (Mean Squared Error)- It helps with penalizes large errors by taking squares of deviations
- RMSE (Root Mean Squared Error) - It can be in terms of error of original units.
- MAE (Mean Absolute Error) - It can get mean prediction deviation.

We ensured that the values were compared fairly so that the evaluation was fair.

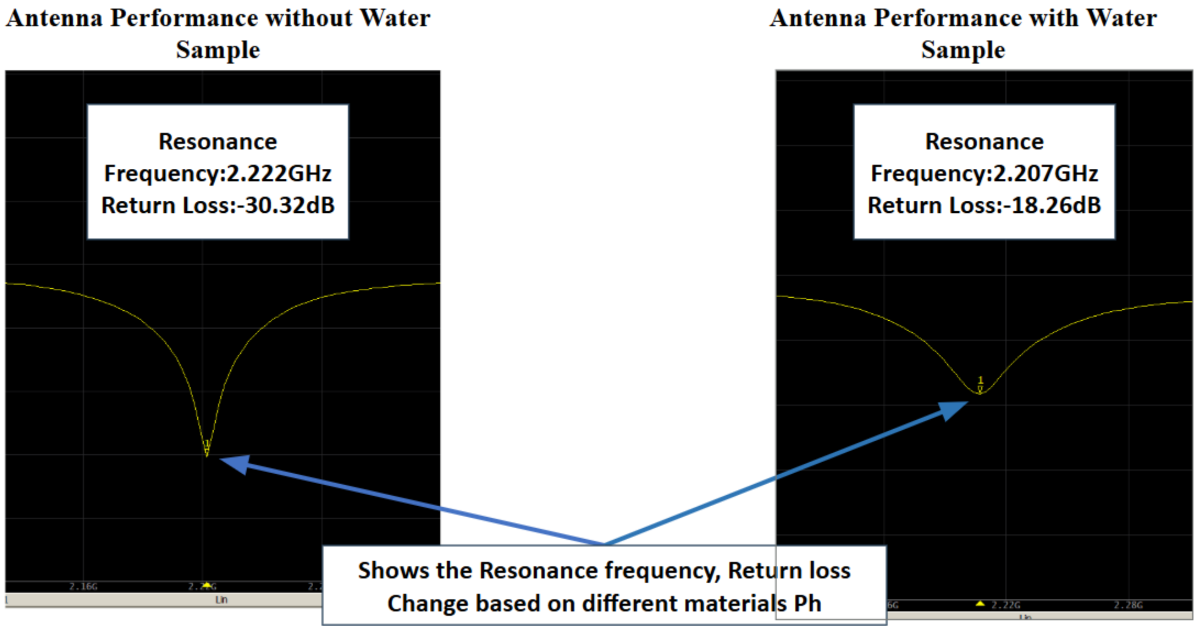
CHAPTER 5

INVESTIGATION, RESULTS AND DISCUSSION

5.1 Experimental Results

To test the fabricated antenna a Vector Network Analyzer was used to evaluate the performance of the antenna with and without water and observe the response of the antenna to different pH solutions. All measurements were conducted under a controlled environment in a laboratory. For each test 10 mL of the sample of the liquid specimen was placed in the said container above the antenna.

5.2 Baseline and Water Measurements



(a) (b)

