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HYDROPONIC IoT MONITORING SYSTEM
FOR DECISION-SUPPORT IN SMALL FARMS

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As an activist for education through the Board of European Students of Technology (BEST), aiming to grow soft skills for these students whose training focuses on the hard skills, the breadth of this topic this has been a good fit, as they have been for me in my life at college.

My family and friends, as always, were of constant support and they know how much they are treasured.

ABSTRACT

In a world where dwindling resources have become harder to manage, the basis for a flourishing society must be assured for a growing population. Progress in the field of Agriculture has leveraged newer technology, such as Digital Twin, for off-field simulation and modeling, Big Data techniques, to account for its characteristics and efficient data collection and processing capabilities, and Artificial Intelligence, to aid in decision-making and faster automation. This dissertation applied these solutions in a proof of concept design – with a focus on the potential for automating hydroponics, where the manual collection of data is no longer required, – by integrating the Internet of Things (IoT) and cyber-physical system (CPS) technologies into an architecture for data processing. Using water as a growth medium for plants, Nutrient Film Technique (NFT) hydroponic systems pose a viable solution to the steady depletion of soil, with added benefits related to accuracy, logistics, and time. This design was successfully prototyped, with data-driven IoT and CPS technologies for contemporary Small-Farms. A scalable solution for real-time monitorization and decision-support with an interactive user interface was implemented to leverage Artificial Intelligence and contribute to a more sustainable and circular economy within Agriculture 5.0. Future research will involve optimizing the synergies of the system presented, focusing on the sensors, actuators, and decision-support unit for data reporting and monitoring.

Keywords: Real-Time Monitoring, IoT, CPS, Small-Farms, Hydroponics, Agriculture 5.0

RESUMO

Num mundo de recursos limitados, a gestão dos mesmos deverá assegurar o bem-estar de uma população em crescimento. Para isso, servem as novas tecnologias da agricultura contemporânea, tais como o Gêmeo Digital, para simulação fora do campo, bem como técnicas de *Big Data*, para promover eficiência na recolha e processamento de dados e a Inteligência Artificial, que torna mais rápida a automação e a tomada de decisões. A presente dissertação aplicou estas soluções numa prova de conceito que valida a tese proposta, focada no potencial para automação de sistemas de hidroponia, onde a recolha manual dos dados torna-se desnecessária. Integrando numa arquitetura as tecnologias da Internet das Coisas (IoT) e dos sistemas ciberfísicos (CPS) para o processamento de dados, utilizou-se água como meio de crescimento na Técnica de Película Nutritiva em sistemas de hidroponia. Esta solução mostra-se viável para a constante erosão do solo agrícola, com benefícios adicionais relacionados à precisão, logística e tempo. No protótipo criado, que validou a prova de conceito, aplicaram-se tecnologias IoT e CPS orientadas a *Small-Farms*. Assim, foi implementada uma solução escalável para monitorização em tempo real e auxílio no suporte à decisão com uma interface de utilizador interativa de modo a tirar partido da Inteligência Artificial e contribuir para alcançar uma economia mais sustentável e circular no contexto da Agricultura 5.0. A investigação futura envolver-se-á na otimização do sistema apresentado, focando nos sensores, atuadores e unidade de auxílio no suporte à decisão para reportar e monitorizar dados.

Palavras-chave: Monitorização em tempo real, IoT, CPS, *Small-Farms*, Hidroponia, Agricultura 5.0

TABLE OF CONTENTS

ACKNOWLEDGEMENTS	vii
ABSTRACT	ix
RESUMO	xi
LIST OF FIGURES	xvii
LIST OF TABLES	xix
ABBREVIATIONS AND ACRONYMS	xxi
1. INTRODUCTION	1
1.1 Context	1
1.1.1 Hydroponics and technology in brief	1
1.1.2 Problem statement	3
1.1.3 Hydroponics and Agriculture 4.0	3
1.2 Research Question	4
1.3 Challenges and Objectives	5
1.3.1 Hydroponics	5
1.3.2 IoT and CPS	5
1.3.3 Objectives and expected contributions	6

1.4 Research Methodology	9
1.5 Overview of the Document.....	9
2. STATE OF THE ART.....	11
2.1 Agriculture 4.0.....	11
2.2 IoT for Agriculture	13
2.2.1 IoT Architectures	17
2.2.2 IoT communication protocols.....	24
2.3 Big Data for Agriculture	30
2.4 Digital Twin in Agriculture 4.0	33
2.5 Towards Agriculture 5.0.....	36
2.5.1 Sustainability	38
2.5.2 Circular economy	39
2.5.3 Artificial Intelligence in Agriculture 5.0.....	41
2.6 Technology used in small farms.....	44
2.7 The place of hydroponics in Agriculture 5.0	46
2.7.1 CPS in hydroponics.....	47
2.7.2 Types of hydroponics.....	48
3. PROOF OF CONCEPT DESIGN	58
3.1 Specific Architecture	59
3.2 Physical Layer	61
3.2.1 pH sensors	61
3.2.2 Electrical conductivity sensors	62
3.2.3 Environmental sensors	63
3.2.4 Triggers of each event.....	64
3.3 Communication Layer	64
3.3.1 Communication Protocol.....	64
3.3.2 Data Handler.....	65

3.4 Information Layer.....	65
3.4.1 Database Repository	65
3.5 Function Layer	67
3.6 Application Layer.....	67
3.7 Systems Behavior.....	68
3.7.1 Activity diagram for processes.....	68
3.7.2 Sequence diagram for data flow.....	71
3.8 Plants and Necessary Characteristics	72
4. PROTOTYPE IMPLEMENTATION	75
4.1 Physical Prototype.....	75
4.1.1 Materials	76
4.1.2 Selected sensor outputs, thresholds, and specifications	77
4.1.3 Creating the IoT Node	78
4.2 Data Handler and communication protocols	83
4.3 Creating the Database Repository.....	84
4.4 Graphical User Interface of the prototype	85
4.5 Decision-Support Unit	87
4.6 Testing the Prototype.....	90
5. CONCLUSIONS AND FURTHER RESEARCH	93
5.1 Main Results.....	93
5.1.1 Sensors, actuators, and GUI.....	94
5.1.2 Future Work	95
5.2 Concluding Remarks.....	96
5.3 Debating Ethics in Hydroponics for Agriculture 5.0.....	98
5.3.1 A professional perspective	99
REFERENCES	103
APPENDICES	117

A1: The historical geography of hydroponics	118
A2: Hydroponics in the early literature	119
A3: Background on Cyber-Physical Systems.....	120
A4: Economic and physical types of water scarcity [160].....	122

LIST OF FIGURES

Figure 1 – Nutrient Film Technique.....	7
Figure 2 – Iterative research methodology for this dissertation.....	9
Figure 3 – Edge Computing.....	17
Figure 4 – Proposed Reference Architecture of Edge Computing.....	18
Figure 5 – Architecture of Agricultural IoT.....	20
Figure 6 – Building the Web of Things.....	23
Figure 7 – Main relationships between the concepts of the IoT-Lite ontology.....	24
Figure 8 – Top 12 IoT protocols and standards.....	25
Figure 9 – MQTT's publish-subscribe model.....	29
Figure 10 – The 17 Vs and 1 C of Big Data.....	31
Figure 11 – Data processing activities.....	33
Figure 12 – Three levels of integration to Digital Twin.....	35
Figure 13 – Service categories and TRL for Digital Twins in Agriculture.....	35
Figure 14 – Technical and biological cycles of the circular economy.....	40
Figure 15 – Various sensors for smart farming.....	44
Figure 16 – Different types of hydroponic systems (a-d).....	49
Figure 17 – Entity Relationship model for this hydroponic proof of concept.....	66
Figure 18 – Activity diagram of the processes of the IoT Node.....	68
Figure 19 – Activity diagram of the data flow from the IoT Node to the IoT hub.....	69
Figure 20 – Activity diagram of the data flow from the IoT Node to the IoT hub.....	71
Figure 21 – Sequence diagram for this hydroponics proof of concept.....	72
Figure 22 – First setup of the prototype.....	76
Figure 23 – Setup of the circuit for the pH, EC, and temperature sensors.....	79

Figure 24 – Setup of the circuit for the EC sensor	79
Figure 25 – Setup of the circuit for the pH sensor	80
Figure 26 – Setup circuit of the environmental	80
Figure 27 – Setup of the water temperature sensor	80
Figure 28 – Circuit diagram of the thesis prototype.....	82
Figure 29 – Photo of the IoT Node	83
Figure 30 – GUI of the prototype	86
Figure 31 - Integrating the AI chatbot into the GUI, example	89
Figure 32 – Screenshot of our debate on the sociological impacts of hydroponics.....	101
Figure 33 – Where the Mediterranean meets hydroponic farming Babylon-Cairo-Rome.....	118
Figure 34 – von Scheel's 5 metamorphosis stages of paradigm-shift with Industry 4.0	120
Figure 35 – Navigating the next industrial revolution per the WEF.....	121

LIST OF TABLES

Table 1 – Towards Agriculture 5.0.....	8
Table 2 – <i>Agricultural concerns and characteristics of Industry 4.0</i>	15
Table 3 – A partial comparison of protocols and standards.....	27
Table 4 – Characteristics of Industry 4.0 transformed into Industry 5.0	37
Table 5 – Pros and cons of Deep Water Culture	51
Table 6 – <i>Pros and cons of a Drip Irrigation system</i>	53
Table 7 – <i>Pros and cons of Aeroponics</i>	55
Table 8 – Pros and cons of the Nutrient Film Technique.....	56
Table 9 – IoT architecture for the proof of concept.....	59
Table 10 – <i>A selection of scenarios for the sensors in this prototype</i>	64
Table 11 – Characteristics of the sensors for implementing this prototype	78
Table 12 – Output on the serial monitor of all of the four types of data from the sensors	79
Table 13 – Output on the serial monitor of the EC sensor.....	79
Table 14 – Output on the serial monitor of the pH sensor	80
Table 15 – Output on the serial monitor of the environmental temp/hum sensor.....	80
Table 16 – device_message table	85
Table 17 – nutrient_solution table.....	85
Table 18 – plant table	85
Table 19 – sensor table	85
Table 20 – Results of the testing stage of the prototype implementation.....	90
Table 21 – Matching concerns about the sociological impact of hydroponics.....	100

ABBREVIATIONS AND ACRONYMS

AgEng	International Conference on Agricultural Engineering
AI	Artificial Intelligence
API	application programming interface
AR/VR	Augmented/Virtual Reality
ATS	Attribute Time Series
BCE	Before Common Era
BEST	Board of European Students of Technology
BLSS	bioregenerative life support system
BPGV	Portuguese Plant Germplasm Bank [in Portuguese, the <i>Banco Português de Germoplasma Vegetal</i>]
C	Centigrade
C2C	Cradle-to-Cradle®
CAIR	Cisco Annual Internet Report
Caltech	California Institute of Technology
CEN	European Committee for Standardization [from the French, <i>Comité Européen de Normalisation</i>]
CERN	European Organization for Nuclear Research, originally the provisional <i>Conseil Européen pour la Recherche Nucléaire</i> [European Council for Nuclear Research]
CIAT	International Center for Tropical Agriculture
COVID-19	COrona Virus Disease, 2019
CPS	Cyber Physical System
CTSD	(United Nations') Commission on Science and Technology for Development
DARPA	Defense Advanced Research Projects Agency
DATA	data pin
.db	database file
DLM	Data Lifecycle Management
DM	Digital Model
DQ	describes a data pin, where the data is either D for <i>input</i> or Q for <i>output</i> in a bi-directional memory data bus
DS	Digital Shadow
DSS	decision-support systems

DT	Digital Twin
DTS	Data Time Series
DWC	Deep-Water Culture
E ² PROM	electrically erasable programmable read-only memory (also EEPROM)
EC	electrical conductivity
EEA	European Environment Agency
EEPROM	electrically erasable programmable read-only memory
ER	Entity Relationship
ESA	European Space Agency
ETL	extract, transform, and load (processes)
FAO	(United Nations') Food and Agriculture Organization
FCT	Faculdade de Ciências e Tecnologia
FLW	Food Loss and Waste
GCC	Gulf Cooperation Council
GIS	geographic information systems
GND	ground pin
GNSS	global navigation satellite system
GRIN	Germplasm Resources Information Network
GUI	graphical user interface
H ⁺	Hydrogen ion
H ⁻	Hydroxide ion
HPA	High-Pressure Aeroponics
HTTP	Hypertext Transfer Protocol
HTTPS	Hypertext Transfer Protocol Secure
hum	humidity
I4.0	Industry 4.0
IC	integrated circuit
ICT	Information and Communication Technologies
IEEE	Institute of Electrical and Electronics Engineers
IIoT	Industry IoT
IoE	Internet of Everything
IoT	Internet of Things
IPPMD	Integrated Product, Process, and Manufacturing System Development Reference Model
ISO	International Organization for Standardization
ISP	Internet service provider
JSON	JavaScript Object Notation
KB/s	kilobytes per second
KPA	Key Performance Area
LAN	Local Area Network
LCS	(MIT) Laboratory for Computer Science
LiDAR	Light/Laser imaging, Detection, and Ranging
LLM	Large Language Model
LPA	Low-Pressure Aeroponics

MAC	Medium Access Control
MELISSA	Micro-Ecological Life Support System Alternative
MIT	Massachusetts Institute of Technology
ML	Machine Learning
mm	millimeter
mmWave	millimeter-wave
MQTT	Message Queuing Telemetry Transport
MQTT-SN	MQTT for Sensor Networks
NFT	Nutrient Film Technique
NIH	National Institutes of Health
NIR	near-infrared
NLP	natural language processing
NPEC	Netherlands Plant Eco-phenotyping Center (NPEC)
NTC	negative temperature coefficient
NVMe	non-volatile memory express
OAuth	Open Authorization
OS	Operating System
OSI	Open Systems Interconnection
PAN	Private Area Networks
pH	power/potential of Hydrogen
PHY	Physical layer
PIL	Pillow
PSCI	Princeton Student Climate Initiative
PVC	poly(vinyl) chloride
PwC	PricewaterhouseCoopers International Limited
REST	Representational State Transfer
REST API	Representational State Transfer Application Programming Interface
RFID	Radio-frequency identification
RGB	red, green, blue
RPA	robotic process automation
RS	remote sensing
RTD	resistance temperature detector
S3-Product	sensing, smart and sustainable product
SAO	Stream Annotation Ontology
SAR	synthetic aperture radar
SDG	(United Nations') Sustainable Development Goals
SI	International System of Units
SMAS	the water authority [<i>Serviços Municipalizados de Água e Saneamento</i>]
SOIC	small outline integrated circuit
SQL	Structured Query Language
SSD	solid-state disk
SSL	Secure Socket Layer
SSN	Semantic Sensor Network
SWP	Sliding Window Prediction

TCP/IP	Transmission Control Protocol/Internet Protocol
temp	temperature
T _H	trigger-high
T _L	trigger low
TIA/EIA-644	low-voltage differential signaling, also known as LVDS
TLS	Transport Layer Security
TRL	technology readiness levels
UI	User Interface
UNCTAD	United Nations' Conference on Trade and Development
URL	Uniform Resource Locator
V	Volt(s)
V _{cc}	power pin
VDC	Volt Direct Current
VIS	Visible RGB
VNI	(Cisco's) Visual Networking Index
W3C	World Wide Web Consortium
WAN	Wide Area Networks
WEM	weather and environment management
WGS	World Government Summit
WNS	Wireless Networking System
WoT	W3C Web of Things
WST	wireless sensors technologies
XML	Extensible Markup Language

1.

INTRODUCTION

1.1 Context

The current state of Agriculture 4.0 means that digital technology can be harnessed to further improve farming conditions anywhere, whether in small farms or at home. The present research will demonstrate how the potential of hydroponics can be extended by automating the systems for sensors and control through decision-support systems, moving towards Agriculture 5.0.

1.1.1 Hydroponics and technology in brief

Hydroponics, the ancestral method of growing plants in a nutrient-rich water solution without the use of soil, has gained popularity due to results in production quality and quantity [1]. With the introduction of innovative uses of technology, hydroponics can produce high-quality crops with greater yields while reducing water and land usage compared to traditional farming methods. Hydroponics can also diminish the carbon footprint associated with agriculture, as noted by the Princeton Student Climate Initiative (PSCI) [2]. Note that, by 2050, in less than three decades at the time of writing, up to 70% more food production will be required for a global population projected to reach the varying figures of 9.1 billion per the Food and Agriculture Organization of the United Nations [3], 9.8 billion [2], or of 10 billion as predicted by the World Resources Institute [4], [5]. The advantages of hydroponics are, nevertheless,

offset by the precise control required for environmental factors such as temperature, humidity, electrical conductivity, pH, and nutrient levels to ensure optimal plant growth and yield.

The oldest mention of a hydroponic system was known as the Hanging Gardens of Babylon, one of the Seven Wonders of the World, where the Euphrates River, in the Middle East, was diverted to a system of stone shelves where plant roots would be invested so that the issues of nutrition and aeration could be solved (for a more complete overview of the geographical history of hydroponics, see Appendix A1) [6]. In the modern world, the first reference in the literature to this technology was in the early 20th century at the University of California, Berkeley, where William Frederick Gericke proposed that water could substitute soil as a growth medium for plant life (for a more complete overview of the early literature on hydroponics, see Appendix A2) [7]–[10].

Currently, hydroponic systems, especially in small farms, use a variety of sensors to monitor these environmental factors, but the data gathered is often collected manually. To avoid the subsequent delays in identifying and resolving issues, the Internet of Things (IoT) can be involved to solve these problems. By using sensors that are connected to the Internet, data can be collected and analyzed in real-time, effectively accelerating the timeline dedicated to identification and resolution of issues. Additionally, IoT can offer advanced interpolation capabilities to predict future environmental changes and adjust growing conditions accordingly, which all contributes to improved efficiency.

Then, integrating IoT with cyber-physical systems (CPS) can take hydroponics to the next level. The combined changes in farming practice and enhanced equipment can have a positive impact on creating sustainable practice, where CPS can improve human interaction in this farming context through new instrumentation and software. With CPS, data collected from sensors can be used to control actuators, such as water pumps or lighting, in a closed-loop [11]. This system can then make real-time adjustments based on the data received, leading to increased precision and efficiency in the hydroponic system.

In short, the use of IoT in hydroponics has the potential to revolutionize the farming industry by providing real-time monitoring and control of environmental factors, allowing for greater crop yields and improved efficiency. By integrating IoT with CPS, a closed-loop system can be created, resulting in more precise control and greater automation of the hydroponic system. Although this procedure may seem relatively simple, challenges are great, posing an interesting topic for research.

1.1.2 Problem statement

Working with data without access to data analysis tools, farmers miss out on a plethora of opportunities, beginning with rapid and even real-time visualization, with the added benefits of better communication and potential for insights. When automated data can be cleaned and preprocessed, both data quality and reliability improve because datasets are minimized for errors and inconsistencies, which can then be identified and corrected. Note that data collection enables comprehensive analysis and decision-support since data from various sources or even formats can be combined into unified datasets. This data integration for efficient retrieval, sharing, and management can take place when data is stored and managed, on any scale, in databases, in data warehouses, or in cloud platforms. Sharing, collaboration, and data-driven decision-making would be time-prohibitive and domain-limited if limited to manual activity but, through automation, internal and external stakeholders, collaborators, and partners can be involved in collaborative research, analysis, and even decision-making that is strategic, operational, or even tactical.

Implementing an automated system, especially a system that builds in a decision-support system, could streamline workflow and reduce labor costs, which together can improve the overall efficiency and re-imagine the connection with the land.

1.1.3 Hydroponics and Agriculture 4.0

Agriculture 4.0, defined as the optimization of traditional agricultural practices through integrated systems, offers numerous benefits for farmers, the environment, and society [12]. Ranging from automation to robotics, artificial intelligence, and data analytics, these technologies can enhance productivity, sustainability, and efficiency in food production. The European Environment Agency (EEA) points out that one of the most significant benefits is increased efficiency and productivity in the agricultural value chain. By implementing precision agriculture techniques and utilizing IoT and CPS technologies, farmers can optimize their crop yields, reduce waste, and enhance the quality of their products. This, in turn, can lead to increased profitability and competitiveness for farmers, which is especially important in the face of growing global demand for food [13].

Another major benefit of Agriculture 4.0 is improved sustainability. By utilizing smart technologies, like precision irrigation and crop monitoring, farmers can reduce their use of water, fertilizers, and pesticides. This conservation of natural resources not only helps to

protect the environment but also ensures the long-term viability of agricultural production in the face of climate change and other ecological challenges.