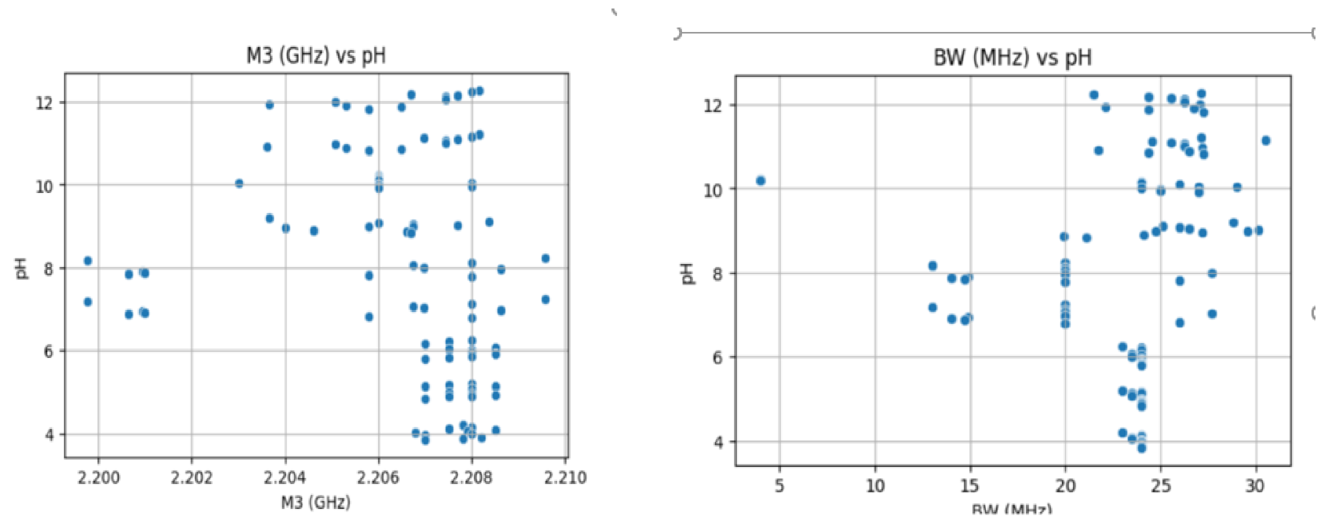
Fig. 5.1. Compares the antenna’s frequency response under two conditions(a) Without water sample (b) With distilled water sample

Without water sample (air + container) Resonant frequency was measured to 2.22 GHz with return loss of -30.32 dB. Strong impedance matching was shown. With distilled water sample - The resonant frequency changed to 2.207 GHz and return loss decreased to -18.26 dB as shown in Fig 5.1

This reduction of frequency to the lower values can be explained because water has much higher dielectric constant than air. As a result, it raises the effective permittivity around the patch lowering the resonance. This confirms the sensitivity of the antenna to changes of the medium surrounding the antenna.

5.3 pH-Dependent Frequency and Bandwidth Variation

Measurements were conducted for pH 4-12 solution, each of which are poured into the container while maintaining a constant volume of 10 mL. For each solution, the resonant frequency (M3) and the - 10dB bandwidth were measured.



(a) (b)

Fig. 5.2. Scatter plots (a) frequency vs pH and(b) bandwidth vs pH

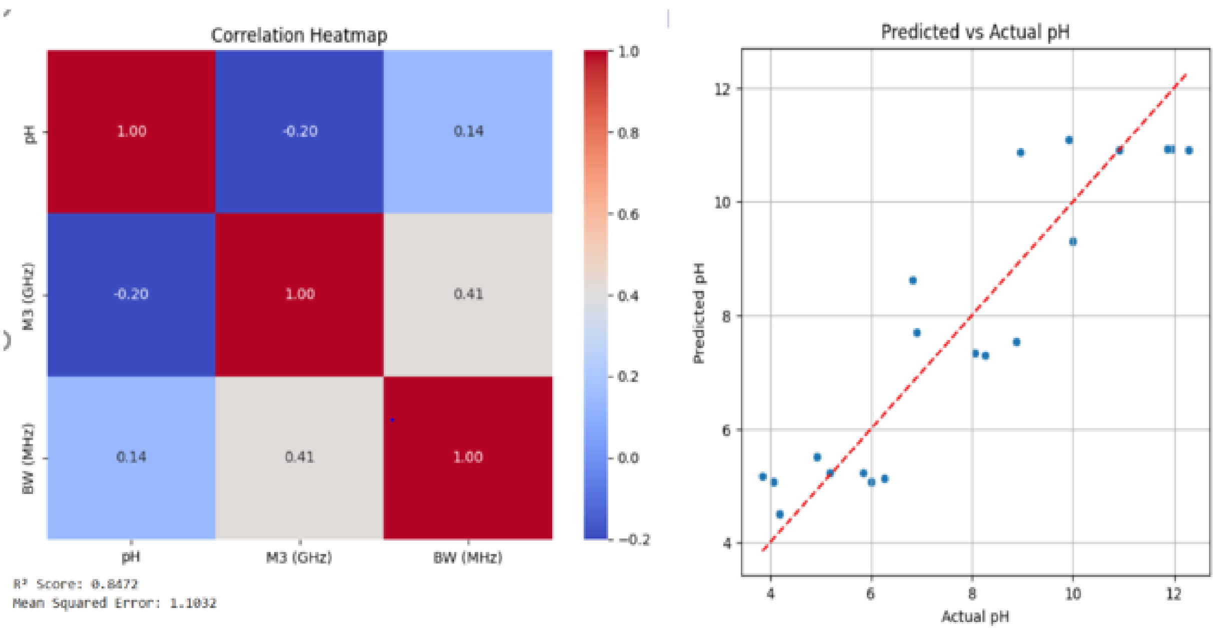
An increase pH level causes a systematic decrease of resonant frequency, especially in highly acid and alkaline areas. Bandwidth values are also found to vary with pH corresponding to the impact of dielectric loss and mismatch on the liquid composition.