In addition to these benefits, Agriculture 4.0 also offers opportunities for greater transparency and accountability in the agricultural sector. Farmers can provide consumers with more detailed and securely protected information about the origin, production methods, and quality of their products by utilizing blockchain technology for data security, via decentralization and encryption as well as other digital tools. The transparency of the chain of activity and information about food production, processing, distribution, and consumption, and even the prevention of food loss and waste, is reflected in the popular "farm to fork" movement, originated in Northern California at the famed restaurant Chez Panisse. In the past 50 years, the movement for sustainability has raised consumer interest in reducing shipping, energy consumption, and chemicals, while increasing quality and safety in growing food products, whether animal or plant-based. The European Union specifically recognizes the Farm-to-Fork strategy [14], at the core of the European Green Deal, to build trust between farmers and consumers and support the development of more sustainable and ethical supply chains.

Overall, Agriculture 4.0 has the potential to revolutionize the way food is produced and consumed, making food cultivation more efficient, sustainable, and equitable. By embracing new technologies and practices, farmers can not only improve their own livelihoods, but also contribute to the health of the planet and the well-being of future generations.

1.2 Research Question

Within the context thus far defined, the research question for this thesis is:

"Given the growth of a worldwide data-driven mindset, how can we use IoT and CPS technologies in contemporary small-sized hydroponics systems in order to provide a scalable solution for monitorization and decision-support with an interactive user interface?"

1.3 Challenges and Objectives

1.3.1 Hydroponics

Hydroponics emerged as an innovative approach to agriculture, where plants are grown in a soil-free environment using nutrient-rich solutions. However, traditional hydroponic systems require constant monitoring and maintenance to ensure optimal plant growth, which can be time-consuming and prone to errors. Moreover, the lack of real-time monitoring and control in conventional hydroponics limits its potential for efficient resource utilization and yield maximization.

To overcome these and other challenges to be identified in the state of the art in section 2.6 and section 2.7, the integration of Internet of Things and Cyber-Physical Systems in hydroponics has been proposed. The use of IoT sensors and devices in hydroponics can enable real-time monitoring of key parameters such as temperature, humidity, nutrient levels, and pH, allowing for precise control and optimization of plant growth conditions. Additionally, the integration of CPS can enable automated decision-making and control of the hydroponic system, improving the efficiency and productivity of the entire process.

1.3.2 IoT and CPS

Despite the benefits of IoT and CPS in hydroponics, their implementation poses the challenges of interoperability, quantity of data, and installation, each of which is reflected in this thesis.

Firstly, the lack of standardization in IoT and CPS technologies can lead to interoperability issues between different systems. By making it difficult to integrate different systems and devices, the potential for incompatibility limits widespread adoption and integration. Irrefutably, standardization and interoperability of IoT and CPS technologies are crucial for seamless integration and easy adoption of hydroponic systems.

Secondly, the large amounts of data generated by these systems require efficient procedures and methods to extract useful insights. For efficient data management, in the context of IoT and CPS in hydroponics, the data must be collected, stored, processed, and analyzed in real-time to optimize plant growth and resource usage. For the analysis of the vast amounts of data collected, beginning with access to data, data location, data collection, creation of data formats, establishing data APIs, and the creation of data access tools, data analytics and

decision-making processes could lead to precision monitoring and optimal resource allocation. This can streamline repetitive tasks, reducing manual labor, and minimizing human error. The sensors that control the key parameters of nutrient levels, pH, temperature, and humidity could be monitored and algorithms could be run on that data to ensure, for example, efficient water management and energy consumption. Maintaining these optimal growth conditions could result in more uniform plant growth and improve crop yields and plant quality, especially by minimizing stress factors from the environment on the plant. Finally, remote access and control would ideally provide opportunities for monitoring for anomalies and adjusting settings anywhere and at any time. In fact, the analysis of historical data trends using predictive analytics could foresee crop performance and identify unknowns in advance. Overall, the time savings could be applied to proactive measures and strategic activity that could increase overall productivity.

Thirdly, the high initial cost of implementing and maintaining IoT and CPS in hydroponics can be significant, which may limit its adoption by small-scale growers. Added to the above challenges that need to be addressed, other costs derive from the complexity of hydroponic systems. The need for technical expertise can make it difficult for farmers without specific training or experience to understand and utilize them effectively. Obtaining appropriate training and gaining experience can be quite costly, depending on the local costs for (higher) education and/or accessibility of information for autonomous learning.

When these challenges are met in the context of Agriculture 4.0, IoT and CPS in hydroponics can, as already mentioned, improve crop yield, reduce resource consumption, increase efficiency and sustainability as well as ensure the quality and safety of the produce [15].

1.3.3 Objectives and expected contributions

This dissertation aims to automate a working Nutrient Film Technique (NFT) hydroponic system and integrate a decision-support unit. In a world where soil is a valuable resource, due to mismanagement as well as a growing world population, other sources for creating food are needed. An NFT hydroponics system offers a solution to substitute soil-grown agriculture. In this system, which will be described in greater detail in section 2.7.2, water would flow from inside a reservoir and into a pipe, lined with holes for plant root insertion (fig. 1).

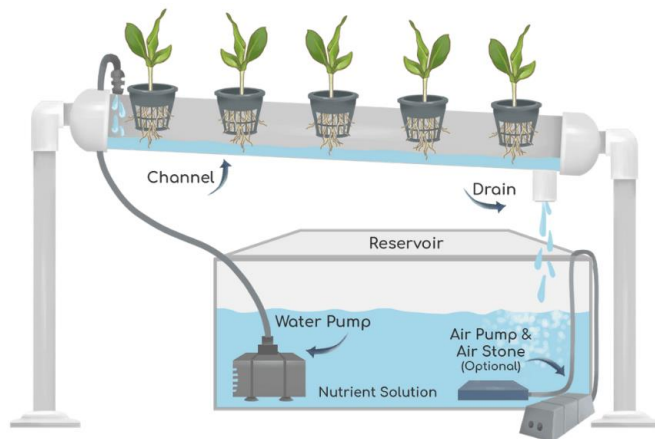


Figure 1 – Nutrient Film Technique
Source: [16]

Water would then flow downward at an angle so that the "film" that is created by the flow of water over the roots provides appropriate nutrition. At the end of the growing channel, the waste that gathers is piped so it can be mixed again into the reservoir. The collected waters are treated and sensors are integrated to measure the pH, electrical conductivity (EC), and oxygen levels.

Although the system can be simple to install, to gain the maximum effect, hydroponics should be monitored and automated. Automating and upkeep for the system to allow for growth without human intervention will require the installation of pipes for water cleansing and material for pH modulators, among others, to allow for nutrition control in this select environment. In a final phase of the research, all the monitored data will be stored in a database created for this effect. The data set will be accessible through a decision-support tool to allow the user to query a decision-support unit to know the state of the plant growth and optimize resource management in hydroponics for Agriculture 5.0.

Our contribution to the field should be understood as building a NFT system that is compatible with the guidelines of Agriculture 5.0. We aim to integrate IoT and CPS tools with full automation for collecting data and with systems that allow for data to be actuated upon once certain triggers are acknowledged. Data storage should allow for data analysis as well as integration of an AI to help in decision-support that can solve the users' problems without much further education in hydroponics. It should be clear as well that the concepts of

sustainability and circularity of the proof of concept are consequences of having selected the NFT system, given that hydroponics itself is already aligned with the guidelines of Agriculture 5.0. The contributions of this proof of concept aim at optimizing the levels at which the hydroponics NFT system operates within the field. While the integration of IoT and CPS tools for full automation brings the traditional hydroponic system into the field of Agriculture 4.0, considerations on sustainability and resource management will lead toward satisfying the required parameters emerging in Agriculture 5.0 and identified in Table 1.

Planned action for the present research	Intended outcomes per Agriculture 5.0 parameters
By implementing a sensorized and automated system, it is expected that the hydroponic system will be able to optimize the use of resources such as water and nutrients, leading to improved yield and resource efficiency.	Improved yield and resource efficiency
The use of IoT and CPS technologies will allow for real-time monitoring and control of key parameters, enabling prompt corrective action to be taken in case of any deviations from the desired values.	Real-time monitoring and control
The use of decision-support unit through AI will aid in the decision-making for data analysts.	Robots and humans working together
The automation of the hydroponic system will reduce the need for manual labor, potentially leading to lower labor costs.	Improved human-machine interaction
Hydroponic systems are known to have a lower environmental impact than traditional agriculture, and the use of IoT and CPS technologies will further enhance their environmental sustainability.	Environmental sustainability

Table 1 – Towards Agriculture 5.0

1.4 Research Methodology

A defined research methodology supports concision in developing a thesis through scientific techniques used to identify, process, and analyze information. As depicted in figure 2, the stages flow iteratively from the initial problem identification to determine and refine the problem. After that, defining the research question drives the dissertation, the aims, and potential doubts, with the background research providing a well-organized agglomerate of information sources that is collected to define the state of the art.

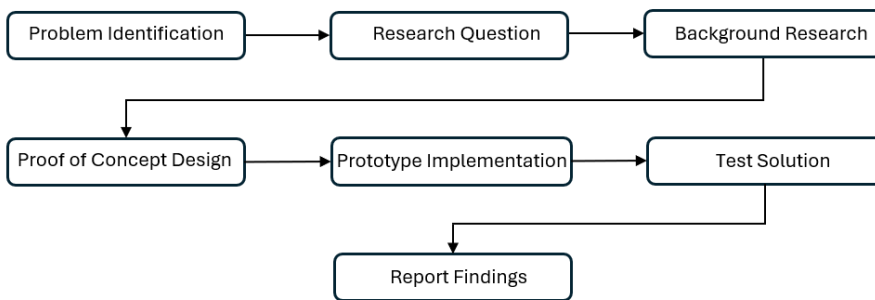


Figure 2 – Iterative research methodology for this dissertation

The proposed solution to the research question designed as a proof of concept, is then prototyped to test the solution and assess the results so that further research can be identified.

1.5 Overview of the Document

In Chapter 1, the context, research question, challenges and objectives, and research methodology are presented. Based on technical knowledge acquired in *Chapter 2: State of the Art*, the solution is then developed in *Chapter 3: Proof of Concept Design*, constituting the core of the dissertation. After that, *Chapter 4: Prototype Implementation* reports on the solution piloted in the real world through carefully monitored tests and analysis of the findings and comparison with the background research to determine whether the solution works. If the solution does not work, the equipment and software must be reevaluated, applying techniques for troubleshooting the problems. Whether the solution works or not, and to complete the

dissertation, the findings are reported so that conclusions can be drawn in *Chapter 5: Conclusions and Further Research*, where a space is opened for ethical considerations that move the research toward Agriculture 5.0.

2. STATE OF THE ART

2.1 Agriculture 4.0

A decade ago, at the Massachusetts Institute of Technology (MIT), *Mission 2014: Feeding the World* reinforced the outlook for food security and supported hydroponics as a solution [17]. As part of Terrascope, the 2014 MIT course, the objective was to identify a number of important practices and viable solutions. Shortly after, in 2018, the term *Agriculture 4.0* was coined in the report commissioned for the World Government Summit, *Agriculture 4.0 – The Future of Farming Technology* [18], where the map of technologies and maturity established expectations for Agriculture 4.0.

People, production, and the planet are interlinked in Agriculture 4.0 [19], also known as the Fourth Agricultural Revolution, which integrates emerging technologies [18]. The global management consultancy, Oliver Wyman, in collaboration with the World Government Summit (WGS) most recently published the report “Food Loss & Waste: GCC Solutions for a Global Challenge” [20] launched at WGS2023 to promote government and private sector investment in reaching the UN's Sustainable Development Goal (SDG) 12.3 by 2030 [21]. Specifically, SDG 12.3 uses the indicators (a) food loss index and (b) food waste index to measure the goal of halving “per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses” [22].

The location of the 13-15 February 2023 summit in Dubai is significant since the Gulf Cooperation Council (GCC) of these countries "particularly vulnerable to the issue of food loss and waste, due to their hot and dry climates and high reliance on food imports" demonstrates the clear need to implement "new regulations, doubling the efforts to raise awareness, and leveraging innovative technologies" [22].

From Artificial Intelligence to robotics, Big Data, and the Internet of Things [23] as well as gene editing [24] and drones [25], food production solutions are being proposed [18], [26]. Notably, in Braga, in 2015, an information system of strategic importance for national and global food security was launched to manage the collection of plant genetic resources. As the precursor to the National Program of Plant Genetic Resources, the Portuguese Plant Germplasm Bank [27] [BPGV, the *Banco Português de Germoplasma Vegetal*] is also known in translation as the Portuguese National Gene Bank [24], [28], or the Portuguese National Genebank [29]. The Germoplasm Resources Information Network, known as GRIN-Global, the free platform jointly developed by the Global Crop Diversity Trust, the Agricultural Research Service of the United States Department of Agriculture and Bioversity International [28] since 2011, hosts the Portuguese collection of "45,000 samples from 150 species and 90 genera of cereals, aromatic and medicinal plants, fibers, forages and pasture, horticultural crops and other species" [24]. GRIN-Global is "a database application that enables genebanks to store and manage information associated with plant genetic resources (germplasm) and deliver that information globally" [30]. The use of open-source software and freely available source code means that the technology can be tailored to meet the specific needs of any genebank.

Artificial Intelligence has been the growing backbone of new techniques and services that allow for more tools in Agriculture. AI can be used to "provide intelligent software applications and systems that can perform knowledge work operations involving subtle judgments and unstructured commands" [31]–[33]. This technology has the potential to reduce prediction costs on decision-making, enable risk management, improve agricultural accuracy and increase productivity.

Among the solutions proposed up until the year 2021, declared the beginning of the era of "Industry 5.0" [34] (see section 2.5 for further development), the primary academic literature for Agriculture 4.0 hailed a "digital agriculture revolution" [35]. The research explores how technology can transform and enhance agricultural practices for improved sustainability, productivity, and efficiency. Although research shows that precision agriculture "started in the US, Canada, Australia, and Western Europe in mid-to-late 1980s" [36], precision

agriculture and smart farming [12] today use advanced technologies such as remote sensing, Internet of Things (IoT) [37], and big data analytics to optimize crop management, resource allocation, and decision-making in agriculture [38]. Supply chain traceability harnesses blockchain technology [39] to enhance transparency, traceability, and trust in the agricultural supply chain, ensuring food safety and quality. Agri-tech startups are exploring innovative technologies and solutions for agriculture, such as AI-driven farm management systems [40], [41], and agricultural drones [42]–[44]. Robotics and automation are included to develop autonomous systems and robots for various agricultural tasks [45], including planting, harvesting, and crop monitoring. A metastudy of 119 articles related to eleven technologies confirmed that "5 key disruptive technologies, including Internet of Things, Drones, Blockchain, Big Data, and Robotics, are emblematic of Agriculture 4.0 [46]–[48].

Despite more than a decade of controversy [49], other solutions of vertical farming [50] and controlled environment agriculture aim to solve space constraints [51] by implementing indoor farming techniques that utilize controlled environments [52], hydroponics [53], and LED lighting to maximize crop production efficiency and reduce resource consumption. The literature exemplifies the demonstrable problems in the field and, more importantly, why hydroponics is worth working on as an engineer and inventor. The economic impact of IoT was declared to have a probable range of \$2.7 to \$11.1 trillion by 2025 [54]–[56], followed by the most recent prediction of \$5.5 trillion to \$12.6 trillion by 2030 [57], affording a window for the 2022 declaration by the Association of Equipment Manufacturers that "the era of precision agriculture has arrived" [58].

2.2 IoT for Agriculture

The current state of IoT technologies allows for several key development features in agriculture [24]. In addition to the benefits of IoT mentioned in section 1.2.2, this decentralization of the analytical process has paved the way to the field of Edge Computing, which allows for information to be gathered on-site and then processed in other locations through specific communication protocols that must be evaluated according to location, as well as the known economic variables.

The information that is broadcasted is gathered through sensors on-site. The network uniting the sensors must then be created to aggregate information accordingly, depending on different techniques, which may even use AI to ease the transition. Aggregation techniques

are numerous and may vary according to the needs of the sector. This allows for then processing data on, for example, seed growth time and its relationship to sunlight exposure, wind speeds affecting crop stability, and reproductivity. All variables that can be generated through the sensors may be correlated and used in decision-making to help farming and farming techniques to better serve the identified needs. Once a decision is made, communication protocols again are used to make the farmer's decision into an efficient process, where IoT allows for CPS actuators to then impact the site where the user decided to employ it.

These processes can start with a plan, or Architecture, through which it is understood how the devices are tied in to the system as well as the communication protocols used, the tools used in decision-making, where information is processed, and the software used to do so. That said, to introduce IoT specifically for Agriculture, note the prominence of agriculture throughout history as a major sector of primary industry, which can explain why the finest technology available should be applied to solve agricultural dilemmas. For the United Nations Food and Agriculture Organization (FAO), the consequences of a growing world population require an increase in production by 60% during the 21st century. In 2017, the United Nations Conference on Trade and Development (UNCTAD) published their paper on "The role of science technology and innovation in ensuring food security by 2030" [24]. As the leading entity for this topic, this document represents the combined plans for the UN Economic and Social Council and recommendations from the UN Commission on Science and Technology for Development (CSTD). UNCTAD reflects their three pillars of research analysis, consensus-building, and technical cooperation. The UN's FAO then fielded the global commitment to precision farming, also referred to as precision agriculture, to achieve the following key performance areas (KPAs) [59]:

- Optimizing resource use to reach goals more sustainably and with more profit from agricultural production;
- Reducing negative environmental impacts;
- Improving the markets' social status by benefiting the relationships amongst stakeholders through improved transparency and volume of information.

To achieve these objectives, precision farming has in turn harnessed the capabilities of technology in Industry 4.0 (tab. 2).

Agricultural concerns	Industry 4.0
Farm labor	Digital tech COMPLEMENTS traditional farming
Cultivation and post-harvest systems	Food waste is REDUCED and soilless techniques are REINFORCED
Green products and services	Smart factories ALTER the supply chain and company models
Agricultural supply chain	Smart links CONNECT consumers and the market

Table 2 – *Agricultural concerns and characteristics of Industry 4.0*
Source: Adapted in part from [60]–[62]

In Table 2, words in capitalized letters indicate the actions prevalent in each of the agricultural concerns, as the interlinking activities for Industry 4.0. For example, the function of complementing comes from digital tech and its impact on farm labor while the actions of reduction of food waste and reinforcement of soilless techniques occur in cultivation and post-harvest systems. Similarly, alteration is the activity of the smart factories producing green products and even of the services so that the supply chain and company models change. Finally, connection between the consumers and the market occurs through Smart links in the agricultural supply chain. These areas of concern for agriculture – farm labor, cultivation and post-harvest systems, green products and services, and the agricultural supply chain – can in large part be resolved with innovative applications of technology and human ingenuity.

In addition to AI [31], Big Data and Analytics together are byproducts of the growing capacity, through sensorization and growing data markets, to create greater volumes of information at a rate never before seen. Specifically, Big Data systems applied in the Agricultural sector can "enable the acquisition and comprehensive evaluation of large amounts of heterogeneous data from numerous sources" [33]. This technology has the potential to promote close to real time support, enhance efficient sources for administration, and optimize production quality.

Cloud Computing is itself an essential aspect of this growing capacity since it allows storage and processing at great distances, using servers and processing power to be able to "provide hardware, software, and storage computing resources delivered as a service over a network or the Internet" [33]. Cloud Computing technology dramatically reduces costly computing resources, facilitates information management and dissemination, and supports decision-making.

Cyber Physical Systems (CPS) have created the opportunity to visualize the world through a more thorough lens that assesses greater detail with sensors, which allow for automation through actuators. This connection amongst "the physical world agricultural operations with computing and Information [and] Communication Technologies (ICT) infrastructures" [33] takes full advantage of networking to integrate innovative applications. CPS technology allows for timely modification of workforce performance to promote safety, flexibility, and reliability of field activities and to produce higher quality yield at a lower cost (for further development on this topic of CPS, see Appendix A3). Especially in conjunction with autonomous machinery, manpower is freed up for other activities while increasing the yield of farming processes, especially in precision farming, like "sowing, pruning, phenotyping, targeted fertilization, harvesting, and sorting in automated or near-automated mode" [33], this technology reduces the workload on farmers, increases production rates, and optimizes the management of resources.

Recently, based on Patent Office registers, the data-driven economy is projected based on a combination of Big Data, 5G, and AI with an estimated 29 billion devices that will be creating data in real time through global connections of Internet Protocol networks [63]. This automation of entire business processes that involve IoT, which can draw everything together, allow for the field of edge computing, for example, to come into fruition so that data aggregation can be applied more efficiently. Edge computing (and fog computing) are "intermediary computing technologies that help move the data collected by IoT devices at remote locations to a company's cloud" [64] (fig. 3).

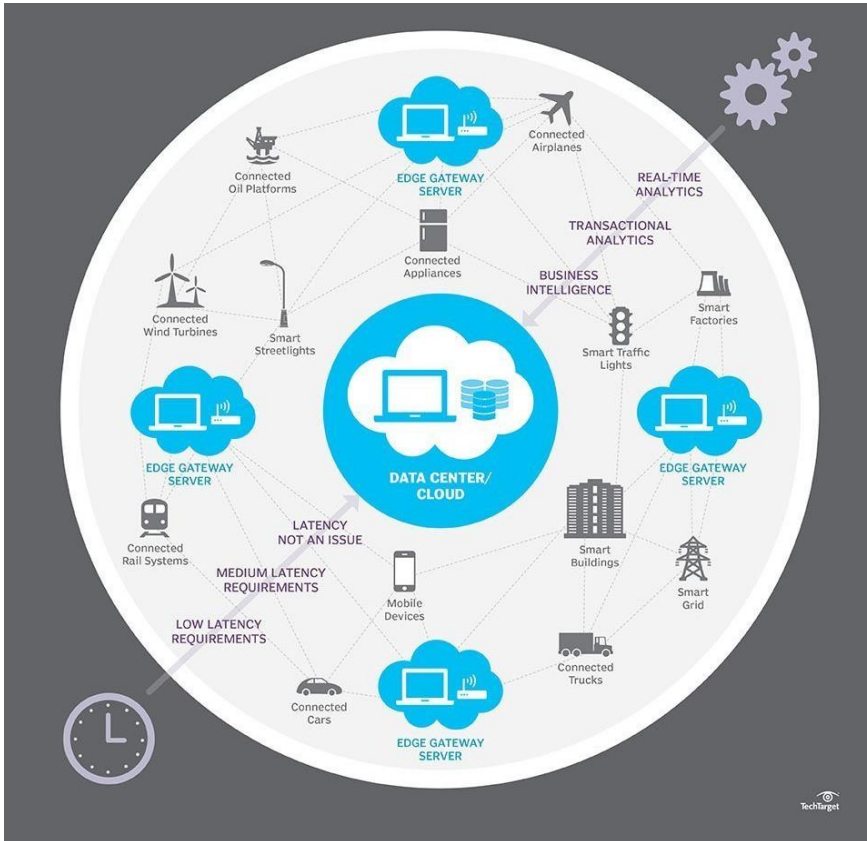


Figure 3 – Edge Computing
Source: [64]

2.2.1 IoT Architectures

Architectures used in other areas of industry such as Industry IoT (IIoT) may follow the following proposed reference Architecture of Edge Computing (fig. 4):

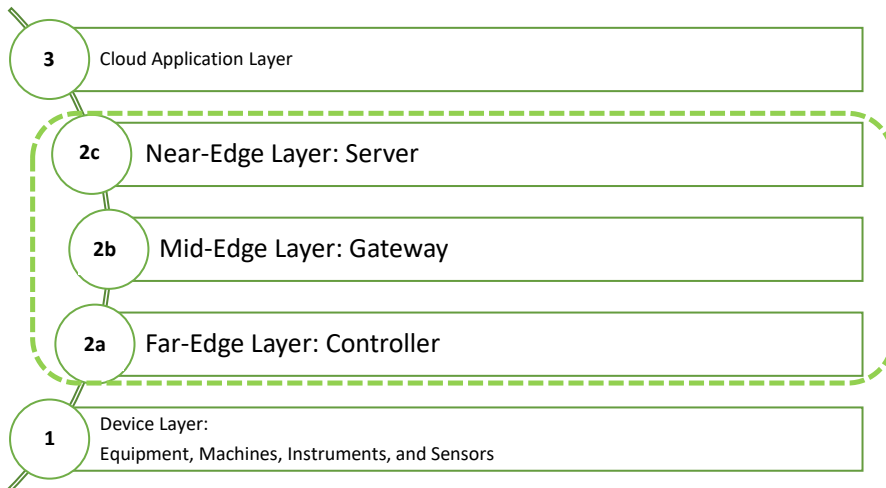


Figure 4 – Proposed Reference Architecture of Edge Computing
Source: Interpreted from [66]

As seen in figure 4, the above architecture is partitioned in three layers:

(1) The Device Layer describes the devices present on site, such as sensors, handheld terminals, instruments and meters, smart machines, smart vehicles, robots and other devices or equipment. Together, the devices transmit a large amount of on-site data and are broadcasted through wireless networks, such as Wi-Fi, Zigbee, 5G, RFID, or Bluetooth, to the Edge Layer. This communication is maintained, and control instructions flow back from the Edge Layer into the Device Layer for actuation to be performed.

(2) The Edge Layer – itself composed of three layers (2a-2c in fig. 5) is the core layer in IIoT; it receives, processes, and forwards the data flow from the Device Layer. It is in charge of data security, edge data analysis, intelligent computing, process optimization, and real-time control. To encompass all these responsibilities, the Edge Layer is itself further divided into three sub-layers.

(2a) The Far-Edge Layer, describing its position relative to the Cloud Layer, contains the controllers that collect data from the Device Layer. These controllers perform preliminary decisions that may work with the processing power at their disposal on the Edge and pass on information to the Cloud Layer. Due to the variety of sensors in the Far-Edge Layer, many protocols must assure compatibility with this layer and, as the volume of data grows, so must the on-Edge pre-processing power. An algorithm library is integrated to gauge the

effectiveness of the strategy being implemented. While this happens, edge controllers such as PLC are responsible for moving the decision-making down to the Device Layer after the decision has been received in the Far-Edge Layer. For all of these processes to work, this Far-Edge Layer must itself work with millisecond-level latency as judgment and feedback are important for dealing with emergencies that may occur.

(2b) The Mid-Edge layer is mainly responsible for data collection and may use wired networks such as Fieldbus, Ethernet, Optic Fiber, or other wireless networks that were used previously in the other layers, to achieve this goal of receiving data. This layer is also responsible for passing on the decisions made from the layers above to the one below. Since this is the main potential for this layer, it has more storage space as well as processing power to execute the data from the IIoT system, caching the data. After the desired amount of data is cached, then any preprocessing protocols that are necessary for treating Big Data can be initiated. A management module is also implemented in this layer to achieve synchronicity in between layers and devices. This leads to the layer needing more time for processing and is not as fast as the Far-Edge layer, resulting in second-level latency.

(2c) The Near-Edge Layer contains powerful servers that are responsible for performing critical data processing and making nuanced decisions based on the information that comes from that data collected in the Mid-Edge Layer. The servers should be then directed toward business and platform management functions. This layer is mainly used for bulk processing, obtaining better production scheduling decisions and operation of heterogenous data. This layer aims to achieve process optimization, operating at hour-level latency.

(3) The Cloud Application Layer is responsible for data mining, allocating optimal resources wherever needed. The layer communicates through the public network with the Edge Layer and then supports the upper application layer, sending whatever pertinent information it asks to receive. The Cloud Layer can share in collaboration with other clouds, functioning with day-level latency [66]. While the Cloud Application Layer primarily handles tasks such as data mining and resource allocation, data is often stored in specialized storage layers within the cloud infrastructure, in cloud storage services or databases. The Application Layer primarily focuses on processing and manipulating data rather than long-term storage.

In Edge computing, data can also be stored locally on the client devices, on-premises servers, hard drives, or other storage mediums connected to the client device or server that are directly accessible to the user or application. For redundancy or accessibility from multiple locations, the data stored locally may be synchronized or backed up to the cloud, but the

primary storage location for Edge computing is on the local storage devices, like solid-state disks (SSDs), via non-volatile memory express (NVMe) protocols, or in removable storage like memory cards [67].

Understanding the way the above Architecture approximates the Open Systems Interconnection (OSI) model [68], the base principles used to create IoT systems can be similarly recognized. Although they may vary, there is an underlying logic to it by dividing the space for devices and processing, thus creating the Edge concept. Also essential is that real-time actuation works with bidirectional gateways that function with multiple actuators to impact the system, so low latency decision-making can occur efficiently and automatically. This can also be seen in Smart Agriculture systems, as conceptualized in figure 5.

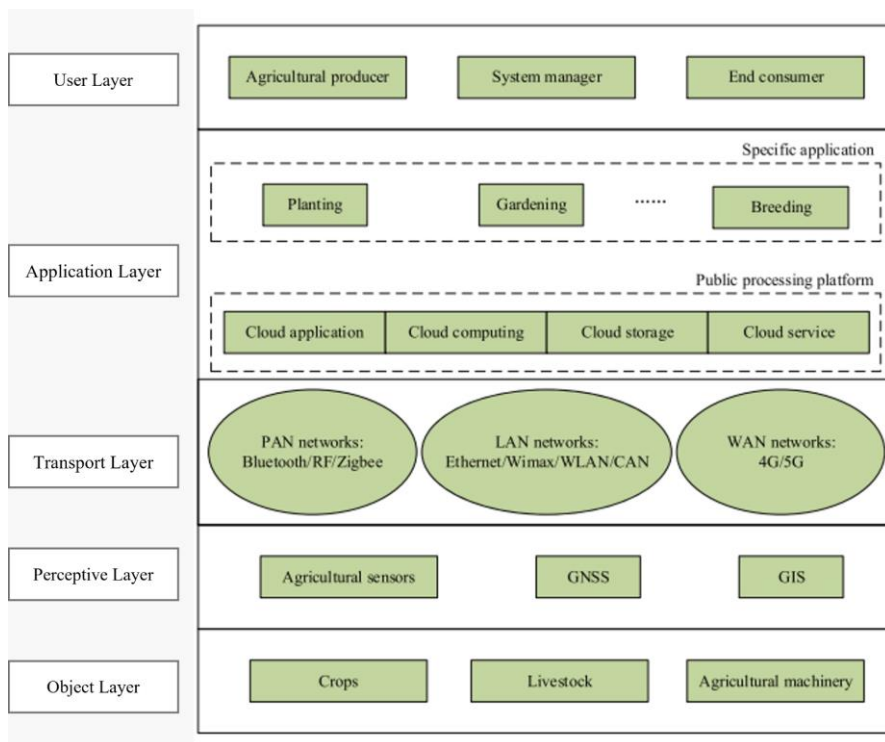


Figure 5 – Architecture of Agricultural IoT
Source: Adapted from [69]

Starting with the Object Layer, the target of the Agricultural asset to be impacted via IoT is described as an Object. The Object layer encompasses all the fields on the farm, from crops to livestock, and even agricultural machinery.

The Perceptive layer refers to the devices, sensors, or APIs, all of which allow for not only the sensorization of the objects through on-site sensors but also the actuation of the decisions that are brought down from the final top User layer. Satellite imagery may also be employed in different spectrums through the Global Navigation Satellite Systems (GNSS) to better understand geography as well as the Geographical Information System (GIS) for photometry models and heat maps.

The Transport Layer focuses on communication protocols. As the objective of IoT is to connect all devices, it is important that the system can implement different networks to assure a more adaptable system, with Private Area Networks (PAN) for low range, Local Area Network (LAN) for medium range, and Wide Area Networks (WAN). The diverse protocols in each of these systems may only be compatible with certain sensors and technology, so it is important to understand how to communicate with devices properly and in different ways, allowing for redundancy to be used correctly in these systems. Preprocessing and aggregation also occur in this layer.

The Application Layer is used for storage and processing, which holds a large amount of data and should be understood as the Cloud Application Layer in the IIoT Architecture, holding data structures for easy consultation by the user through a graphical user interface (GUI).

Finally, the User Layer represents the end consumer, in the case of Agriculture, specifically the farmer or technician who then uses that data for decision-making and economy-driven decisions.

Upon observing these proposed architectures for IoT and the way they are organized, a common question is, "So are all of the architectures in IoT structured this way? Is this the standard?" Although they are similar, when Industry 4.0 brought forth all of these more complex systems that use CPS and IoT, they did not settle on a standard of use recognized by the IEEE or OSI. Nevertheless, the Architecture of a system is extremely important to separate processes and to allow scalability and compatibility with sensors, protocols, and standards, using an interoperable reference architecture as a key process for preparing a successful implementation that is able to process and integrate heterogeneous data and assets, in different real-world settings.

Since differing architectures working together can cause problems, issues of interoperability and how to include various CPS technologies used in this field must be discussed [33], involving the World Wide Web Consortium (W3C) and the Web of Things (WoT). The W3C was formally established in 2003 as a new public-interest non-profit organization although it had functioned as a hosted model from its founding in 1994 by Sir Tim Berners-Lee, inventor of the World Wide Web. The WoT pioneers are also cofounders of a large-scale IoT cloud powering billions of Web Things, called EVERYTHING. Together they wrote *Building the Web of Things* to show "how to use web protocols to connect real-world devices to the web, including the Semantic and Social Webs" [70]. The WoT, established in 2007 to explore the future of the physical Web, unites a community of developers, researchers, and designers. The interconnection from embedding devices and tagging products in classic Web applications makes Things easier to use on a WoT that follows Web standards so that it is open, flexible, and scalable.

The W3C Web of Things (W3C WoT) specification family aims to support the use of Web technologies in IoT by filling in the gaps of existing standards to counter the tendency toward fragmentation. The W3C WoT is designed to support the integration of new CPS devices, known as Things in this specification, across multiple platforms, standards, and application domains, with a recent emphasis on "out-of-the-box interoperability of network interfaces, focusing on devices which are using the HTTP(S) protocol" [71]. Allowing this model to function as intended (fig. 6), each layer describes functionalities of the architecture.

The Access Layer 1 is responsible for turning a *Thing* into a *Web of Things' Thing* that can be accessed with an HTTP request. Using a Representational State Transfer Application Programming Interface (REST API) to make the request provides simple, uniform interfaces used to make data, content, algorithms, media, all available through web URLs [72]. The Thing's information can be viewed in JavaScript Object Notation (JSON) on a terminal and can be event driven by using WebSocket protocols, creating marks on Things akin to a Token.

Find Layer 2 aims to create an understanding of what the Thing created means. This layer allows for HTTP clients to automatically find and use the new Thing, which in turn enables searching for Things through Web indexes and allows for the creation of tools that may interact with the WoT.

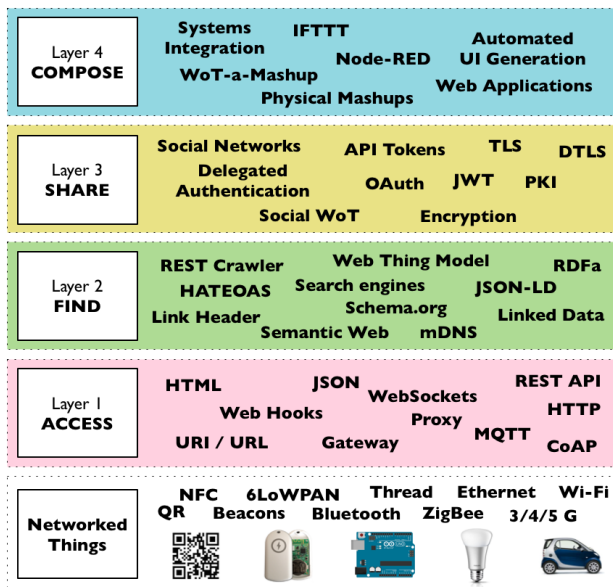


Figure 6 – Building the Web of Things
Source: [70]

Compose Layer 4 makes it possible to build large-scale applications for the WoT. It does this by providing tools to integrate data and services from Things into other ecosystems like analytics software and mashup platforms. Allowing for dashboards and programable Widgets to use all of the shared information from the Thing.

Overall, W3C WoT is a High-Level application protocol – edited by multinational representatives of Oracle, Fujitsu, Intel, Hitachi, Panasonic, and Huawei – that attempts to curb the issues that come from the high variability of CPS technologies that are integrated in IoT [73], [74].

Another W3C project that aids in building IoT Architectures is the IoT-Lite Ontology, helping define the nature of the resources, devices, and entities that may exist in the Architecture. IoT-Lite is an instantiation of the Semantic Sensor Network (SSN) ontology. The lightweight nature of this ontology reduces processing time when querying and, since the nature of data is not confined to one domain, other domains can be described and then mixed with other ontologies that represent IoT data streams, such as the Stream Annotation Ontology

(SAO). Quantity taxonomy such as gu-taxo, which allows for discovery and interoperability of IoT resources in heterogenous platforms and is commonly used with IoT-Lite (fig. 7).

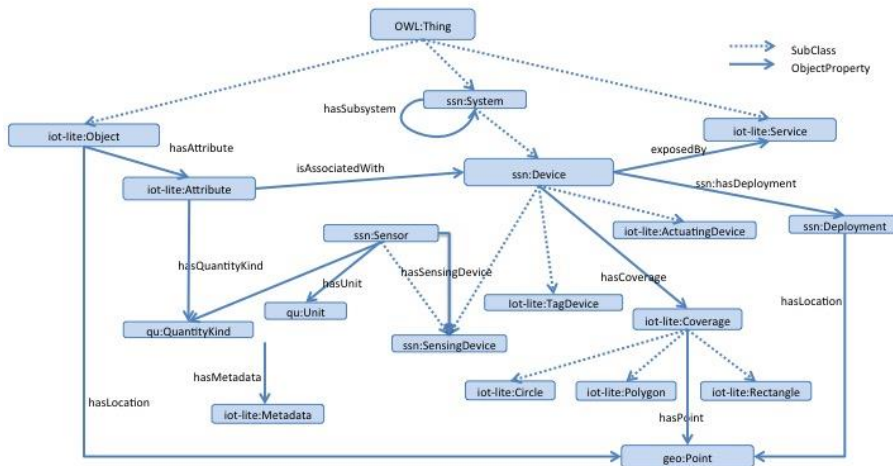


Figure 7 – Main relationships between the concepts of the IoT-Lite ontology
Source: [75]

As can be seen in figure 7, W3C confirms the three classes of IoT concepts in IoT-Lite: *“Objects, system or resources and services. IoT devices are classified into, although not restricted to, three classes: sensing devices actuating devices and tag devices. IoT-Lite is focused on sensing, although it has a high level concept on actuation that allows any future extension on this area. Services are described with a coverage. This coverage represents the 2D-spatial covered by the IoT device.”* [76]

Having analyzed a variety of Architectures and all of their components, including the techniques and ontologies used for interpolation and ease of use, allows for an adaptable architecture that can easily add new CPS technologies as well as share with new clients [76]. After the architecture is decided, missing parts can be filled in with the actual hardware, sensors, actuators, and servers as well as all the necessary communication protocols that the system may need to satisfy its requirements.

2.2.2 IoT communication protocols

The State of the IoT was reported at 12 billion IoT connections for 2020, the first year non-IoT connections had ever been surpassed [77], and then at 14.3 billion, up 18%, for 2022

[78]. A follow-up from IoT Analytics, a self-denominated "leading provider of market insights and strategic business intelligence for the Internet of Things (IoT), AI, cloud, edge, and Industry 4.0" [79] reported an update on the number of connected IoT devices to 16.7 billion globally [78], almost a 40% growth in just two years.

Note then that each of the devices connected to the IoT requires specific communication protocols that follow standards, the most prevalent of which have been collected in figure 8.



Figure 8 – Top 12 IoT protocols and standards
Source: [80]

By enabling the components to communicate, data can be moved from endpoint devices – like sensors – following a sequence of steps, where the data is not only received but also understood, to reach central servers via the IoT Architecture as previously presented in section 2.2.1. Bluetooth [81] and Wi-Fi [82] (or 5G), with their respective examples of applications in smart farming, are protocols that work at the lowest (bottom) layers while Zigbee [83] and MQTT [84], also implemented in the accompanying references, work in the application layer.

For the purposes of this MSc thesis, these four protocols will be compared to better understand their capabilities and combinations of features for distance, ease of access, and pairing/set up. Although all protocols enable communications or combinations of communications as device-to-device, device-to-gateway, or device-to-cloud/data center communication, the IoT deployment will also be conditioned by factors such as cost, geospatial location,

levels of energy consumption and sourcing – whether battery-operated or not – and other physical barriers.

Bluetooth, “a short-range wireless technology that uses short-wavelength, ultrahigh-frequency radio waves” [80], enables wireless and connected devices with its low-power, low-range connectivity. More recently, the newest version is Bluetooth Low Energy (Bluetooth LE or BLE), which has been optimized beyond standard Bluetooth for IoT connections, consuming even less power.

As Bluetooth is a widely adopted standard, this ensures compatibility with a host of devices and platforms and is easy to integrate into IoT systems. This paired with its cost effectiveness allows for suitable mass adoption for IoT systems in need of cheap and easily applicable communication standards.