In Fig 5.2 shown in scatter plots of M3 frequency vs. pH and bandwidth **vs.** pH at a constant temperature (26 °C) are depicted. The plots clearly show that:

The antenna’s ability to clearly demarcate different pH levels electromagnetically, which form the foundation for machine learning modeling, is demonstrated.

5.4 Machine Learning Data Exploration

The generated correlation heatmaps and predicted vs. actual plots for machine learning regression models had a helping hand in further analysis of the experimental data [26].



(a) (b)

Fig. 5.3. Random Forest Regression (a)Heatmap and (b)Predicted vs Actual pH

An inverse correlation between pH and resonant frequency is represented in the heatmap. Meanwhile It also shows bandwidth has a weaker but positive correlation. These relationships were used as an input feature for the model to learn. The Predicted vs. Actual pH plot contains the performance of the Random Forest model. Most data points closely located on or near with the y = x line, show a good prediction accuracy, as shown in Fig 5.3

5.5 Model Performance Comparison

The performance of three machine learning algorithms, namely Random Forest, SVR, and kNN were compared with R^2, MSE, RMSE, and MAE.

In Fig 5.3 presents the performance comparison plots. Out of the algorithms, Random Forest performed the highest coefficient of determination, R^2 thermally approached to 0.85, and the lowest number of errors, in this case, Random Forest surpassed both SVR and kNN. Evidently nonlinear relationships resulted in SVR struggling and kNN was moderately accurate and higher variance.