The phonetic fun of *lo-fi*, *hi-fi*, and *then wi-fi* represents the range from *low-* to *high-* to *wireless fidelity*. The level of performance of Wi-Fi networks depends on the technology standard although the theoretical speed is indicated by the Wi-Fi 802.11 standard, with the most common being 802.11n. The IEEE 802.11ax wireless standard, introduced in 2019, corresponds to Wi-Fi 6, reflecting the IEEE certification practice. Although Wi-Fi 7 may be ready in 2024, standardized as 802.11be, Wi-Fi itself is a frequently-used IoT protocol that offers fast data transfer with a large data processing capacity in the short- and medium-range distances of a LAN environment [80].

According to the Communications Standards Alliance [85], Zigbee – promoted as *The Full-Stack Solution for All Smart Devices* [86] – is used for high-level communication protocols as an IEEE 802.15.4-based specification, which uses Medium Access Control (MAC) and Physical layer to offer a low-cost system with low power consumption and a low data-rate [87]. The Zigbee Alliance, a non-profit organization established in 2002 [88], updates and maintains this wireless networking standard, as well as its specifications. The funny name actually stands for “Zonal Intercommunication Global-standard, where Battery life is long, which is Economical to deploy, and which exhibits Efficient use of resources” [89]. This definitive guide to *Zigbee Wireless Networking* has steered small businesses as well as multinationals, like Mitsubishi, Motorola, and Siemens [89] in their plans to develop low cost and low power networks and applications using sensors, actuators, and wireless control for industry, medicine, remote controls, and security. The key features of Zigbee are that it is globally adopted, interoperable over a large ecosystem of products, offers security mechanisms like over-the-air

AES-128-CCM encryption, reliable due to its self-healing mesh network, and uses minimal power consumption – lasting years rather than months.

With strong, stable coverage, the Zigbee standard can broadcast data on the 2.4GHz, 90MHz, and 868MHz frequencies across distances of up to 10-100 meters indoors [87] or 300 meters outside, with a data transfer rate of just 40-250 KB/s. On the one hand, based on the mesh, commands are passed along; on the other hand, a Zigbee-enabled hub can ensure the commands are relayed to all of the correct devices. Instead of using the Zigbee-enabled hub, the Amazon Echo smart speaker and the Samsung SmartThings hub, for example, offer connection to a third-party Zigbee-enabled hub. Within the same Zigbee network of up to 65,000 nodes, the instructions data spread because each device acts as a node, receiving and transmitting data to every other device attached to the network, although distance decreases the signal, which can even be blocked by physical barriers. Although battery-powered Zigbee devices simply send and receive commands, when devices are powered from the mains, they broadcast, as repeaters, all the signals received from the other network nodes [88].

Merging the information presented above with [90], Table 3 was created for an at-a-glance comparison of the protocols and standards of Bluetooth, Wi-Fi, and Zigbee.

Capabilities	Bluetooth	Wi-Fi	Zigbee
transmission range	8-10 m	20-150 m	10-100/300 m longer than BLE
power use	medium	high	ultra-low
data rate	1-24 MB/s	2-54 MB/s	40-250 KB/s lower than BLE
security mechanisms	AES-CCM cryptography, performed in the Controller	Wired Equivalent Privacy (WEP) Wi-Fi Protected Access (WPA), WPA2, WPA3	over-the-air AES-128-CCM encryption
specification standards	IEEE 802.15.1	IEEE 802.11 n/ax/be	IEEE 802.15.4
frequency	2.4 GHz	2.4 GHz	868/915 MHz, 2.4 GHz
cost	low	low	low

Table 3 – A partial comparison of protocols and standards
Source: Adapted from [90]

Functioning in the same layer as Wi-Fi and building on earlier generations of cellular networks, 5G technology – also called the *Fifth Generation of Mobile Telephony* based on “a set of dedicated technologies, such as ‘Network Function Virtualization’ and ‘Slicing’ to increase the modularity, ‘EDGE computing’ for faster response time, Non-Terrestrial Networks (NTN)/Satellite Communications for ubiquitous coverage, etc.” [91] – is expected to be

essential for connecting devices like environmental sensors and thermostats in near real time. Although 5G operates at low-, mid-, and high-band, the mid-band, operating between 1 and 6 GHz, can achieve speeds up to 1 GB/s. WIRED reported that “South Korea had the top 5G download speed at 432.7 MB/s, followed by Malaysia, Sweden, Bulgaria, and the United Arab Emirates” at the end of 2022 [92]. Stability and speed are major aspects, since multiple devices can be connected given 5G’s capacity and response time, although it seems that at the low-band, 5G resembles 4G.

The 5G requirement of millimeter-wave (or mmWave) technology, which uses the high end of the wireless spectrum, operating at 20 GHz and up, enables what are called *multi-gig speeds*. Instead of tall cell towers, the 5G network relies on many small access points. Nevertheless, these signals cannot overcome obstacles so they simply are not reliable over long distances. Open fields with no trees or people, for example, are good candidates as long as it is not a rainy day, since even raindrops can disrupt the signal. 5G’s rapid transmission of high-resolution images for use in predictive analysis in autonomous farming potentially bodes well for other agriculture technology, like remote-piloting drones, cloud computing services, and augmented reality.

It may seem that 5G will be replacing Wi-Fi, but the suspicion is that they will co-exist [93], with the free use of Wi-Fi’s relatively weak signal on the unlicensed spectrum. A vast array of specifications and technical reports from 3GPP – with the slogan *A Global Initiative* – stand out with their mission to create the Mobile Broadband Standard, not only connecting the IoT reliably and with low latency but also “for energy efficient low-cost, low-power sensors and devices” [94]. Once the information is gathered from the physical layer with these communication protocols and processed upwards through gateways to further higher layers, it is then necessary to use other communication protocols that function in the application layer so that an interface can be created to track device information and visualize said data.

Originally developed by Andy Stanford-Clark and Arlen Nipper at IBM’s Cambridge software lab and launched in 1999 as a proprietary protocol called *Message Queuing Telemetry Transport* (MQTT), the MQ part of the protocol no longer exists; instead, it offers a simple messaging protocol that works with constrained devices, simultaneously enabling communication amongst multiple devices.

Machine-to-Machine (M2M) communication is enabled by publish-subscribe architecture in this open-source protocol. Unreliable networks can work in MQTT's low-bandwidth situations, where devices can be connected with a small code footprint and where wireless networks offer varying levels of latency stemming. Based on TCP/IP, the MQTT protocol's OASIS standard specification is managed by the OASIS MQTT Technical Committee [95], which states that

"MQTT for Sensor Networks is aimed at embedded devices on non-TCP/IP networks, such as Zigbee. MQTT-SN is a publish/subscribe messaging protocol for wireless sensor networks (WSN), with the aim of extending the MQTT protocol beyond the reach of TCP/IP infrastructure for Sensor and Actuator solutions".

MQTT's publish-subscribe model is depicted by Behr Tech as follows (fig. 9):

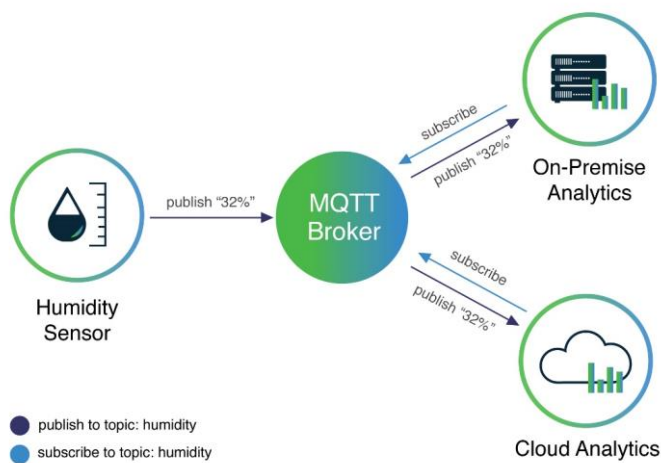


Figure 9 – MQTT's publish-subscribe model
Source: [96]

Based on figure 10, devices are MQTT *publishers* that send data while processing systems are MQTT *subscribers* that receive the data in question. In terms of process, in a hydroponic system set up with an MQTT broker, the humidity sensor, for example, is an MQTT *publisher* that publishes (sends) the data collected to the MQTT broker, as the exclusive point of contact. Described as a traffic cop, the MQTT broker *brokers* the communication when it

publishes (sends) the data from the humidity sensor to the subscribers, here subscribing for separate purposes of local and cloud analytics. Note that the publisher and subscribers are never in direct contact with each other because the MQTT broker (in the center of the figure) moves the messages from the publisher to the end-point subscribers.

Efficiency in communication, control, and data management are the primary drivers for including MQTT in a hydroponic system aiming for improved crop yield, resource efficiency, and sustainability. With real-time monitoring, for example, the system can track the conditions of the hydroponic environment remotely and even respond to eventual anomalies related to the published data on pH, nutrient levels, temperature, and humidity. This prompt response is a characteristic of the bidirectional communication facilitated via MQTT, whereby control commands can be sent from the MQTT broker, understood as a central management system, to the actuators and control devices in accordance with preset parameters or AI-driven algorithms that enable automated adjustments to the system.

The MQTT subscribers can be databases and cloud platforms which receive the transmission of data streams. When collecting historical data from the system, the stream can be analyzed to optimize growing conditions with other trends and insights identified over time. These advantages of data logging and analysis are also supported by scalability and flexibility since MQTT is light and integrated with the publish-subscribe messaging architecture. The accommodation of vast numbers of sensors, actuators, and control devices makes MQTT adaptable and ensures efficient communication across a system, regardless of the size.

2.3 Big Data for Agriculture

Within the area of IoT, many other uses and niche resolutions to problems [97] have become apparent from the volume of information. Big Data, which allows for the capture of data, which can then be stored and analyzed efficiently with appropriate technology, like decision-support units that are designed for this scale. By avoiding the extra hardware costs required by printed hard copies, this technology also offers an excellent compatibility to store data in digital form, lending credence to its easy access and scope. The volume of data processing enabled by this technology creates an added opportunity to not only store all

agricultural sensor data but also create and manage a more streamlined agri-tech business on any scale, optimizing all aspects of the information gathered.

With all this data being acquired by the sensors, the information must be categorized within Big Data. This type of data is characterized by what is known as the 3 Vs [98]:

- *Volume* is a principal characteristic due to the sheer amount of information, hence "Big" Data. Agricultural data on all of the related environmental factors as well as plant health make the datasets rich in information, which in turn can lead to petabytes of data being processed to reach conclusive analysis.
- *Velocity* is another characteristic as the speed at which data is produced reflects an effort to achieve a continuous feedback system. For accurate analysis, new instances are produced for every clock measurement that then need to be stored.
- The last V is for *Variety*, whereby the process involves several sensors and different information types, whether nominal, ordinal, or graphical information. These different datatypes are processed differently from structured data, which is tagged for easy sorting and access before entering the storage system, or even from unstructured data which is random and difficult to analyze. A flexible storage system can take on the characteristics of Big Data and work based off its weaknesses and strengths.

After the advent of the 3Vs, a myriad of characteristics of Big Data, all beginning with the letter V, have been proposed in an animated recount, reaching up to 17 Vs in 2017 with mention of the eventual need to add in a C for *complexity* (fig. 10).

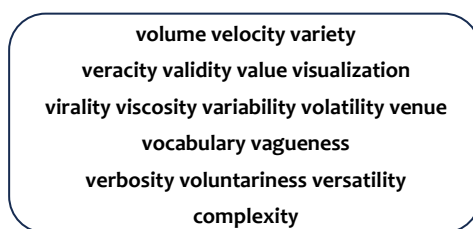


Figure 10 – The 17 Vs and 1 C of Big Data
Source: Interpreted from [99]

By analyzing Big Data, advantages are gained, allowing for multimodal information with high variability and variety. The ease in updating and access to data has led to the

development of other stronger systems, such as using Deep Learning. In India, for example, researchers at the Sri Sai Ram Engineering College in Chennai applied the Random Forest machine learning algorithm for classification and regression tasks to predict the weather and reduce crop yield output losses and point out a certain personalization involving the human touch in Industry 5.0 [100].

The heterogeneous data from the field of agriculture must be dealt with according to different methods for treating data. *Collecting* involves gathering raw data from various sources, such as sensors, databases, or manual inputs, acquiring data in its original form, whether in real-time or periodically. Following through, the data must be iteratively cleaned and aggregated for transformation. Non-differentiated data, from one instance to another, is common because either the sensor has read the same value in a series of clocks or a calibration error shows the maximum value all the time. Maximal visualization and analysis and the setting of temporal boundaries for getting a task done, for example, requires that data be temporally bound. In addition to this temporal distinction between instances, agricultural aggregation parameters contribute to data aggregation through Attribute Time Series (ATS) and Data Time Series (DTS). These two techniques are particularly used in the agriculture industry because of the data characteristics of time and attribute. As such, these techniques lend relevance to the timebound requirement at all instances so that data can be monitored in real time [101].

Data *aggregation* is also part of the process of collecting the data from multiple sensors to then eliminate redundant transmission and provide fused information to the base station. *Clustering* is at the core of what can be done in the area of sensors, particularly in maximizing the overall network lifetime of a Wireless Networking System (WNS) [102]–[104]. The subsequent application of data transformation effectively transforms all the data into a standard and readable format through *extract*, *transfer*, and *load* (ETL) processes, using scripting languages such as Python as well as SQL.

Cloud storage, as previously mentioned, provides a global platform for storing ubiquitous sensor data anytime and anywhere so that each instance of data can be transmitted and then stored in a cloud database for remote access to provide farmers with the privacy and security required.

Of the methods related to data *cleaning* that must also be applied, *preprocessing* refers to the processes used for data cleaning so that it becomes uniform through the following steps [105]:

- *Data audit*, in which the data is analyzed through a particular statistical model so that anomalies can be detected within the dataset. The data audit may be done through code or other data management systems with already integrated processes to apply to the dataset.
- *Error detection*, where the outliers and missing values are discovered and considered.
- *Post-processing and controlling*, where the data can be analyzed cleanly and then inspected to determine its validity.

More specifically, for example, to properly clean DTS, which is prone to outliers, the data must be improved by applying either the k-nearest neighbor or sliding window prediction (SWP) [106]. Other more robust methods of data cleaning, such as MLClean, use unfairness mitigation as well as data sanitization to detect outliers and remove them from the original data [107]. Figure 11 outlines some of the activities data can be subjected to.

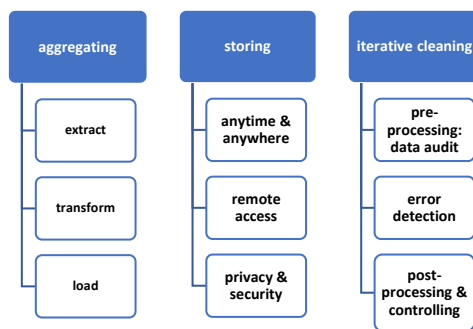


Figure 11 – Data processing activities
Source: Interpreted from [105]

In light of the 2018 EU Code of Conduct for Agricultural Data Sharing by Contractual Agreement, a discussion of problems, specifically related to farm machinery and processes management on data used in precision agriculture, problematizes the rights to data and its administration [108].

2.4 Digital Twin in Agriculture 4.0

Research on Digital Twin (DT) reports that "the earliest documented DT application (2011) was that of an aircraft, which was used in production" [109]. Through the concept of

real-time virtual representation, DT in general is "the effortless integration of data between a physical and virtual machine in either direction" [110], which enables digitization in agriculture. Although major developments have taken off only in recent years, these advances have made it possible to effectively test and develop new products, which encourages the open mindedness required for the adoption of new methods and eventually innovation [111].

More specifically, DT distinguishes "between state sensing, entity understanding, and physical automation to be eliminated, through high-fidelity modelling and bi-directional data streams" [112]. Through the union of data, modelling, and *what-if* simulation, the area of digital twinning in agriculture [113] can provide an approach to overcome current limitations in decision-making support and automation, across a diverse range of agricultural endeavors [114], where the categorization methods described provide the basis of the inclusion and classification criteria in coherence with the CIRP definition [115]. For example, in Europe, Wageningen University & Research is working on Digital Twins for tomatoes, food, and farming with the Netherlands Plant Eco-phenotyping Center (NPEC) [116]. For the virtual tomato crops, specifically, they are using a 3D simulation model that receives real-time data from sensors in a greenhouse. The constant interaction that keeps the data up-to-date translates into more refined prediction and, thus, choices about the real crop. Tomatoes were chosen due to their extensive experience with tomato cultivation and results on their fully developed prototype, which were expected in 2023, are not yet available at the time of publication [117].

The integration of a digital twin is integrated through various levels, from (i) the Digital Model (DM) of a physical entity to (ii) a Digital Shadow (DS), representing an automated information flow that is uni-directional, to (iii) a Digital Twin (DT), where the information flow is, as intended, bi-directional (fig. 12).

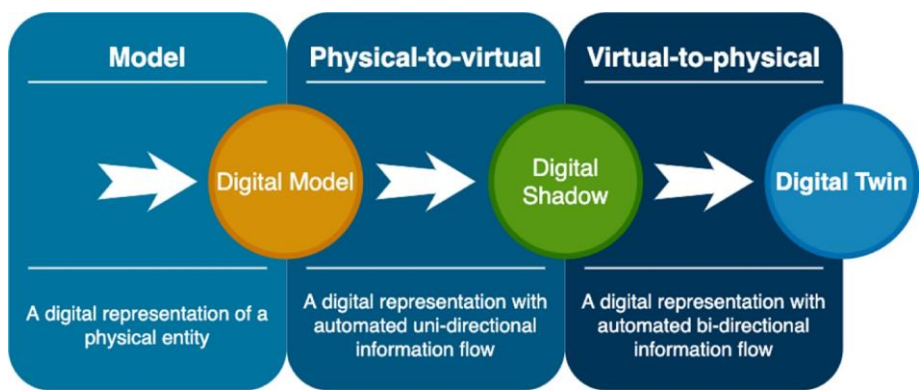


Figure 12 – Three levels of integration to Digital Twin
Source: [112]

To use the terminology properly, a physical entity whose existence is independent of a Digital Twin can be considered a “real-world” entity, while the term *Physical Twin* is used when a Digital Twin does in fact exist [118]. Consequently, a virtual entity is “an un-twinning general model or similar domain-specific virtual representation of a product, process, or environment” although the term *Virtual Twin* “should be used when a virtual entity is twinned to a physical entity” [112].

The “previously unheard levels of control over physical entities and help to manage complex systems by integrating an array of technologies” reported by [109] was based on a comparison – of 28 use cases for agriculture with use cases in other industries – to identify the resulting added value and technology readiness levels. Their resulting “application-based roadmap for a more extended adoption” of DT [109] illustrates the typical components described across the industries to include monitoring, simulation, user interface, learning, actuators, and analytics. These use cases of agricultural DT perform “energy consumption analysis, real-time monitoring, system failure analysis and prediction, optimization/update, and technology integration” [109], which can all be understood as clear benefits. The research has also considered their *technology readiness levels* (TRL) – ranging from *concept* (red) to *prototype* (yellow) to *deployed* (blue) – as indicated (fig. 13).

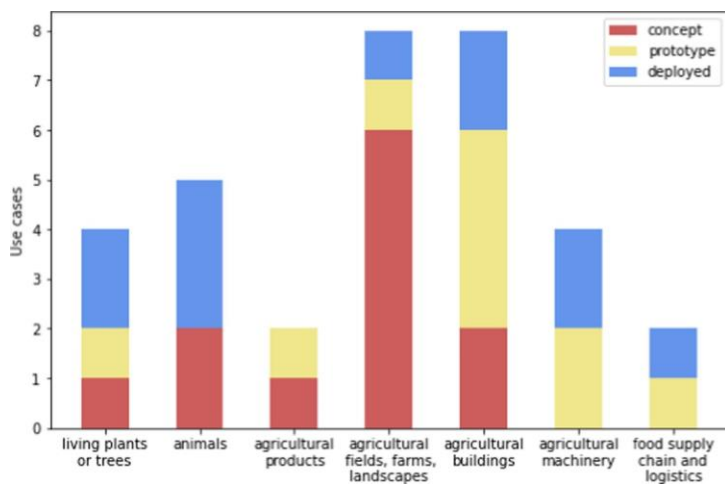


Figure 13 – Service categories and TRL for Digital Twins in Agriculture
Source: [112]

According to these results on TRL for DT in agriculture, the service category of *real-time monitoring* has the most user cases for conception, prototyping, and deployment, followed by conception for optimization/update and *system failure analysis and prediction*, although this last category has far fewer user cases for prototyping and deployment, similar to the least "technologically ready" categories of *technology integration* and *energy consumption analysis*. Joint research by the Universidad Tecnológica Metropolitana and the Universidad de Santiago de Chile has resulted in the proposed "Guidelines for Digital Twins in 5G Agriculture" [119], presented in 2022 in Oporto, Portugal, at the IEEE's 13th International Symposium on Communication Systems, Networks and Digital Signal Processing, complementing the World Economic Forum's Industry Report, "Digital Twins in Agriculture", and other supporting documents [120], like the 2021 report from the World Bank, *What's Cooking: Digital Transformation of the Agrifood System*, commissioned to "explore how digital technologies are improving the food system and provide a roadmap for countries to scale up their own digital agriculture, which is the use of digital technologies in the agriculture and food system" [121].