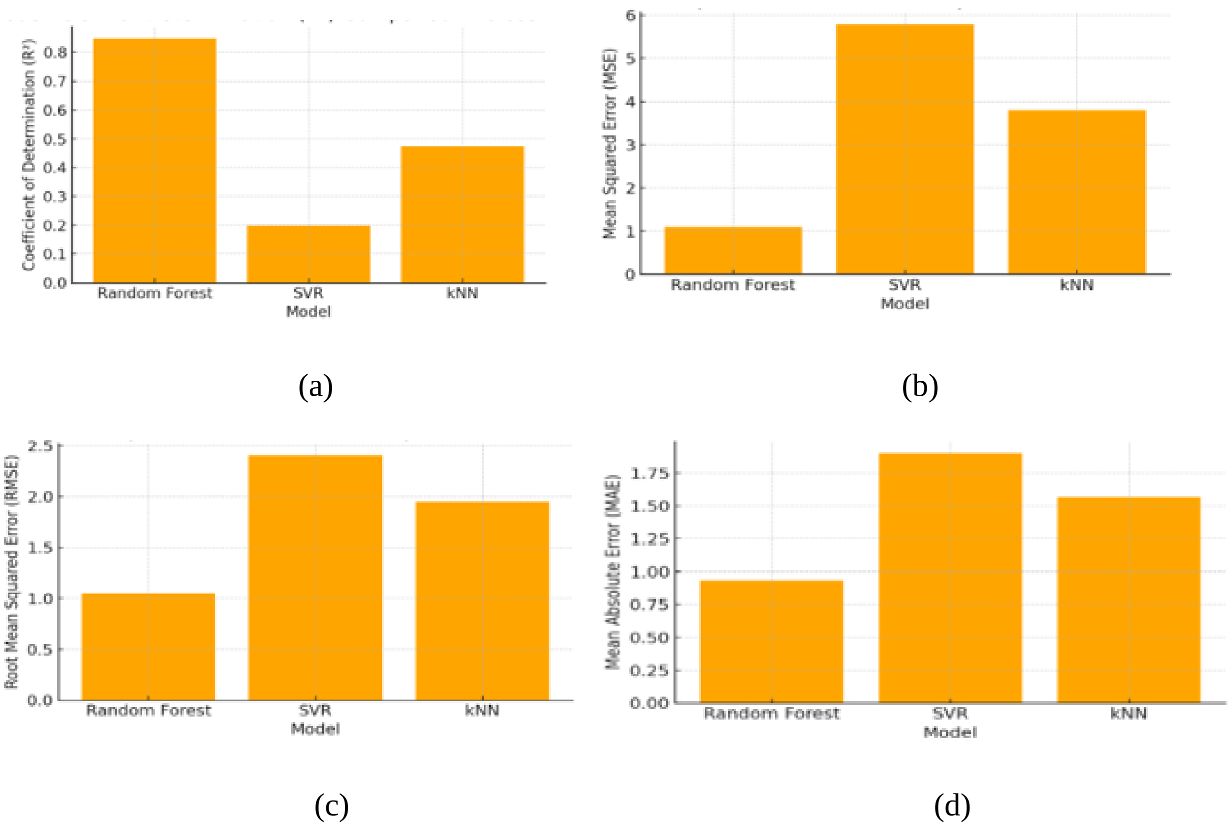


Fig. 5.4 The performance of three machine learning algorithms—Random Forest, SVR, and kNN(a) R^2 (b) MSE) (c) RMSE (d) MAE

This bar chart is a comparison between Random Forest has the highest R^2 and performs the best. kNN has a medium performance and SVR has the lowest R^2 and weaker predictive accuracy as shown in Fig 5.4

The Mean Squared Error (MSE) of three models is contrasted in this bar chart. Of the three, Random Forest performs the best with the lowest MSE, kNN exhibits significant inaccuracy, and SVR performs the worst with the greatest MSE.

Three models' Root Mean Squared Errors (RMSE) are contrasted in this bar graphs exhibits the largest RMSE, signifying the poorest performance, Random Forest has the lowest RMSE it means best accuracy, and kNN has a moderate error.

Three models' Mean Absolute Errors (MAE) are contrasted in this bar chart. SVR has the highest MAE, signifying the least accurate model, Random Forest has the lowest MAE it means best performance, and kNN exhibits intermediate error.

5.6 Result Comparison

A comprehensive comparison between simulation and experimental results was performed so that the antenna design could be validated and the accuracy of the CST model relative to the fabricated prototype could be assessed. The parameters that were deemed critical for comparison were resonant frequency, return loss (S_{11}), bandwidth, and overall response trends.

Table 5.1: Three Comparison of simulation and experimental antenna performance.

Parameter	**Simulation**	**Experimental**
Resonant Frequency (Baseline – Air)	2.40 GHz	2.22 GHz
Minimum Return Loss (S_{11})	42 dB	30.32 dB
Peak Gain	4 dB	(Not measured directly)
Bandwidth (−10 dB)	120 MHz	115 MHz
Frequency Shift (Water)	Clear downward shift around 2.4 GHz	Shift from 2.22 GHz to 2.20 GHz
Overall Trend	Sharp resonance, clean gain curve	Similar frequency behavior, slight loss difference

The results show a close convergence between the simulation and experimental measurements and Bandwidths exhibit consistent quality, as shown in Table 5.1

- The difference in the baseline resonant frequency is around 178MHz. This is considered to be acceptable for two reasons: the tolerances of fabrication and the variance of the actual dielectric constant of FR4 vs ideal for CST.
- Connector losses, and soldering imperfections and noise measurement may have met such worse results slightly.
- The minimum return loss (-30.32 dB) in the experiments is slightly greater than the simulated (-42 dB).
- The bandwidths are seen to be in good consistence with small deviations caused by practical measurement conditions.
- The presence of water results in a decrease in frequency, demonstrating that he dielectric sensing principle was operating as expected for both simulation and measurements.
- Radiation pattern and gain was stable in simulation. Though gain was not directly measured in experiments. The antenna maintained stable resonance curves which were suggestive of proper operation.

Overall results of the experiments were in good agreement with the simulated models of the antenna. Small differences were observed, and these can be expected because of fabrication tolerances as well as surrounding environmental conditions. A similar pattern was observed for frequency response and return loss trends in both cases. This agreement validates the idea of the antenna fabricated in accordance with the proposed design and functioning in a reliable manner in practical sensing conditions.

Table 5.2 Comparison between different machine learning models.