As for further research involvement, the International Center for Tropical Agriculture (CIAT) conducts research on digital twinning in agriculture, particularly in the context of sustainable farming systems while the International Conference on Agricultural Engineering (AgEng) and the Precision Agriculture Conference & Ag Technology Showcase both feature emerging technologies in agriculture, including digital twinning.

2.5 Towards Agriculture 5.0

To better understand the urgency of Agriculture 5.0, this is an opportunity to recall figure 3 in section 2.1, which in 2018 illustrated a map of technologies and maturity for three aims of Agriculture 4.0, with the following three intertwined objectives:

1. Produce differently using new techniques
2. Use new technologies to bring food production to consumers increasing efficiencies in the food chain
3. Incorporate cross-industry technologies and application

Since then, the growing awareness of dramatic and diverse needs for industrial advances has been accelerated by a pandemic, resulting in the European Commission's

determination that 2021 officially marks the beginning of the era of “Industry 5.0” [34]. Two government agencies serve as an example of support for Agriculture 5.0.

- CropWatch, at the Chinese Academy of Sciences' Institute of Remote Sensing and Digital Earth, for example, offers farms valuable evaluations of their crop yield at various spatial scales using ground-based indicators and remote sensing technologies in space [122];
- Anomaly Hotspots of Agricultural Production (ASAP), the web-based decision-support system with a fitting name, was developed by the Joint Research Centre (JRC) of the European Commission for the early warning of hotspots of agricultural production anomalies, using weather satellite and Earth observation data analysis for the anticipation and prevention of food security crises [123], [124].

With robotic solutions incorporating AI techniques, data-driven agriculture is the basis of sustainable agriculture. As reported by researchers and the University of Granada, Spain, in the context of this 5th Industrial Revolution, remote sensing (RS) is potentially the top technology for agriculture, especially given RS centrality for both soil studies and precision agriculture [125].

Joint research from Manila at De La Salle University and Italy's University of Naples Federico II proposes integrating the Industrial Revolution 4.0 with 5.0 (tab. 4) [60].

Agricultural concerns	Industry 4.0	Industry 5.0
Farm labor	Digital tech COMPLEMENTS traditional farming	Cobots INTERACT so that humans and robots can WORK TOGETHER
Green products and services	Smart factories ALTER the supply chain and company models	All areas of agriculture are BRIDGED through mass customization
Cultivation and post-harvest systems	Food waste is REDUCED and soilless techniques are REINFORCED	Efficiency is BOOSTED with digital technology and AI-based solutions
Agricultural supply chain	Smart links CONNECT consumers and the market	Losses are REDUCED through a green supply chain and design customization

Table 4 – Characteristics of Industry 4.0 transformed into Industry 5.0
Source: Adapted from [60]

To reconcile agriculture with planetary health, Agriculture 5.0 aims to meet the Global Food-Security Challenge for the 21st Century [5]. This research from Canada's First Research Excellence Fund Project "Food from Thought" at the University of Guelph paired with funding from the Social Sciences and Humanities Research Council of Canada and the Ontario Ministry of Agriculture, Food, and Rural Affairs, indicates a population of ten billion (10,000,000,000) in the year 2100, which obliges greater pursuit of sustainability through a circular economy.

2.5.1 Sustainability

When space agriculture becomes sustainable, it will be due to projects like MELiSSA (Micro-Ecological Life Support System Alternative), the European closed life support system project [126]. Initiated in 1987, with contractual obligations beginning in 1989 [127], the European Space Agency (ESA) aimed for maximum autonomy for producing food, water, and oxygen from mission wastes. This regenerative life support system approach exemplifies sustainability and circularity, much like further research that has been examining the potential for developing "bioregenerative life support system[s] [BLSS] and the core aspects of circular economy in space" that supports "adaptive cropping system, robot-based operations, and carbon neutrality" [60], especially for crop monitoring [128] and for aeroponics [129].

More specifically, researchers point out "the opportunity of connectivity of technology with resources and skills in terms of sustainability benefits (zero impact – lower cost – social equity) [... to] reduce the environmental impact of a product, a process, or a service based on footprint data availability and traceable analysis" [130]. The three research questions posed by these researchers are related to economic, social, and environmental sustainability as follows:

*"RQ1. How **applications** of Industry 4.0 can contribute to sustainable development?"*

*RQ2. How Industry 4.0 **technologies and tools can be integrated** into sustainability practices on a theoretical and practical basis?"*

*RQ3. What are **the main approaches/methodologies/frameworks/tools** that should be considered for integrating Industry 4.0 with sustainable development?"*

Examples that respond to the research questions range from "a mathematical model of municipal waste collection routing using I4.0 technologies (big data, CPS, cloud computing, RFID) which allows optimization of the waste collection process" [131] to a reference framework for the sensing, smart and sustainable product development (S3-Product) "based on the Integrated Product, Process, and Manufacturing System Development Reference Model (IPPM)" [132].

Research on sustainable and dynamic competitiveness for the East African community aims for technological leadership "through the convergence of disruptive technologies [...] the remarkable power of Industry 4.0" [133]. Parallel calls are made for the nascent concept of *energy 4.0*, due to the unprecedented levels of energy required by automation, as well as for the "[a]doption of *education 4.0* through implementation of the learning factory [...] for building the requisite skills into the workforce" (italics added) [133].

The World Wildlife Fund [134] and the global *Save Soil* Movement [135], the global initiative led by environmental activist Sadhguru Jaggi Vasudev, in Portugal *Salve o Solo*, promotes hydroponics as a solution for soil depletion through the development of non-soil food production systems, scientifically supported by Soil Scientist Rattan Lal, World Food Prize Awardee 2020 at Ohio State University. In just two years, the Save Soil Movement has elaborated soil policy guidelines for 193 countries, each respecting top agricultural experts, scientists, and lawmakers and respective country's "latitudinal position, climatic conditions, soil type, economic status and agricultural traditions" [136].

Keeping a circular economy in mind to enhance sustainability, it is interesting to note that tools are being created to measure a city's capacity for response, recovery, and transformation. For example, the World Government Summit in collaboration with Strategy&, part of the PwC network (PricewaterhouseCoopers International Limited), offers an Urban Resilience Tool that "provides a composite index based on 131 key performance indicators (KPIs) that cover 36 dimensions, as well as an institutional readiness checklist" [137]. Zurich, Toronto, London, Singapore, and Tokyo are the top five performers of the 20 cities analyzed to date.

2.5.2 Circular economy

The primary concern with access to goods and services, resource management, and waste reduction throughout the product lifecycle sets up the synergetic relationship between sustainability and the circular economy, recognized by Industry 4.0, which has "initiated new forays into digitalization such as crowd sourcing, micro work, and the emerging sharing economy" [138]. In a sharing economy, digital platforms are leveraged to maximize the use of and access to existing resource, whether goods or services. Similarly, the circular economy aims to maximize resource efficiency and minimize waste through products, processes, and business models designed through strategies like recycling and remanufacturing.

Circular Sourcing, Circular Design and Circular Systems are cited as pillars for intentional product design, preparing in advance for their next use so that the products are actively

cycled in their intended cycling pathways. Nevertheless, *recycling* itself is under scrutiny as a sustainable activity. Waste industry expert, operational consultant, and co-founder of Cup Zero, Michael Cyr in his talk at TEDxBuffalo [139] on behalf of the zero-waste movement and to enhance pro-active practices for saving water, encourages that the 3Rs be reformulated, from the original *reduce, reuse, and recycle*, to *reduce, reuse, and reTHINK* in an attempt to mitigate what is commonly referred to as society's collective *single-use plastic addiction*.

The *Financial Times* FT ReThink, for example, points out some companies practicing within the ethos of the circular economy [140], like Cradle-to-Cradle® (C2C) Certified products. Promoting the circular economy via the C2C Certified Products Innovation Institute, these products are recognized under the Responsible Products Framework with Green Star [141], powered by renewably powered electricity, made with safe and healthy chemicals, and designed for disassembly. When "a product's materials or parts are reprocessed for a new product use cycle" [141], specifically *return* and *disassembly* in the technical cycle of figure 14, via recycling, repair, refurbishment, remanufacturing or reuse.

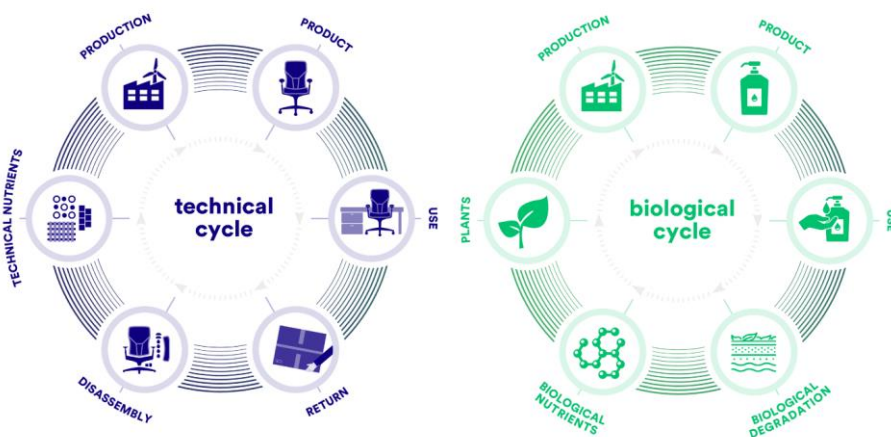


Figure 14 – Technical and biological cycles of the circular economy
Source: [141]

Shown conversely in the biological cycle of figure 14, where *biological degradation* and *biological nutrients* of materials or parts are "released, and ideally reprocessed" [141], the action could include composting, nutrient extraction, or other biological metabolic pathways. The parameters of *production*, *product*, and *use* overlap across the technical and biological cycles of a circular economy.

Hydroponics promotes a circular economy by minimizing resource consumption and waste generation in agricultural production. Water- and nutrient-efficient techniques precisely control the delivery of nutrients directly to plant roots for a dramatic savings in soil and water. These closed loop systems can be integrated with renewable energy sources and established in urban areas or even repurposed industrial spaces, which dramatically reduces transportation costs and, subsequently, carbon emissions associated with food distribution. In a controlled indoor environment, where crops can be grown year-round without pesticides and herbicides. The sustainable cultivation offered by hydroponics optimizes crop yields and ensures consistent food availability, as described in the Farm-to-Fork movement in section 1.1.3, especially when upgraded with agricultural technology.

Not surprisingly, food and agriculture are naturally included in a description of yet another *Something 5.0* called *Society 5.0*, with origins in Japan as “a human-centered (smart) society that balances economic advancement with the resolution of social problems by a system that highly integrates cyberspace and physical space”, also described as human-centric, decentralized, and hyper-automated [59], [142].

2.5.3 Artificial Intelligence in Agriculture 5.0

Considering the progression of technology and the growing need for sustainable, efficient, and precise agricultural practices, the potential place of AI can be envisioned in "Agriculture 5.0," a hypothetical future phase of agriculture parallel to the growth of Industry 5.0 [109]. The potential to revolutionize farming practices, increase productivity, and address sustainability challenges within the fifth wave of the agricultural revolution comes from the application of AI technologies to transform and optimize precision agriculture AI-driven decision-making, sustainable farming crop and livestock monitoring, robotics and automation for autonomous farming, smart sensors and predictive analytics, crop breeding and genomics, and supply chain optimization as described and illustrated with concrete examples from the research.

Precision Agriculture with AI-Driven Decision-Making: AI enables farmers to make data-driven decisions by collecting and analyzing information from various sources such as sensors, satellites, drones, and other sources. These real-time insights contribute to making data-driven decisions regarding irrigation or fertilization, and even pest management, resulting in improved crop yields and reduced environmental impact. To contribute to reducing the 19-29% of total greenhouse gas emissions generated by agriculture, researchers at the

International Institute of Information Technology and the Indian Institute of Horticultural Research in Bangalore together explored Controlled Environment Agriculture in AutoGrow, an instrumented Greenhouse using IoT and AI/ML, for autonomous farming [143].

Crop and Livestock Monitoring: AI-powered systems can monitor crops and livestock health in real-time, detecting diseases, pests, and nutrient deficiencies. This early detection allows for timely intervention, reducing crop losses and improving animal welfare. In the USA, for example, researchers at South Carolina State University in Orangeburg worked with bell-pepper plants, using leaf images obtained from the PlantVillage dataset and video data to detect bacterial spots and then track the pattern of development via drones to predict the way the disease would spread [144].

Robotics and Automation for Autonomous Farming: AI-powered robots and autonomous machinery can perform various tasks, such as planting, harvesting, and weeding, with precision and efficiency, reducing the dependency on manual labor and increasing productivity. Researchers in India point out that the "development of hyper cognitive systems, the incorporation of extended and virtual reality, the prototyping of digital machinery, and twin designs have all been cited as contributing factors to the shift". They highlight the role of collaborative robots, trusted machine boundaries, and supply chains powered by AI [145].

Sustainable Farming: AI can support the implementation of sustainable farming practices through optimizing the use of resources like water, reducing chemical inputs, and promoting biodiversity, thus promoting environmental conservation. In India, researchers at the Amity Institute of Nanotechnology integrated sensors with portable electronics based on Arduino microcontroller and AI to build a biosensing platform for ultrasensitive detection of pesticides, specifically chlorpyrifos, that was affordable, portable, and user-friendly [146].

Smart Sensors and Predictive Analytics: AI can process data from various sensors placed in the soil, on plants, or even on livestock, enabling farmers to predict weather patterns, disease outbreaks, and crop growth, thereby allowing for proactive management strategies. The potential for accurate predictions can help farmers interpret market trends to optimize their production strategies, manage risks, and make better and more informed decisions. In India, researchers applied the Random Forest machine learning algorithm for classification and regression tasks to predict the weather and reduce crop yield output losses [100]. Other researchers in Nigeria at Landmark University and the Federal University Wukari concluded that "Climate Smart Agriculture strategies had positive impacts on crop productivity" [147].

Crop Breeding and Genomics: AI can accelerate the process of crop breeding and genetic research by analyzing vast genomic data and identifying desirable traits, leading to the development of resilient and high-yielding crops as well as predictive models for plant and animal breeding. Recall the potential of the Portuguese National Germoplasm Bank [the *Banco Português de Germoplasma Vegetal*] in Braga, Portugal, as pointed out in section 2.1.

Supply Chain Optimization: AI can improve supply chain efficiency, ensuring that crops are transported, stored, and distributed in the most cost-effective and environmentally friendly manner by optimizing logistics, inventory management, and quality control. By enabling traceability and transparency, AI can not only ensure food safety but also reduce waste. McKinsey & Company especially promote digital twinning for supply chain optimization given that, "[f]or each decision, the number of possible solutions mires optimization analysis in complexity". Specifically, they recommend a variety of objective functions be calibrated in mathematical models to include not just profit but also throughput, cycle time, and inventory optimization. As they explain the logistics, "supply-chain fragmentation multiplies the number of possible flows at each step, giving rise to thousands of possible outcomes" [148].

Large Language Models (LLMs): AI has matured into LLMs like GPT-3, as will be demonstrated in section 4.4.3, contributing to Agriculture 4.0 by facilitating knowledge sharing among farmers to include research, best practices, and real-time advice through digital platforms and predictive analytics. Also, because LLMs can analyze agricultural data, precision farming is conceivable, with smart farming solutions being powered through AI algorithms and predictive analytics while smart sensors monitor plant health and environmental conditions.

Natural Language Processing (NLP): Other AI creation tools harness NLP technology, whereby farmers can engage in seamless knowledge exchange, leveraging digital platforms to access research findings, best-practices, and real-time advice on topics ranging from the weather to market prices and even diagnosing crop disease, which facilitates informed decision-making and optimization of agricultural practices. Through the integration of AI algorithms and predictive analysis, smart farming solutions driven by NLP can enhance efficiency, productivity, and compliance.

Note that the full integration of AI into agriculture will require overcoming various challenges, including data privacy, infrastructure, and regulatory considerations. AI's potential to revolutionize agriculture and address the global challenges of food security and sustainability is undoubtedly significant. Note that even researchers at the Universities of Banja

Luka and East Sarajevo in Bosnia and Herzegovina have recently reported on small farmers actually using digital solutions in the region [149]. Overall, AI in Agriculture 5.0 offers immense potential to enhance knowledge sharing, productivity, sustainability, and profitability in the industry. By leveraging AI technologies, farmers can make more informed decisions, optimize resource allocation, and contribute to a more sustainable and efficient food system.

2.6 Technology used in small farms

According to researchers at the University of Granada, Spain, remote sensing (RS) began in the 19th century, when, in 1858, air balloons were deployed for aerial observations [34]. A variety of technological systems are used for RS, including satellites, robotic process automation (RPA), GNSS, GIS, Big Data analysis, IoT, the Internet of Everything (IoE), cloud computing, wireless sensors technologies (WST), decision-support systems (DSS), and autonomous robots [125]. Today, the sensors involved in smart farming will typically involve the parameters depicted in figure 15.

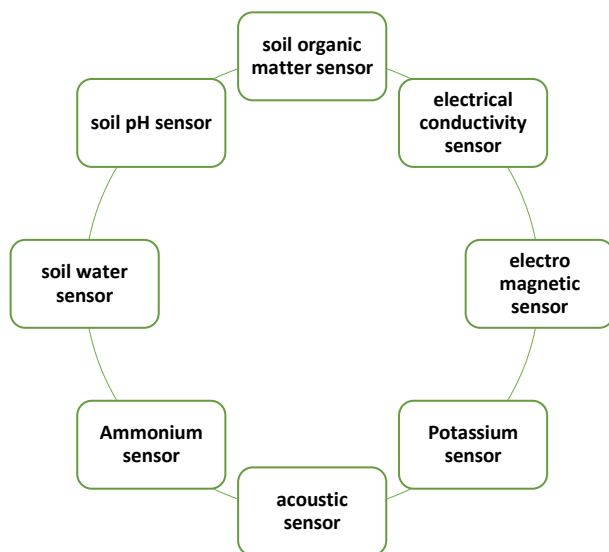


Figure 15 – Various sensors for smart farming
Source: Adapted from [150]

Smart sensors make it possible to monitor wirelessly and at a great distance. Coupled with the above-mentioned IoT technology, smart sensors allow for the transformation of the data acquired into practical knowledge that can then be acted upon. To achieve this wireless dynamic for tracking plants, plant-based products, and equipment, a growing and easy-to-integrate technology within the field is used: Radio Frequency Identification (RFID). This electromagnetic technology identifies and tracks tags through electromagnetic fields at a distance and in continuous real-time monitoring.

The benefits of integrating the food supply and distribution chain with RFID systems resides in the valuable insights to farming operations and even to customers. Note that, in the context of Farm-to-Fork (section 2.5.2), packaging of plant-based products and automated systems with integrated tag readers can represent complete traceability of the entire production lifecycle make it easier to identify and quickly recognize the correct environmental conditions that influence yields and then transfer that capacity and information to smart farming contexts. Beyond the control of plants, plant-based products, and farming equipment, RFID is also capable of aiding in information management for monitoring livestock, crops, and decision-making in smart farm management [151].

Other equipment and activity involving sensors with specific functions related to smart farming include drones and 3-D modeling with LiDAR as well as a variety of environmental sensors. The sensors in a farm perform a number of essential functions so their devices interact with the plants to produce particular types of data output [152]. When the data output from the sensors has been collected, the data is further aggregated and analyzed.

Regardless of the management scenario determined for the growth process, reliable information on the actual status of the vegetation must be prepared to deal with spatial variability and local variations in composition, moisture, and nutrition content. Expected development and crop yield will be conditioned by sensor identification of, for example, the location of suboptimal growth. In smart farming research nearly ten years ago, in 2014, on potato farms in the Dutch North East Polder [152], the data-driven approach successfully determined location and probable cause, based on observations not only from multi-temporal satellite and unmanned aircraft systems, but also in the field regarding soil, vegetation, and yield. Other data related to maps of soil type and height as well as historic parcel and crop information with meteorological data. Using correlation, regression and histogram analysis techniques to analyze the data integrally, the spatial layers could then be visualized in a GIS-based web service environment.