Model	Coefficient of Determination (R^2)	Mean Squared Error (MSE)	Root Mean Squared Error (RMSE)	Mean Absolute Error (MAE)
Random Forest	0.85	1.10	1.05	0.93
SVR	0.19	5.78	2.40	1.89
kNN	0.47	3.80	1.94	1.56

Comparison between the different machine learning model and Random Forest produced best prediction results for their parameter as shown in Table 5.2

Among all models best predictive results were obtained with Random Forest, algorithms. Therefore, this algorithm is suitable to be used for correlating nonlinear relationships between the antenna electromagnetic response and pH level. As traditional analytical models proved inadequate in their ability to accurately map the complex nonlinear relationship between dielectric properties and electromagnetic resonance, the analysis supported the thesis of vast and improved interpretability as well as prediction power of microwave-based sensing systems using machine learning. The system uses the ensemble-based learning paradigm and delivers reliable and repeatable operation when estimating the pH from the measurements from the antenna. In brief, it proves the power of combining microwave sensing the laws of data.

CHAPTER 6
SOCIO-ECONOMIC IMPACT AND SUSTAINABILITY

6.1 Impact of the project on societal, health, safety, legal and cultural issues

Unlike electrochemical pH the proposed microstrip patch antenna-based sensing system does not suffer several known limitations. At the same time, the system has a strong potential for real world use. Water quality has a direct effect on agriculture, aquaculture and public health. This makes proper and scalable pH monitoring a must. The proposed approach is applicable to support the rural and industrial applications. It may be particularly useful in developing nations, like Bangladesh. By decreasing reliance on expensive electrochemical study, the system gives a less expensive option for long term pH study. Clear economic benefits are also afforded by the system. Conventional pH electrodes need regular calibration process and replacements. This increases the cost and maintenance work in practical use. In contrast, the proposed sensor is based on low-cost fabrication of PCB. The FR4 substrate was enough to ensure the design. Large FR4 sheets could be bought locally starting from about 900 to 1000 taka. As a result, the costs of the overall production and maintenance are lower. This makes the system suitable for small scale applications such as farming, educational use and local water monitoring. It may also help out with strengthening the local manufacturing and reduce dependency on imports devices.

From a technical point of view the design of the antenna was successfully reduced in size. The system also had good measurement accuracy in various environmental conditions. These results show that development of the approach is suitable. The fusion of the microstrip antennas with machine learning methods also brings some researches in value. It gives some new opportunities for pH sensing estimation in academic and industrial applications.

At the societal level its continuous monitoring ability for soil and water pH can bring long term benefits. Farmers can be more effective in controlling fertilizer use. This prevents the soil from being degraded and enhances the yield of the crop. Fish farmers may be able to monitor pond conditions to keep an aquatic environment healthy. Local communities may also use such systems to carry out environmental monitoring. In this way the proposed work supports sustainability, public health awareness, and practical scientific education.

6.2 Impact of project on the environment and sustainability

Due to the adverse effects of climate change modern engineering solutions also have to be sustainable and environmentally friendly. We strive to put into practice sustainable engineering norms and improve recyclability of the system.

If environmental sustainability effects are deliberated the project falls in line with the principles of sustainability. It minimizes pollution risks uses resources responsibly and maintains environmental stability. FR4 substrates are not considered wholly environmental and recycling FR4 is also troublesome. Therefore, we focused on the system's compactness so that we could reduce FR4 usage. We also assess that the impact of accurate pH measurement on aquatic and soil environments would outweigh the meagre possibility of biodiversity disruption and chemical contamination.

Conventional sensors create a lot of chemical waste. Our system avoids this. It works in real-time and is non-invasive. We focused on making it reusable. We also wanted it to last long. This way it reduces material waste and is better for the environment. If we look at the bigger picture, the project fits two of the 17 UN Sustainable Development Goals:

- SDG 6 – Clean Water and Sanitation. Our system provides reliable and cheap means of monitoring pH. This helps keep water safe.
- SDG 9 – Industry, Innovation and Infrastructure. It promotes research in sustainable engineering and local innovation of sensor design. It can also assist in transferring technology.

The system is applicable to different environments. We only built the parts that we really need. It can be extended for other purposes. It could be used in waste-water management, irrigation or industrial effluent monitoring. It is energy efficient and requires almost no maintenance. Can operate for a long period of time in cities or the countryside.

CHAPTER 7

ADDRESSING COMPLEX ENGINEERING PROBLEMS AND ACTIVITIES

7.1 Addressing Complex Engineering Problems

From the beginning we knew it was a problem that was complicated. We tried to bring the ideas from different fields of. Electromagnetics Materials science Data Analytics. The system has to operate in various weather. We needed to ensure that the environment does not mess up the measurements. We also had some out of the box ideas for designing. Figuring out new ways to model the data was hard too. The main solutions we used are listed below.

Table 7.1: Complex Engineering Problems

Complex Engineering Problems		Addressing the complex engineering problems in the project
WP1	Depth of knowledge required (WK3-WK5, WK8)	Reviewing and understanding relevant research literature including scientific publications and standards Depth of knowledge required (WK3) Build upon existing knowledge and best practices (WK8). Including electronics, signal processing which is important for (WK5, WK8) sensor development (WK3). Knowledge In Microstrip Patch Antenna microwave sensing technologies and pH measurement methodologies (WK4). Develop a Meeting Requirements Sensor (WK5).
WP2	Range of conflicting requirements	Achieving a balance in the design involves making careful trade-offs between making it smaller yet powerful, precise yet affordable and durable yet sensitive.
WP3	Depth of analysis required	Achieving accurate pH measurements involves analysis of electromagnetic fields, material characteristics and signal processing algorithms. Analyses to optimize the sensor's performance, considering factors like antenna impedance matching and calibration
WP4	Familiarity of issues	Familiarize with microstrip antenna, microwave sensing, and pH measurement technologies. An understanding of the complexities associated with signal integrity, and chemical sensing is crucial
WP5	Extent of applicable codes	ASTM D1293. ICS Number Code 17.220.20. UNSPSC Code 41115406, 41113605. ISO Code 17025. IEEE Code 149. those codes are applicable to current pH sensor
WP6	Extent of stakeholder involvement	Antenna manufacturers like Taggles. Tess wave, Pulse Electronics, research communities, environment preservation entities, pH meter manufacturers like Hach company, ebru, GHM Group.
WP7	Interdependence	Independence between signal source, sensor and the signal processing unit is emphasized. Each element, from the antenna's performance to the accuracy of pH measurements and the efficiency is interlinked

we had to use both theory and practical engineering judgment. The problems were not easy. Our main goal was to get accurate results. Also, we wanted results that can be repeated. We worked on the system design to make it better. We tested it many times to make sure it works, as shown in Table 7.1

7.2 Addressing Complex Engineering Activities

The whole project was sub-divided into interrelated engineering activities. Design, fabrication, testing, and data analysis constituted a cluster. The researchers were obliged to plan and coordinate efficiently. In a few tasks, technical proficiency was also required. The major complex activities and the approaches used to address them are listed below:

Table 7.2: Complex Engineering Attributes

Attributes		**Addressing the complex engineering activities in the project**
EA1	Range of resources	Select suitable dielectric materials and utilize simulation software for antenna design, along with measurement equipment for performance testing.
EA2	Level of interactions	Create a user-friendly interface for monitoring pH levels and ensure seamless integration with sensing and signal processing components.
EA3	Innovation	Explore advanced design techniques and develop smart algorithms for predictive analytics to enhance pH measurement capabilities.
EA4	Consequences to society / environment	Assess the environmental impact of materials used and ensure safety, promoting sustainability environment in sensor design and deployment.
EA5	Familiarity	Conduct educational outreach to inform users about sensor functionality and gather feedback for continuous improvement.

The problems were often open-ended and real-world. We used a number of engineering principles, including analysis, synthesis, experimentation, and decision-making, to tackle those, as shown in Table 7.2

CHAPTER 8
CONCLUSIONS, LIMITATIONS AND FUTURE WORKS

8.1 Conclusion

This thesis presents a comprehensive experimental investigation demonstrating the feasibility of using a microstrip patch antenna as a microwave-based sensor for pH measurement. The sensing mechanism relies on monitoring key antenna parameters such as resonant frequency, return loss (S_{11}), and bandwidth, which vary according to the dielectric properties of the tested solutions. Through both simulation and experimental measurements, a systematic relationship between the pH value of aqueous solutions and the antenna response was successfully established. Experimental results show that the proposed sensor shows a good sensitivity in a pH range of 4 to 12, while experiments were performed in a controlled temperature condition of (20°C–30°C). The sensor was able to effectively discriminate between the different acidic, neutral, and alkaline solutions and confirm its potential as a sensing approach based on dielectric properties. The research employed a full design to validation process, starting with the design of the antenna and electromagnetic simulation, then creating the prototype and testing it in the real world to confirm the simulation result. During the implementation process, practical problem such as corrosion, maintenance and contamination, generally experienced with conventional electrochemical sensors, were also taken into consideration. The development of microwave sensing techniques helped eliminate these problems and offered a promising alternative sensing technique. Overall, the results demonstrate that a compact, low-cost, and reusable microstrip antenna–based sensor can effectively estimate pH levels without direct electrical interaction with the solution. These characteristics make the proposed sensing system a promising candidate for biomedical, environmental, and industrial monitoring applications.