Organizing agricultural data retrieving approaches a mere five years later in 2019, contemporary remote sensing can be considered in just three categories – *purely empirical*, *mechanistic*, and *contextual* – involving the following aspects [153]:

- In purely empirical methods, the measurement represents the direct relationship between the RS signal and biophysical variables using linear and nonlinear regressions for machine learning.
- In methods categorized as mechanistic, radar interferometry and polarimetry draw on Maxwell's equations in a model inversion. Optical and projective geometry can also be used for LiDAR and photogrammetry while solar and microwave domains are used in radiative transfer theory.
- Finally, in the category of contextual methods, segmentation techniques process spatial and temporal characteristics identified in the images that are captured [125].

Specific characteristics have been outlined for each of the current sensors for precision farming, like classification of crops and crop growth monitoring with synthetic aperture radar (SAR) [154] or classification and estimation of geometric attributes of vegetation with Visible RGB (VIS) sensors [155]. Multispectral and hyperspectral sensors identify physiological and biochemical attributes, like crop water content, leaf/canopy chlorophyll content, and nitrogen content [156]. The leaf area index can also be identified with fluorescence spectroscopy and imaging sensors that indicate the chlorophyll and nitrogen content and the nitrogen-to-carbon ratio [157]. Laser/light detection and ranging (LiDAR) identifies horizontal and vertical structural characteristics of plants [158] while near-infrared (NIR) sensors are used to gather data about crop health, water management, soil moisture analysis, plant counting, and erosion analysis [133], [159].

2.7 The place of hydroponics in Agriculture 5.0

Hydroponics offers an important alternative and even contributes to the resolution of a number of burning issues, from the need to substitute soil-grown agriculture to the need to create food for the growing world population. Using water on a significantly reduced scale, hydroponics also goes a long way toward developing practice that can itself inform policy on water usage, thus providing a viable solution to the scarcity of water issue (for a valuable infographic on the economic and physical types of water scarcity, see also Appendix A4) [160].

As the basis of economies over time, the potential for saving not only water but also space validates the application of engineering to hydroponics to bring it up to the finest levels of technology. Based on improved results in so many relevant factors from quality to quantity of production, as argued in section 1.2, the easy-to-install system, which eventually could even be installed by robots, justifies full automation for complete system monitoring, maintenance of equipment, and integration of nutrients, securing environmental vigor that sustains plant growth.

To reach the goals of Agriculture 5.0, a sensorized and automated system should optimize the use of resources to improve yield and resource efficiency, including reduced labor costs due to automation. Real-time monitoring and control of key parameters can also be achieved for light, temperature, humidity, barometric pressure, ground chemical concentration, drone equipment, video cameras, agricultural information management systems, GPS, and communication networks [82], via IoT and CPS technologies, which should enable prompt corrective action to be taken in case of any deviations from the desired values. Environmental sustainability is also impacted positively by the use of IoT and CPS technologies for hydroponic systems.

2.7.1 CPS in hydroponics

Given that as a part of small farms, hydroponics may make extensive use of sensors to monitor plant life, the present research explores why these sensors are used and justify their place in IoT systems. Plants need nutrients, which in turn must be monitored through sensors for pH, electrical conductivity (EC), temperature, oxygen, and light.

Sensors that monitor pH, which defines the level of absorption that the plants need for nutrients, can help to identify the moment when the pH levels deviate excessively from the ideal, when a nutrient lockout may occur that is damaging to the plant roots. In general, a safe range for plants is in between 5.8 and 6.5 but may vary according to plant type [161]. Employing pH sensors promotes the dedicated maintenance of the growth medium.

EC is an indicator of the accessible nutrient in the water used for absorption by the plant. EC is a way to gauge the amount of nutrients available thanks to their electrical charge. If there is a greater variation in the EC levels this can lead to a lower yield because of the paucity of available nutrients and the vulnerability to disease due to either extreme levels of salt or overfeeding. The optimal EC level is different for every plant [162].

Temperature is another vital characteristic of the hydroponic environment, especially since plants species all have designated environments. By sensing temperature, the plants' potential for growth is maximized.

Oxygen, the molecule, plays an important part in all life forms. For plants to grow, it aids in aerobic respiration where nutrients are broken down so they can release energy. Monitoring the oxygen levels in the water makes it possible to determine when to activate the air pump, pumping new air into the system, effectively reoxygenating the hydroponic system.

Light plays an essential role in photosynthesis, the process that converts carbon dioxide into oxygen and energy into sugar. As plants are sensitive to wavelengths from 400 to 700 nanometers, sensors can be used to identify when that wavelength is no longer being produced and adjust appropriately for the plant's needs using the wavelengths made available by the Sun.

Sensors are also used for characteristics caught on camera, to visualize live data remotely, and to interfere with the system at a distance with actuators or characterize plant life according to data such as number of leaves or color of flowers.

After sensing these environmental attributes of the system, a control system must be employed for the necessary processing activities of the data from the sensors. A number of use cases exist within other projects using Arduino [163], [164] and Raspberry Pi [162], [165]. Once the data has gone through aggregation and has been processed, decision-making occurs through the use of LLMs or NLPs, and CPS actuators are used to implement those decisions into the hydroponic system. Several common actuators are used in hydroponics [166]:

- Water pumps are responsible for cycling water as an important part of hydroponic systems, especially in models with no air pumps to reoxygenate the water or where the water level must be adjusted.
- Air pumps reoxygenate the water through acting directly within its medium.
- Vents or fans manage alterations and stabilization of temperature as required in the system.
- Nutrient pumps dispense the nutrient solution into the water.
- pH corrector pumps dispense the right amount to regulate the pH levels in the water.

2.7.2 Types of hydroponics

As nutrient monitoring occurs via these sensors, it is essential to understand the types and the respective pros and cons of the hydroponic methods available. This section details

four different methods that would allow for implementation, labeled *a-d* (fig. 16), where (a) is Deep Water Culture; (b) is Drip Irrigation; (c) is Aeroponics; and (d) is the Nutrient Film Technique.

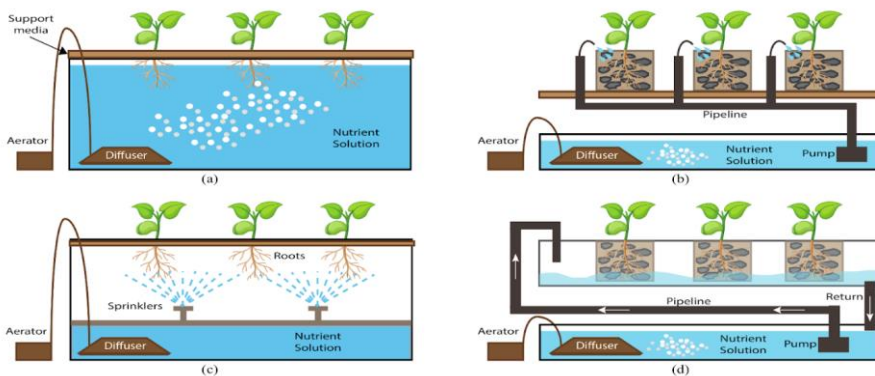


Figure 16 – Different types of hydroponic systems (a-d)
Source: [167]

To better understand which of these systems is more appropriate for the project at hand, research has revealed their strengths and challenges.

a) Deep Water Culture (DWC) is a system where the roots are suspended in water 24/7. It is called *deep* because the reservoir requires at least 22 cm of water [168]–[170]. Steps to create a functioning DWC system:

1. Set up a reservoir containing water and a nutrient solution dissolved within.
2. The water is then oxygenated with air pumps using air stones. Alternatively, waterfalls can also be used to allow for more oxygen to enter the system through water displacement. Nevertheless, this technique is used more in commercial areas due to the amount of water that can be displaced in those cases.
3. A lid is secured above the reservoir with holes that are used to secure the net pots.
4. The net pots are then filled with growing media, like Hydroton or Rockwool, to hold the base of the plant.
5. Seedlings are placed in the net pots so that the only part of the plant that stays submerged is the roots.

There are four main types of DWC systems that are commercially used, some more widespread than others. In the **Kratky Method**, the plant roots are not completely submerged in water. The reservoir is left with openings at the top to allow for the circulation of oxygen

although solving the oxygenation issue is often limited in scalability by the small size of most reservoirs that are essentially designed for single-use cases. The **Recirculation DWC** method involves connecting multiple reservoirs through a pipe system, allowing the nutrient-rich water to flow between the reservoirs. This setup saves time as it eliminates the need to individually fill each reservoir; nevertheless, one drawback is that, when a disease occurs in an isolated reservoir, it can quickly spread to the other connected reservoirs, potentially affecting the entire system. The **Commercial DWC system** is commonly used in larger-scale operations and utilizes rafts floating on ponds or large reservoirs. It is a straightforward and widely adopted method without any unique features or characteristics. Finally, the **Bubbleponics variation of DWC** circulates the water from the reservoir directly into the plant roots, providing accelerated growth during the initial stages of the plant's development. Bubbleponics utilizes a combination of air and water to deliver nutrients and oxygen to the roots efficiently.

Table 5 provides an at-a-glance view of the many pros and cons of DWC, organized into areas of concern, like *equipment and maintenance*, *dimension and layout*, and finally, *growth, environment, and nutrition*.

DISADVANTAGES OF DWC	ADVANTAGES OF DWC
Equipment & Maintenance	
<p>Difficulty in calibration: In smaller reservoirs, it can be challenging to calibrate the pH and nutrient levels accurately. Precise calibration is essential for maintaining optimal growing conditions and avoiding nutrient imbalances that can harm the plants.</p> <p>Regular cleaning required: DWC systems require regular cleaning to prevent the buildup of algae, bacteria, or other contaminants. Neglecting to clean the system can lead to health issues for the plants and negatively impact their growth.</p> <p>Risk of pump or power failure: If the pump or power supply fails in a DWC system, the water may not be properly oxygenated, leading to oxygen deprivation for the plants and potentially causing their death.</p>	<p>Easy and inexpensive setup: Setting up a DWC system is straightforward and cost-effective. Basic materials are all that's needed to get started.</p> <p>Low maintenance: Once set up, DWC systems require minimal maintenance. Monitoring the pH, EC, and temperature is crucial, but overall upkeep is relatively low.</p> <p>Easy to clean: Maintaining cleanliness in a DWC system is relatively simple. Regular cleaning ensures a healthy growing environment for the plants.</p> <p>No timers required: Unlike some other hydroponic systems, DWC does not require timers for irrigation. The roots are constantly submerged in nutrient-rich water, eliminating the need for periodic watering.</p>
Dimension & Layout	
<p>Smaller size compared to other hydroponic systems: DWC systems typically have smaller reservoirs compared to some other hydroponic systems, which may limit the number of plants that can be grown or the overall yield.</p>	<p>Space-efficient: DWC systems require minimal space, making them ideal for indoor gardening or areas with limited room for traditional soil-based cultivation.</p> <p>Ability to grow multiple plants: DWC systems can accommodate multiple plants, making it a suitable choice for growers looking to cultivate a variety of crops.</p>
Growth, Environment, & Nutrition	
<p>Seedlings: Seedling growth must be done outside of the DWC system as they have no conditions to grow inside this system.</p> <p>Variations in pH, EC, and water level: In smaller DWC reservoirs, there can be significant fluctuations in pH levels, electrical conductivity (EC), and water levels. These variations need to be monitored manually and adjusted accordingly to maintain optimal growing conditions.</p> <p>Increased water temperature: The constant operation of the air pump in a DWC system can lead to an increase in water temperature. Higher water temperatures can affect the oxygen levels in the water and potentially impact plant health.</p>	<p>Accelerated growth and larger yield: DWC systems promote faster growth and increased yield due to the improved absorption of nutrients and oxygen by the plant roots.</p> <p>Stable pH, EC, and temperature: In large DWC reservoirs, fluctuations in pH, EC, and temperature are minimized, providing a stable environment for plant growth.</p> <p>Reduced nutrient usage: Compared to other hydroponic systems, DWC requires less nutrient solution, making it cost-effective and environmentally friendly.</p>

Table 5 – Pros and cons of Deep Water Culture
Source: Adapted from [170], [171]

b) **Drip Irrigation** uses an active irrigation system via water pump and small emitters to trickle nutrient solution into each plant's net, for better controlled moisture and food delivery. Instead of overhead irrigation, the pumps are set up directly at the base of the plants to protect them from evaporation. Drip systems can be set up individually, in separate containers, should that be required. With the use of a cycle timer, the growth medium can be soaked and then

turned off at a desired time to allow for less excess solution to be drained into the reservoir [170], [172].

Steps to create a functioning Drip Irrigation system:

1. An oxygenated, nutrient filled water reservoir is positioned at the base of the plants.
2. This solution is then sent via a water pump through drip lines to feed the plants at their root mass; these smaller tubes inside the net are called *drip emitters*.
3. Excess solution will then drip to the reservoir to be re-used or discarded.

The two main types of Drip Irrigation system are both related to the objective of recovering the excess nutrient solution (or not) [172]. In a **Recovery Drip Irrigation** system, the unused or excess nutrient solution is returned to the reservoir for recycling. Although this process is beneficial for home setups, over time, effective recycling can affect pH levels so that they require regular monitoring and adjustment. In a **Non-Recovery Drip Irrigation** system, the unused nutrient solution is not recycled but is instead disposed of. This outcome is often desired in commercial settings where maintaining consistent nutrient balance is crucial. However, the disposal can result in waste generation and may require proper waste management practices.

Table 6 provides a clear visualization of the pros and cons of Drip Irrigation, organized like *Deep Water Circulation* (tab. 5 above) into the same areas of concern:

DISADVANTAGES OF DRIP IRRIGATION	ADVANTAGES OF DRIP IRRIGATION
Equipment & Maintenance	
<p>Clogging of drip emitters: Drip emitters can become clogged with algae or nutrient mineral residue over time, affecting the even distribution of water and nutrients. Regular maintenance and cleaning are necessary to prevent this issue.</p> <p>High accuracy cycle timers: Drip systems rely on cycle timers to control the frequency and duration of irrigation cycles. These timers need to be accurate to avoid under- or over-watering, which can impact plant health.</p>	<p>Affordable and easy installation: Drip irrigation systems are cost-effective and simple to set up, making them accessible for a wide range of growers.</p> <p>Controllable water input and drip locations: Drip systems allow precise control over water delivery and nutrient distribution, enabling targeted irrigation and customization for different plant needs.</p> <p>Scalable: Drip irrigation can be easily scaled up or down to accommodate different garden sizes or agricultural operations.</p>
Dimension & Layout	
<p>Complex layout: More tubes means that there is necessarily more complexity to the design.</p>	<p>Versatility: Drip systems are suitable for various plants, including both small-scale and large-scale cultivation.</p>
Growth, Environment, & Nutrition	
<p>Monitoring pH and EC levels: In a recirculating drip system, it can be challenging to monitor and maintain optimal pH and electrical conductivity (EC) levels in the nutrient solution. Regular testing and adjustments are required to ensure proper plant nutrition.</p> <p>Potential waste disposal: If excess nutrient solution needs to be disposed of, there is a chance of generating excess waste, which may require proper disposal methods to avoid environmental issues.</p>	<p>Resource efficient: Drip irrigation is highly efficient in water usage since it delivers water directly to the roots, reducing wastage and evaporation.</p>

Table 6 – Pros and cons of a Drip Irrigation system
Source: Adapted from [169]

c) **Aeroponics** was created as a system that could combat the deteriorating quality of the soil. This objective should come as no surprise given the growing world population which furthers the need for a robust and efficient agricultural system. Aeroponics, however, is a more technical system due to the absence of a growth medium, whereby the plants are hung in the air in a closed-loop system. The roots then can be sprayed with nutrient-rich water, misting the medium for periodic intervals [173].

Steps to create a functioning Aeroponics system:

1. Prepare a support collar to hold the stems securely airborne.
2. Below that, prepare an open-top reservoir.
3. Install a pump and sprinkler system to create the nutritional mist.
4. Apply a timer to the aforementioned systems for periodic spray intervals.

There are three different types of aeroponic systems available, including variations in pressure and atomizers. **Low-Pressure Aeroponics (LPA)** systems simply create a lower density mist and, thus, require less technical knowledge to operate and maintain. In contrast, **High-Pressure Aeroponics (HPA)** systems are primarily used in commercial environments

due to their high cost. They generate a higher density mist, providing more oxygen to the root zone through a high-pressure pulverization method. HPA is considered the most efficient aeroponic system. Finally, **Ultrasonic Fogger Aeroponics** is a method that atomizes water. The fog resulting from the small droplets is easily absorbed by the plant root mass. While an efficient approach, it is also prone to clogging due to salt accumulation, requiring regular maintenance and cleaning of the foggers.

Following the classification method established to review *Deep Water Circulation* (tab. 5) and for *Drip Irrigation* (tab. 6), a third method is detailed in Table 7, which provides an overview of the lack of balance in the comparison of the pros and cons of Aeroponics.

DISADVANTAGES OF AEROPONICS	ADVANTAGES OF AEROPONICS
Equipment & Maintenance	
<p>High initial costs: Setting up an aeroponic system can be expensive due to the specialized equipment and technology required.</p> <p>Constant supervision: Aeroponic systems demand regular monitoring and maintenance to ensure proper functioning and to avoid issues such as clogging, nutrient imbalances, or equipment failures.</p> <p>Fragility against power outages: In the absence of a growing medium, plants in aeroponic systems rely entirely on the provided nutrient solution. If power outages occur and the plants are not supplied with adequate nutrients, they can quickly deteriorate.</p> <p>Not beginner friendly: Aeroponics can be complex and challenging for beginners, requiring a solid understanding of the system's mechanics and precise management.</p> <p>Need for regular disinfection: Due to the mist environment, regular disinfection is necessary to prevent the buildup of pathogens or contaminants.</p>	<p>Easy cleaning: The absence of a growing medium simplifies the cleaning process, ensuring a hygienic growing environment.</p>
Dimension & Layout	
	<p>Mobility: Plants in aeroponic systems can be easily moved from one environment to another, offering flexibility in gardening or research settings.</p> <p>Little to no space constraints: Aeroponic systems can be designed to fit in small spaces, making them suitable for urban gardening or indoor cultivation.</p>
Growth, Environment, & Nutrition	
<p>System dependency: Plants in aeroponic systems become highly dependent on the system, as all their nutritional needs are solely met through the system's nutrient delivery.</p> <p>Constant attention to pH and nutrient ratios: Aeroponic systems require constant monitoring and adjustment of pH levels and nutrient concentrations due to the system's sensitivity to these factors.</p>	<p>Higher yield: Due to the optimized nutrient absorption and oxygenation, aeroponic systems often result in higher yields compared to other cultivation methods.</p> <p>Resource efficiency: Aeroponics requires fewer resources in terms of nutrients and water due to the higher nutrient absorption rate, making it a sustainable option.</p> <p>Maximum nutrient absorption: Aeroponics allows for maximum nutrient absorption since there is no growing medium, enabling direct contact between the roots and nutrient solution.</p> <p>Improved root oxygenation: The system maximizes root oxygenation, promoting healthier and faster plant growth.</p> <p>Sterilization of mist: The mist used in aeroponics can be sterilized, minimizing the risk of plant diseases and pathogens.</p>

Table 7 – Pros and cons of Aeroponics
Source: Adapted from [173]

d) **Nutrient Film Technique (NFT)** uses a low-flow irrigation system to feed the plants in the system. The water is pumped into a flat channel slowly so that a thin “film” is where the plants get their nutrients from. When the roots touch the film, they “drink” from the solution while maintaining the possibility for aeration [174].

Steps to create a functioning NFT system:

1. Set up a long, flat channel of pipe at a slight angle.
2. Drill holes wide enough to mount net cups through them.
3. Add a reservoir situated so that the nutrient solution that isn't absorbed can move in that direction.
4. Add pumps that go from the reservoir to the top of the channel [16].

Applying the classification of the previous three tables once again, Table 8 illustrates the comparatively fewer concerning pros and cons of the Nutrient Film Technique.