8.2 Limitations

The limitations observed despite the success of the demonstration were small numbers of data, low diversity of samples and sensitivity to noise and scale of the models. The response of the antenna is dependent on the temperature. pH also varies with temperature. This makes it difficult to distinguish the two effects. Small errors might occur while taking resonance measurements. Placing the sample in the container may cause a slight shift in the permittivity. The FR4 substrate that we use is a lossy one. This decreases the sensitivity and lowers the quality factor. Using different substrates such as Rogers RT/duroid could improve the accuracy a lot. Small designs and strong substrates could allow use in wearable or biomedical devices. At some pH levels, S_{11}, and bandwidth values overlap. This makes it hard to clearly separate close pH states.

8.3 Future Works

Some improvements and future directions can improve the sensor, The antenna geometry may be optimized. Changing the patch shape, feed position or the structure of the ground may increase sensitivity and reduce errors. Machine learning can be introduced. Using data-driven approaches for S_{11} analysis and pH prediction can work to improve the accuracy for complicated data sets. Develop wireless or IOT based monitoring Future versions could send data remotely for continuous pH monitoring in the industrial area or in remote areas.

In conclusion this work is a basis of a microwave-based pH sensor. It can be improved through further research in the design, materials, and data analysis. Test sensor using the actual samples. Biological fluids and samples from industrial waste water and the environment need to be included. This will indicate how it works in different conditions.

REFERENCES

[1] Nikkhah, Nastouh, R. Keshavarz, M. Abolhasan, J. Lipman, and N. Shariati. "Highly sensitive differential microwave sensor using enhanced spiral resonators for precision permittivity measurement." *IEEE Sensors Journal* 24, no. 9 (2024): 14177-14188.

[2] M. Hossain, and S. Hannan. "Compact Nested Hexagonal Metamaterial Sensor for High-Sensitivity Permittivity Characterization Across S and X-Band Frequencies." *arXiv e-prints* (2025): arXiv-2502.

[3] Huang, W. Ding, S. Deb, Y. S. Seo, S. Rao, M. Chiao, and J. C. Chiao."A passive radio-frequency pH-sensing tag for wireless food-quality monitoring." *IEEE Sensors Journal* 12, no.3(2011): 487-495.

[4] Vishwakarma, Vinay, A. Gurav, H. Patel, and S. Sahasrabudhe. "Acqua culture monitoring system." In 2018 *International Conference on Smart City and Emerging Technology (ICSCET), pp. 1-4. IEEE, 2018.*

[5] Zhang, Kunyi, Reza, K. Amineh, Z. Dong, and D. Nadler. "Microwave sensing of water quality." *IEEE Access 7 (2019): 69481-69493*.

[6] Islam, Z. Ul, A. Bermak, and B. Wang. "A review of microstrip patch antenna-based passive sensors." *sensors 24, no. 19 (2024): 6355*.

[7] Liu, Changjun, C. Liao, Y. Peng, W. Zhang, B. Wu, and P. Yang. "Microwave sensors and their applications in permittivity measurement." *Sensors 24, no. 23 (2024): 7696.*

[8] Khan, M. Talha, X. Q. Lin, C. Zhe, and A. Saboor. "Design, analysis and validation of a microstrip patch antenna with enhanced coupling for leaf moisture sensing: an IoT approach." *Frontiers in Physics 12 (2024): 1402326*.

[9] Jasim, Hussein, A. A. Behadili, and S. Ahmed. "Highly Sensitive Microstrip Patch Sensor for Water Salinity Monitoring." Progress in Electromagnetics Research C 157 (2025).

[10] Singh, K. Kumar, A. K. Singh, S. K. Mahto, R. Sinha, and A. J. A. Al-Gburi. "Enhanced accuracy and high sensitivity in dielectric characterization through a compact and miniaturized metamaterial inspired microwave sensor." *Sensors and Actuators A: Physical 370 (2024): 115271*.