DISADVANTAGES OF NFT	ADVANTAGES OF NFT
Equipment & Maintenance	
Fragility to power outages: NFT systems rely on a constant flow of nutrient solution. In the event of a power outage or pump failure, the absence of a substrate means that the roots are not retained in any moisture, which can quickly lead to plant stress or damage.	<p>Cost-effective: NFT systems are generally inexpensive to set up, making them accessible for growers on a budget or those new to hydroponics.</p> <p>Simplicity: NFT is a passive system that relies on gravity to create a continuous flow of nutrient solution. It does not require timers or air pumps, resulting in a simpler setup and reduced energy consumption.</p>
Dimension & Layout	
Not ideal for fruit-bearing plants: NFT may not be the most suitable method for plants that bear fruits or crops with heavier nutrient demands. These plants often require a more substantial root support system and a larger nutrient supply.	
Growth, Environment, & Nutrition	
Potential for diseases in recirculating systems: In recirculating NFT systems, where the nutrient solution is reused, there is a higher risk of disease transmission. If one plant becomes infected, the pathogens can spread through the recirculating water to other plants more easily.	<p>Water efficiency: NFT is a water-efficient hydroponic system because it makes use of a thin film of nutrient-rich water flowing over the roots, minimizing water consumption compared to traditional soil-based cultivation.</p> <p>Suitable for leafy vegetables: NFT is particularly well-suited for growing leafy vegetables, like lettuce, spinach, and herbs. The thin nutrient film provides optimal conditions for their growth and development.</p>

*Table 8 – Pros and cons of the Nutrient Film Technique
Source: Adapted from [175]*

Other hydroponic systems, such as Ebb & Flow and Aquaponics, were discarded from this study due to their similarity with other systems. Ebb & Flow particularly presented a lot of similarities with the NFT system but did not offer significant benefits. As for the Aquaponics system, the feature of introducing live fish into this system is not a variable that is foreseen as added value in the context of this dissertation.

2.7.2.1 Choosing Nutrient Film Technique

While other hydroponic systems have excellent capabilities for scalability and implementation, this dissertation aims, primarily, to make a functioning monitoring implementation for a hydroponic system using relevant IoT and CPS concepts and methodologies, considering environmentally sustainable practices within the agricultural sector. Upon debating which characteristics were more important to consider, ease of conception, as well as maintenance, were found to be the foremost criteria and, as such, the NFT system was chosen as the hydroponic system to be developed for this dissertation due to the timeframe available and the opportunity to also pursue other related concepts in the fields of electro-technical engineering and computers, as will be developed in Chapter 3.

3.

PROOF OF CONCEPT DESIGN

This chapter of the dissertation traces the steps taken to create the ideal model to solve the research question: "Given the growth of a worldwide data-driven mindset, how can we use IoT and CPS technologies in contemporary small-sized hydroponics systems in order to provide a scalable solution for monitorization and decision support with an interactive user interface?" (see section 1.2).

To approach this problem, the ideal overall architecture of the system was first conceptualized before zooming in on the specific components and searching for the characteristics of the sensors and defining their outputs. Through these outputs, accurate data parameters were established to be acted upon through the use of actuators. Data management systems should make available data storage and analysis tools as well as Big Data techniques to the user. This will be done through a data reporting and monitoring GUI to allow for user interaction with the system which will be suited with an AI that supports the user with any questions within the field of hydroponics, but even more specifically any problems with this specific NFT system.

After conceptualizing the architecture and its sensors, actuators, data parameters, and decision-making tools, these working parts were then brought together in a sequence diagram and an activity diagram. As such, having clearly distinguished *what* integrates the system and *how* the system interacts with each of its parts, all that remained was to establish *which* events occur in the system and their respective *triggers*.

3.1 Specific Architecture

Based on section 2.2, the specific IoT architecture created for this NFT hydroponics project based on the UNINOVA IoT Hub Architecture [176] is designated in Table 9.

Application Layer	Data Monitoring & Reporting	AI based Decision-Support Tool
Function Layer	IoT Hub	
Information Layer	IoT Node	Database Repository
Communication Layer	<div style="border: 1px dashed gray; padding: 5px; width: fit-content; margin: auto;"> Data Handler MQTT Broker </div>	Communication Protocol(s)
Physical Layer	Environmental Sensors <div style="border: 1px dashed gray; padding: 5px; width: fit-content; margin: auto;"> humidity sensor light sensor temperature sensor </div>	Reservoir Sensors & Actuators <div style="border: 1px dashed gray; padding: 5px; width: fit-content; margin: auto;"> water temperature sensor pH sensor EC sensor liquid pumps </div>

Table 9 – IoT architecture for the proof of concept

The details for each layer, as described below, are based on the state of the art reported on *IoT for Agriculture* and on *Big Data for Agriculture* in sections 2.2 and 2.3.

The *Physical Layer* establishes the integration of various sensors for management and monitoring. Both the environment and the reservoir must be managed, described in section 2.7, by sensors for humidity and temperature as follows:

- Humidity sensors monitor the humidity in the ventilated environment. A well-controlled humidity in the environment helps optimize plant growth by affecting plant transpiration which, in turn, directly affects nutrient uptake. Since high humidity spreads fungi and bacteria, these sensors also help to prevent plant disease. The ventilation in an environment at the ideal humidity helps oxygen exchange, a core functions of the plant's process of photosynthesis.
- Temperature sensors monitor and control the ambient temperature through the ventilation and a heat sink. Heat impacts plant metabolism and, thus, nutrient

uptake to determine plant growth. Like the seasons, higher temperatures support plant health while lower temperatures slow down processes vital to plant growth.

The humidity and temperature sensors manage the environment but monitoring the water reservoir also requires sensors for EC, pH, and temperature for the following purposes:

- EC sensors detect the electrical conductivity (EC) level in the water, which is maintained through nutrition pumps that maintain the pre-determined EC level. EC allows for clear understanding of nutritional density in the reservoir, which in turn allows access to information on nutrient uptake and water management;
- pH sensors monitor the pH level in the water, which is maintained through pH pumps. When activated, the pH pumps add an acid or a base to the water reservoir to reach the predetermined pH levels. Fighting nutrient lockout, which occurs when a plant cannot take in more nutrients due to exterior factors, such as when nutrients become chemically bound to the growth medium;
- Temperature sensors monitor the temperature levels in the water reservoir, which can lead to the use of more predictive models for EC and pH since their values depend on the temperature of the reservoir.

In addition to these sensors, the *actuators* require liquid pumps to manage the flow of pH balancers and necessary nutrient solution into the reservoir. Specifically, peristaltic pumps, which are completely isolated from other systems, work with tubing that further isolates the two interfacing mediums – the reservoir and the nutrient solution dispenser.

The *Communication Layer* is composed of a Data Handler for high-level communication between the IoT Node and the IoT Hub so that the filtered data can be structured. The objectives of the IoT Node are (1) to manage data at a local level, receiving and pre-processing that data at a low level, which allows the actuators to respond quickly; and (2) to execute instructions received from the IoT Hub. In turn, the IoT Hub is responsible for aggregating the data that is received in the nodes and cleaning it for insertion into the database, as seen in section 2.2.1.

Then in the *Information Layer*, data is stored with a microprocessor that filters data at this level when information is received from the sensors and then organizes that data in a pre-determined fashion. The Database Repository contains a database, where both DTS and ATS can be created per section 2.3.

In the *Function Layer*, the IoT Hub, through which all data from the applied system flows, receives all the data from any IoT Node and then stores and processes it regarding

specific events. This concept is inspired by the IoT Architecture from the UNINOVA IoT Hub Architecture [176], where the remaining backend work is processed after the data is consolidated and a Service Manager contains continuous services that handle the general operations through their applications.

At the highest level, the *Application Layer* provides tools that access the data in the system, where DTS and ATS can be requested at any time. The availability of this timebound information is what allows this system can be both accurate and close to real time. Data files are saved in a Data Repository and then reviewed with AI or by data analysts for further aid in decision-making through the UI. With AI, the system should be able to analyze data from the Data Repository and offer services to the user based on the AI's local experience, through a shared history in between the Data Repository, and the conversation with the AI, such as advice on best practices for plant growth or predictions on future light levels of the location.

3.2 Physical Layer

While sensors have been considered from the perspective of electrotechnical engineering, important aspects are related to chemistry, for example, to measure pH and electrical conductivity. The environmental sensors for temperature and humidity, as described in section 2.7.1, will be based on physical factors.

3.2.1 pH sensors

To measure the acidity of a solution, a pH sensor detects the concentration of hydrogen ions through a pH probe and a pH meter, which respectively record and convert voltage into a readable pH value. The pH scale is a logarithmic representation of hydrogen ion concentration, with higher pH values indicating lower acidity, and lower pH values indicating higher acidity [177]

Glass electrodes in pH sensors work by recognizing the positive charge of hydrogen ions, measured in millivolts, and transmitting this signal to the pH meter [178]. The glass electrode encases a silver-based wire in a membrane made from a glass containing sodium and calcium salt compounds [179]. The reference electrode uses a potassium chloride wire and both electrodes are placed in a neutral solution with a pH of 7. The pH measurement is displayed digitally, based on the potential difference between the two electrodes.

The choice of chemicals in these sensors has evolved due to concerns about toxicity. For example, mercury is now less commonly used for the reference electrode, and iodine is emerging as a preference over potassium chloride to avoid crystallization at low temperatures.

3.2.2 Electrical conductivity sensors

Electrical conductivity (EC) sensors measure the EC in the water used for this NFT hydroponics project. By applying conductivity detection, analytical chemistry is being applied to measure the ability of a solution to carry an electric current by detecting changes in ion concentration in a solution without the addition of reagents or complex equipment. This valuable information about the ionic composition and concentration of solutions is derived from the EC sensors [180][181], which contain a sensing electrode (working-electrode or anode), a counter-electrode (cathode), a diffusion barrier, and an electrolyte, all of which may require frequent substitution due to their limited natural life. When fabricated with microfluidic devices, the EC cell is suitable for biosensor applications like the system for this project.

When the two electrodes are immersed in a solution, they pass an electrical current through it. In this electric field, charged ions in the solution start to move. Positively charged ions (cations) move towards the negative electrode (cathode), while negatively charged ions (anions) move towards the positive electrode (anode). This flow is measured based on redox reactions so that the greater the number of ions in the solution, the higher the conductivity, information that can be used to monitor processes like chemical reactions and ion exchange.

Note that, to obtain accurate measurements, calibration of the conductivity meter is essential. The sensor is calibrated using standard solutions with known ion concentrations to establish a base relationship between the measured conductivity and the ion concentration. Because conductivity detection is widely used for quality control, the industrial production areas of food, pharmaceuticals, and chemical research are particularly involved. To date, open-source EC sensors have not been able to meet the precision and accuracy of commercial EC sensors although the specific brands in this project were not evaluated [182]. Nevertheless, it is interesting to note that the performance of all EC sensors in the study had mean errors of less than 10%.

3.2.3 Environmental sensors

The environmental sensors explored cover variables of temperature and humidity. The aim is to normalize an environment where replicable data can be found from successful environments.

3.2.3.1 Water temperature sensors

Temperature sensors involve either an increase or a decrease in response to a rise in temperature, respectively reflecting the reaction of positive and negative resistance sensors. The primary types of contact thermometers are thermocouples, resistance temperature detectors (RTD), thermistor temperature sensors, semiconductor temperature sensors, vibrating wire temperature sensors, or thermometers [183].

A close study of the temperature sensors for this project revealed that the DS18B20 Programmable Resolution 1-Wire Digital Thermometer by Maxim[184] has a 64-bit ROM, where its individual serial code is stored. The scratchpad memory is read via the One-wire bus by the Dallas library [185]. It is through a configuration register that the user selects the resolution of the temperature-to-digital conversion in a range of 9 to 12 bits. Of special note, the configuration registers are nonvolatile (also known as *electrically erasable programmable read-only memory*, or EEPROM/E²PROM), which ensures data retention even when the device is powered off [186].

The bus communication for the thermometer uses Maxim's exclusive 1-Wire bus protocol, utilizing just one control signal. As the devices connect to the bus through a 3-state (in normal mode), the control line requires a weak pullup resistor [185].

3.2.3.2 Air Humidity/Temperature sensors

Another possibility tested for this project was the DHT22 wireless (or AM2302 for the wired version) humidity/temperature sensor [187]. The negative temperature coefficient (NTC) means that the resistance decreases with increase of the temperature. The 8-bit SOIC-14 packaged IC is a *small outline integrated circuit* in an *integrated circuit* of the small PCB. This microcontroller is responsible for measuring and processing the analog signal with stored calibration coefficients. It also converts analog to digital and gives out the digital signal with the temperature and humidity. The DHT22's humidity sensor capacitor comprises two electrodes separated by a substrate that holds moisture, acting as a dielectric material. Variations in humidity levels lead to alterations in the capacitance value. The resulting digital signal is sent to the data pin and new data is made available every 2 seconds [188].

3.2.4 Triggers of each event

Although all the sensing devices represent specific objectives for the system, creating the events that allow for actuation is their main objective. As such, the following table describes a number of possible scenarios for the sensors (tab. 10).

Objective	Associated Devices	Conditions and Possible Actuation
Adequate water pH	pH Sensor	When pH is beyond the suitable boundaries of 5.6 minimum and 6.5 maximum, use the nutrition pumps to pump the correct amount of pH solution until it is within its threshold.
Adequate water EC	EC Sensor	When EC levels are detected to be at or below the established minimum of 6 mS/cm, the nutrition pumps are activated to correct the level of the EC solution.
Adequate water temperature	Temperature sensor	When water temperature is above 27°C, additional water is pumped from the reservoir into the plant channels and new water is pumped into the reservoir.
Adequate environmental humidity	Temperature/humidity sensor	When the humidity level rises, a ventilation fan is turned on to vent new air in and out of the system maintaining the system at 70-80% humidity in the Seeding stage, 50-70% in the Vegetative stage and 40-50% in the Flowering stage.
Adequate environmental temperature	Temperature/humidity sensor	When the environmental temperature rises to above 27°C and threatens plant growth, a coolant device can be turned on to affect the environment. Conversely, when temperatures drop below 15°C, a heat generation device may be activated.

Table 10 – A selection of scenarios for the sensors in this prototype

The data acquired from some of these sensors will be stored in a database to infer event processing and generate further actions for the system. Note that specific thresholds are different on a plant-by-plant case.

3.3 Communication Layer

The Communication Layer aims to establish the connection between the IoT systems, like the IoT Node and the IoT Hub. Applying the protocols that were discussed in section 2.2.2 means that topics can be created, and subscribed to, in this layer.

3.3.1 Communication Protocol

Communication protocols create bridges that enable devices to communicate with one another seamlessly, as interoperability is a big problem in these systems it is important to

choose a reliable protocol that is scalable and in line with this project's needs. The protocols in Section 2.2 are fit to the specifications for this system.

3.3.2 Data Handler

As reviewed in Section 3.1, the data handler manifests itself in this system as an MQTT Broker. Topics for each of the sensors are created for each IoT node and information collected is published in real time to be processed by the IoT Hub, which subscribes to these different topics. The unidirectional communication that is necessary for these systems means that multiple nodes can publish their data and, thus, a scalable system can be built. It is also advantageous that most MQTT systems are lightweight and applicable in any hydroponic space. In this proof of concept, the topics that can be used and subscribed to can be described as simply as "pH" or "EC".

3.4 Information Layer

The Information Layer aims, as in any OSI system, to manage data. The requirements for this layer are that it should be able to manage vast amounts of IoT Node data, requiring a second element – the Data Repository.

The IoT Node allows for implementing processes locally in the realms of data acquisition, data cleaning, and data aggregation, as demonstrated in figure 11. Microprocessors will be responsible for dealing with the instructions needed and can be integrated with commonly used sensors in the field of hydroponics.

The data repository can implement relational rules in between concepts to establish connections between data and allow to create more complex knowledge inference. Using as base the characteristics gleaned in section 2.7.2 for hydroponic projects, a data repository is where the packages of the IoT Node are delivered through MQTT protocol. The data repository should then be able to keep ATS and DTS information readily available so that the IoT Hub may access it without issue.

3.4.1 Database Repository

The entities within the database were first identified – the sensors, reservoirs, plants, and environments – and the species (or the common name) of each plant and the number of each plant in the system were the characteristics to be identified. As a key part of the system,

the characteristics for the sensors in the database had to be as generic as possible to correspond to any sensor brand that might be added to the system and thus creating a digital shadow, as shown in section 2.4 (fig 12). As such, the sensors in the database were categorized by the device's name, the metadata of the sensor (to obtain meta-data, such as time and tokens, from the sensor), and the type of sensor (whether for the reservoir or for the environment). To build the Entity Relationship (ER) model, the tables were filled with the descriptive information: characteristics of the message – description, format, and message type – as in a recent project on plant growth in floating ebb and flow systems [189].

Finally, the last part of this database involved the nutrient solutions, which describe the pump system where the pH balancers and nutrients are kept for when they need to be added to the system. The nutrient solutions were described with their type and the frequency (number of times) they have been used to indicate whether a station needs to be refilled. To analyze this data, MQTT messages were handled as events and stored into the database tables "sensor" and "device_message". With this information, the five database tables are populated with data regarding the reservoir, shown in the ER model of the database (fig. 17).

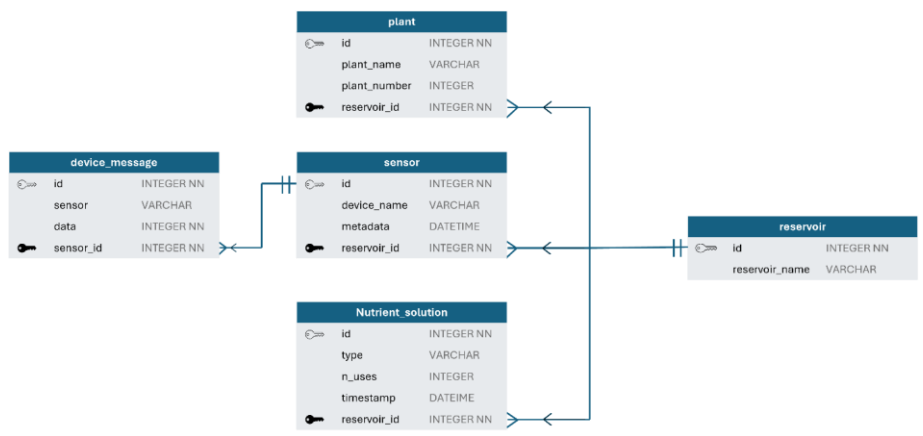


Figure 17 – Entity Relationship model for this hydroponic proof of concept

Following up on the data storage modeling, systems implementation will help to understand the flow of data throughout the project.

3.5 Function Layer

The IoT Hub is part of the Function Layer and, as described in section 3.1, this layer is needed to manage all the processes of the system that are not managed locally by the IoT Node. As such, it must have remote access as well as the ability to interact with the user of the system so that farmers can use the Decision-Support Unit. The GUI and the MQTT Broker are supported by the IoT Hub.

Triggers are setup in the Function Layer to allow for remote supervision in this proof of concept. The Data Repository is supervised and alerted when a trigger, as the ones provided in section 3.2.4, is recognized in the data set. While there is no process that can enact two-way communication in this set-up, as variables are monitored locally through the IoT Node, the user is informed of the trigger rulesets being applied through the UI.

3.6 Application Layer

In the Application Layer, reserved for interacting with the user, the introduction of a GUI and a dedicated AI together move this proof of concept from the realm of Agriculture 4.0 toward Agriculture 5.0, as explored in section 2.5.

Although small farms may integrate automatic processes, as established in the problem statement in section 1.1.2, automated data analysis is seldom used and that is where the GUI can make a difference. With access to data analysis tools, the farmer can track data and apply data analytic models to infer correlation as well as causation in the data through readily available ATS and DTS. In the GUI, through the trigger system that has been integrated in the IoT Hub, the user has access to alerts and enhanced awareness of problems in the system. A debugging window in the GUI finally allows for a complete system review for problem-solving by a technician.

Moving towards Agriculture 5.0 is facilitated by the AI component, where the primary objective is to aid the user in decision-making and provide support on demand by responding to questions about the NFT Hydroponic system. The AI should not only interact with the user eloquently enough so that human language is understood but also have complete understanding of the data held in the Data Repository, as per section 2.5.3.

3.7 Systems Behavior

To work efficiently with these systems, high-level diagrams help establish the flow of information, configuration, functioning, and processes between each element of the system architecture.

3.7.1 Activity diagram for processes

In an activity diagram, message flow is illustrated from one activity to another to visualize the dynamic nature of the system. Applied to the context of this dissertation, three main runtime processes – *configure*, *runtime*, and *actuate* – have been identified that can be translated into the following activity diagram (figs. 18 and 19), illustrating the step-by-step decision-making for each function. Some of the steps are AI-assisted, indicated by the key.