[11] ElAbbasi, Mona, M. Madi, K. Y. Kabalan, and J. Salah. "Optimizing Microstrip Patch Antenna Performance: Leveraging Machine Learning for Comparative Analysis of Antenna Di-mensions and Slot Structures." Results in Engineering (2025): 107523.

[12] Islam, M. Tariqul, F. B. Ashraf, T. Alam, N. Misran, and K. B. Mat. "A compact ultrawideband antenna based on hexagonal split-ring resonator for pH sensor application." *Sensors 18, no. 9 (2018): 2959*.

[13] Peroulis, Dimitrios, K. Sarabandi, and L. P. Katehi. "Design of reconfigurable slot antennas." *IEEE Transactions on antennas and propagation 53, no. 2 (2005): 645-654*.

[14] Mirza, Hidayath, M. I. Ahmed, and M. F. Elahi. "Circularly polarized compact passive RFID tag antenna*." In 2008 International Conference on Electrical and Computer Engineering, pp. 760-763. IEEE, 2008*.

[15] Vishwakarma, R. Kumar, and S. Tiwari. "Aperture coupled stacked patch antenna for dual-band*." International Journal of Electronics and Computer Science Engineering (IJECSE, ISSN: 2277-1956) 1, no. 03 (2012): 933-939.*

[16] Salim, Ahmed, and S. Lim. "Review of recent metamaterial microfluidic sensors." *Sensors 18, no. 1 (2018): 232.*

[17] Karli, Radouane, H. Ammor, and B. S. Virdee. "Early detection of breast tumors using UWB microstrip antenna imaging." *Microwave and Optical Technology Letters 58, no. 9 (2016): 2101-2106.*

[18] Lamani, Ashok, "Influence of particle size on band gap and dielectric properties of TiO2 nanomaterials*." In AIP Conference Proceedings, vol. 1728, no. 1. AIP Publishing, 2016.*

[19] Higuchi, Shogo, H. Okada, S. Takamatsu, and T. Itoh. "Valve-actuator-integrated reference electrode for an ultra-long-life rumen pH sensor*." Sensors 20, no. 5 (2020): 1249.*

[20] Abbasi, Zahra, H. Niazi, M. Abdolrazzaghi, W. Chen, and M. Daneshmand. "Monitoring pH level using high-resolution microwave sensor for mitigation of stress corrosion cracking in steel pipelines." *IEEE Sensors Journal 20, no. 13 (2020): 7033-7043.*

[21] Shimodan, Chihiro, M. Yamamoto, H. Sawada, Y. Muneta, S. Arai, H. Okada, S. Takamatsu, and T. Itoh. "Stability Evaluation of Reference and Indicating Electrodes of pH Sensor during Monitoring of Cow’s Rumen." *Sensors and Materials 35, no. 1 (2023): 15-24.*

[22] Tsitsos, Stelios, and M. Prousali. "Application of Machine Learning and AI Techniques to the Efficient Design and Optimization of Microwave Devices and Components—Recent Advances and Future Trends." (2026).

[23] Carver, Keith, and J. Mink. "Microstrip antenna technology." *IEEE transactions on antennas and propagation 29, no. 1 (1981): 2-24.*

[24] Dinh, T. H. Nhung, E. Martincic, P. Y. Joubert, and S. Serfaty. "Monitoring of yogurt formation using a contactless radiofrequency dielectric sensor." *In 2016 IEEE SENSORS, pp. 1-3. IEEE, 2016.*

[25] Shoaib, H. Mousud, K. M. Hassan, M. Karim, and A. E. Islam. "Study on the Effect of Double Inset Fed for Microstrip Patch Antenna for 5G Application." *In 2023 International Conference on Computational Intelligence, Communication Technology and Networking (CICTN), pp. 283-287. IEEE, 2023*.

[26] Lee, Kibae, A. Hassan, C. H. Lee, and J. Bae. "*Microstrip patch sensor for salinity determination." Sensors 17, no. 12 (2017): 2941*

[27] Bouchalkha, Abdellatif, and R. Karli. "Planar Microstrip Antenna Sensor for pH Measurements." In *2019 International Conference on Electrical and Computing Technologies and Applications (ICECTA)*, pp. 1-5. IEEE, 2019.