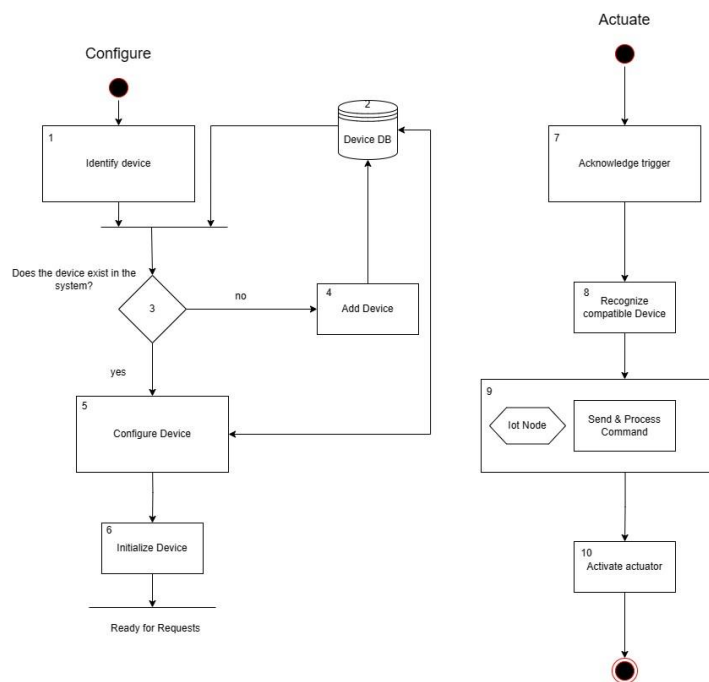


Figure 18 – Activity diagram of the processes of the IoT Node

Identified at the top left of figure 18 and in first place, the Configure process represents the activity in which sensors are integrated into the system so that their data later is saved at the IoT Hub. In further detail, the device is: 1) identified by the system 2) based on previous devices that have already been integrated into the system. 3) If the device does not exist in the system, 4) a new data entry is created in the Device List and then the system proceeds to 5) configure the device so that the data available in the hydroponic system can be dealt with appropriately.

Once the system is ready to receive the data from the sensor, 6) the device is initialized, and data starts flowing into the IoT Node so that the data can be filtered and then appropriately saved in the IoT Hub.

The Actuate process represents how the actuators act. This linear activity has no branches and so relies on its simplicity to be able to be quick in its implementation. Data is processed and a 7) decision is made as to actuation, 8) the associated device is paired to the decision. Through internal language, 9) the command is processed in the IoT Node and 10) the actuator can then be initialized, for example, to start a pump.

Commented [151]: Check numbering of processes

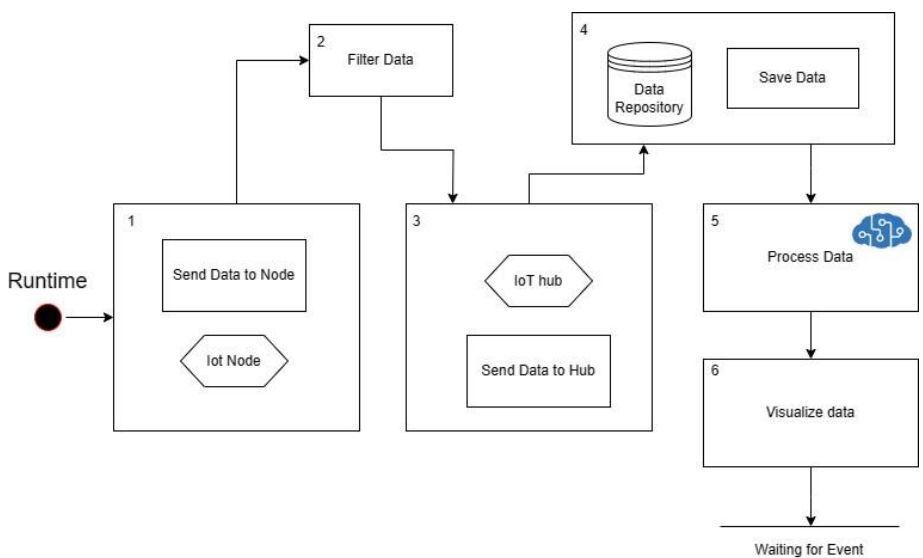


Figure 19 – Activity diagram of the data flow from the IoT Node to the IoT hub

While any new sensors are being integrated into the system, the Runtime process (fig. 19) manages data 1) when the data from the sensors enters the IoT Node we can then 2) proceed to filtering through an outlier system that discards irregular data in accordance with the limits of the hardware and 3) sent to the IoT hub. 4) Data storage in a Data Repository allows for the application of Big Data techniques to create ATS and DTS so that the system can be properly scaled. 5) Data should then be transferred to a decision-support tool, such as an AI that would then allow for new services to be made available to the user. Data should also be made available locally with fundamental techniques like graphs, a data logger; 6) The most recent information that is visualized through a GUI then provides at-a-glance analysis from the user perspective. This service generation is what is being built by the Process Data activity in Figure 19 and can be further described in Figure 20.

To further describe the influence that the GUI and decision-support tools have in data analysis, the Process Data activity aims to develop the services available to the user and can be further described as follows: Whenever data is stored in the IoT hub, it is used in three different activities:

- The first activity aims to create a history. The previous research on how to apply Big Data storage techniques demonstrates that several points of data can be cleanly appended to create a history graph.
- A service that can provide at-a-glance visualization is also important, where the information on the most recent data is also available for consultation. Both of these services should be available to the user through a GUI.
- The final activity involves the decision-support tool, an AI, that is prompted in accordance with the needs of the system and itself also has a history of the information that is stored in the Data Repository and is able to respond to queries from the user.

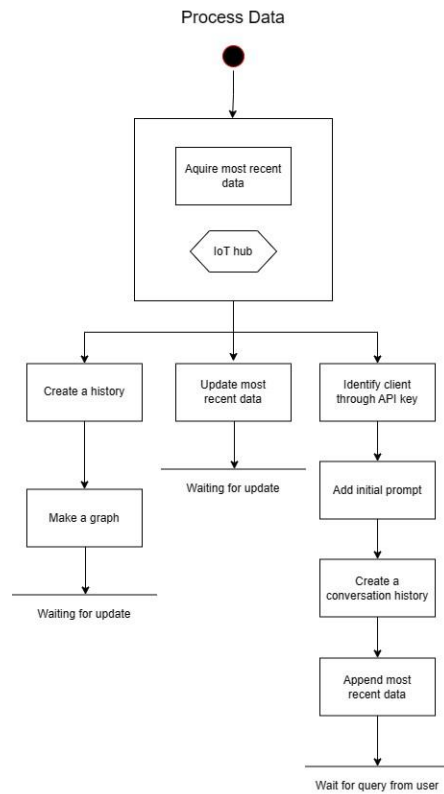


Figure 20 – Activity diagram of the data flow from the IoT Node to the IoT hub

3.7.2 Sequence diagram for data flow

The following figure demonstrates the sequence diagram of the hydroponic system (fig. 21), where the sequence of activities of the system, presented with details on the data exchanged amongst the objects of the diagram in chronological order, starting from the top left, is represented while the system is active.

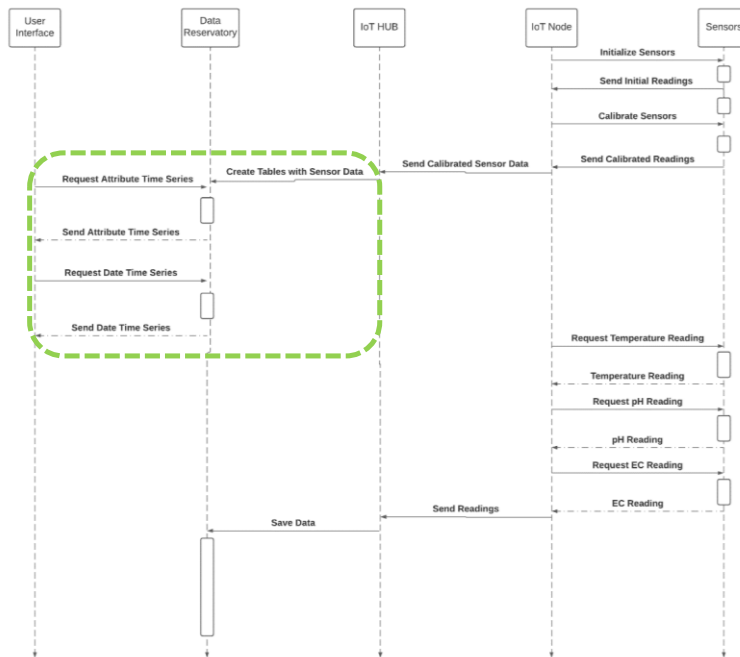


Figure 21 – Sequence diagram for this hydroponics proof of concept

Beginning at the top left of figure 21, the system starts with the user. Within the UI, the user puts in their request for either an ATS or a DTS from the Data Reservoir. If that information is available, the database then sends the information requested by the user. While the user experience involves requesting and waiting, the internal activities of the IoT Hub function (as seen in the dashed green box), independent of the user experience in real time, so that it continually requests information from the sensors through its specific nodes.

3.8 Plants and Necessary Characteristics

As the biological part of this Master’s thesis, the plants used in the hydroponic system need specific environmental characteristics to be able to survive and thrive within an NFT system. Specific plants, listed here in a selection drawn primarily from [190], will have an easier time dealing with the reduced space available to most common NFT systems.

- Bibb lettuce is a species of butter lettuce that harvests in 6 to 8 weeks.

- Leaf lettuce is a species of lettuce that grows leaves rather than a "head" and can be harvested in 6-8 weeks.
- Spinach can grow in cool environments and can be harvested in 5 to 7 weeks.
- Broccoli Rabe can grow in cool environments as well and, although maturation time is variable, it most commonly can be harvested in 6 to 10 weeks.
- Basil is harvested after just 4 to 6 weeks although it needs efficient artificial light sources and monitoring to maintain its mandatory 11 hours of sunlight per day.
- Mint roots grow quickly, in just three weeks, and can speed up the process to integrate into the pipe of the NFT system although their light requirement is even higher than basil, at 14 to 16 hours per day [191].
- Chives are harvestable at 3- to 4-week intervals after maturity in 6 to 8 weeks.
- Strawberries have a growth period of 8 to 12 weeks and are well suited for an NFT system [192].
- Blueberries take up to 20 weeks to grow, much longer than strawberries, but still do well in an NFT with 12 to 16 hours of artificial light per day although they cannot be grown from seeds [193].

For the proposed system, Bibb Lettuce, Spinach, or Mint are recommended because of their availability in Portugal.

After the knowledge gathered in the proof of concept presented in Chapter 3, the next chapter reflects implementation and prototyping.

4. PROTOTYPE IMPLEMENTATION

After conceptualizing the system through models, diagrams, and the necessary previous research, the project prototype was created to meet all the objectives established in the previous chapters and respond to the research question. In this chapter, the methodology, software, and hardware that were used to build the prototype are reviewed and complemented by consideration for the problems encountered and for the new techniques that were learned during this implementation.

Overall, the prototype involves sensors, actuators, a GUI, and a decision-support unit. The IoT nodes, using Arduino, can effectively monitor all the outputs of each of the sensors and pass them on, through the Data Handler described in section 3.1, in this case Mosquitto MQTT, to the IoT Hub, where a Raspberry Pi 3b was used. The information is then saved in the Data Repository, using a SQLite structure. The data is processed in the IoT Hub as *events*, which are compared to specific triggers that can activate the actuators of the system, normalizing the values that must remain balanced. To analyze and manage the data, a GUI, developed in Python, can manipulate the database and communicate with the decision-support system, which also provides a conversational interface powered by OpenAI's ChatGPT API.

4.1 Physical Prototype

The physical prototype implemented based on the design of the proof of concept and informed by the state of the art involved three interrelated areas – the material to create the

structure of the NFT hydroponic system, the sensors required for the automation of the system, and the creation of the IoT Node.

4.1.1 Materials

Following the review of the NFT hydroponic system in section 2.7.2, the items to create the structure were gathered – PVC components for piping, tubes, a pump, boards, and some grow cups, also called *net pots*. The following list annotates the structural items that were required for this prototype:

- 1 m PVC pipe with 90 mm diameter
- Two 90 mm diameter pipe endings, one of which must be fitted/drilled to insert the tube that connects the reservoir to the PVC pipe
- Two 2.25 m transparent silicon tubes to conduct the water
- 3 Velleman water pumps (65 x 40 mm with tubing included, 6 VDC, 5 W, flow rate ≥ 39 ml/min)
- 60 cm x 25 cm x 2.5 cm wooden boards for the base and side supports of the piping (Note that the top ends must then be crafted to support the horizontal PVC pipe)
- 2 "3-inch" net pots (Note that despite the commercial reference to "3-inch" pots, their dimensions are actually 3.25" (top) x 2.25" (bottom) x 2.75" (depth))
- 1 10-gallon plastic box with a removable top for the water reservoir. The box must be fitted/drilled to insert the tubes to conduct the water to the PVC pipe

With these items and the aid of some construction tools, the basic structure required for a hydroponic NFT farm can be assembled (fig. 22).



Figure 22 – First setup of the prototype

The nutrient solution BIONOVA Supermix 500 ml fulfills the three-stage necessities for plant growth – seedling, growth phase, and flowering. The use of the liquid version of the nutrients to be added contributes to the ease of setup and is the one point where the cheaper solid option was not chosen since using a solid would complicate the implementation. Of particular note was the quality of tap water registered by the local water authority (SMAS) – pH, EC, chlorine, calcium magnesium, iron, and sulfites – for the city of Almada [194], which meant that there was no need to buy bottled water for project.

The project was successfully prototyped with the sensors in section 3.2 for four parameters – pH, EC, environmental temperature, and humidity, specifically using the following three units:

- pH Sensor (E-201C-Blue)
- EC Sensor (DJS1C-Black)
- Temperature/Humidity Sensor (DHT22)

In addition to these sensor units, three Velleman 6 V 5 watt mini-pumps with the silicon tubing were used as actuators for this project. These liquid pumps were selected due to their easy integration and ease of access and implementation of five relays allowed for full control of the pumps and the sensors.

With Arduino WiFi rev 2 and Raspberry Pi 3 Model 8 – the microcontrollers implemented as nodes in the system – all the hardware was gathered and the implementation process could begin.

4.1.2 Selected sensor outputs, thresholds, and specifications

As detailed for the Physical Layer in section 3.2, the thresholds and specifications of each of the sensors described in table 11 have outputs related to the power pins (Vcc), ground pins (GND), and data pins (DATA). To clarify, the Vcc pins supply power for the sensor while the ground pins are connected to the ground of the specific microcontroller. Finally, the data pins are used to communicate between the sensors and the Arduino.

The thresholds and specifications indicated refer to the Grove pH sensor (E-201C-Blue) from Seeed Studio, the Grove EC sensor (DJS1CBlack) also from Seeed Studio, the DALLAS digital temperature sensor probe (DS18B20) with TO-92 Encapsulation from Maxim Integrated, a subsidiary of Analog Devices in San Jose, California, and the temperature/humidity sensor (DHT22) from Aosong Electronics Co. Table 11 shows the sensors, outputs, and their thresholds and specifications.

Sensors	Outputs	Thresholds & Specifications
<p>pH Sensor (E-201C-Blue)</p>	<p>Vcc, power pin GND, ground pin DATA, data pin</p>	<p>3.3-5.0 input voltage 0-14 pH range ±0.15 pH range <1 minute response time 0-60° C temperature measurement Waterproof</p>
<p>EC Sensor (DJS1C-Black)</p>		<p>3.3-5.5 V input voltage 0-2000us/cm EC range ±5% error range 5-80° C operating temperature <10 seconds response time Waterproof</p>
<p>Temperature Sensor (DS18B20)</p>		<p>3.0-5.5 V input voltage -55° C to 125° C temperature range ±0.5° C accuracy from -10° C to 85° C 1 wire interface Probe: 7mm in diameter and roughly 26mm long Overall length of the temperature sensor: 6 feet/1.83m Waterproof</p>
<p>Temperature/Humidity Sensor (DHT22)</p>		<p>3.0-5.0 V input voltage 2.5mA max operating current 2-5% accuracy from 0 to 100% humidity ±0.5° C accuracy from -40° C to +125° C includes 4.7-10K resistor 0.5 Hz sampling rate (once every 2 seconds)</p>

Table 11 – Characteristics of the sensors for implementing this prototype

4.1.3 Creating the IoT Node

The construction of the prototype is better understood through a narrative divided into four parts – sensors, actuators, GUI, and decision support unit – accompanied by a series of images of the steps taken to create the IoT Node.

4.1.3.1 Sensor and broker setup

A total of ten sensors were considered at the beginning of the project but narrowed down to the three sensors described in section 3.2 which corresponded to the properties that could be monitored in the system.

For the sensors to work as intended, two-point calibration was required and made possible through the library DFRobot_PH_EC, although the approach differs from the pH to the EC sensor. In the pH sensor, an acidic solution labeled at 4 was applied, with the second point being generated at the 7 neutral solution point. The EC sensor is calibrated similarly, but the points are generated through solutions of 12.88 mS/cm and 1411 μ S/cm, respectively. Note that the DHT22 sensor does not need calibration but the DHTNEW library helps with the sensor's process of initialization and recognition software.

The selection of all three sensors works synchronously in the setup demonstrated in Figure 23, followed by their output data on the Arduino Serial Port in Table 12.

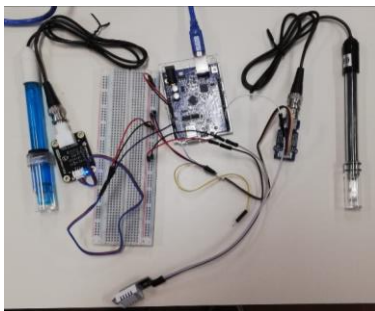


Figure 23 – Setup of the circuit for the pH, EC, and temperature sensors

```
14:43:00.976 -> pH:5.08, EC:3.03ms/cm
14:43:02.941 -> Environment Temperature: 23.9 *C
14:43:02.941 -> Environment Humidity: 49.4 %
14:43:02.986 ->
14:43:02.986 -> pH:5.05, EC:2.19ms/cm
14:43:04.968 -> Environment Temperature: 23.9 *C
14:43:04.968 -> Environment Humidity: 49.3 %
```

Table 12 – Output on the serial monitor of all of the four types of data from the sensors

Using the serial monitor to look at sensor data, tables 13 and 14 are produced based on the Arduino outputs of the EC and pH sensors. Figures 24 and 25, respectively, show the different circuit setups for the EC and the pH sensor.

```
16:06:25.265 -> temperature:25.0*C EC:19.65ms/cm
16:06:26.273 -> temperature:25.0*C EC:17.30ms/cm
16:06:27.284 -> temperature:25.0*C EC:11.67ms/cm
16:06:28.264 -> temperature:25.0*C EC:11.49ms/cm
16:06:29.277 -> temperature:25.0*C EC:11.70ms/cm
16:06:30.283 -> temperature:25.0*C EC:11.82ms/cm
16:06:31.276 -> temperature:25.0*C EC:11.14ms/cm
16:06:32.277 -> temperature:25.0*C EC:11.67ms/cm
16:06:33.277 -> temperature:25.0*C EC:17.54ms/cm
16:06:34.288 -> temperature:25.0*C EC:19.23ms/cm
16:06:35.285 -> temperature:25.0*C EC:17.83ms/cm
16:06:36.282 -> temperature:25.0*C EC:12.15ms/cm
```

Table 13 – Output on the serial monitor of the EC sensor

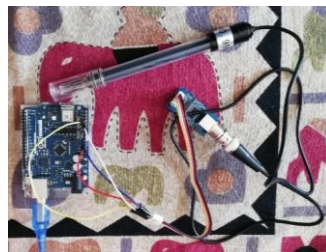


Figure 24 – Setup of the circuit for the EC sensor

```

17:10:44.830 ->    pH:7.78
17:10:45.736 ->    pH:7.78
17:10:46.626 ->    pH:7.65
17:10:47.533 ->    pH:7.58
17:10:48.439 ->    pH:7.68
17:10:49.327 ->    pH:7.77
17:10:50.202 ->    pH:7.79
17:10:51.105 ->    pH:7.69
17:10:52.040 ->    pH:7.56

```

Table 14 – Output on the serial monitor of the pH sensor

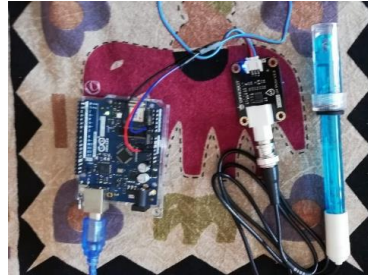


Figure 25 – Setup of the circuit for the pH sensor

The following paired images represent the circuit set up for the environmental temperature (temp)/humidity (hum) sensor (fig. 26) and its output on the serial monitor (tab. 15).

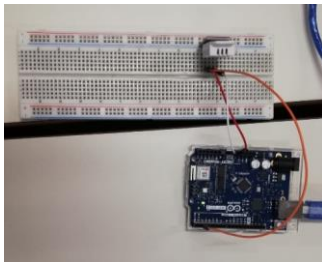


Figure 26 – Setup circuit of the environmental

```

16:34:37.503 -> Humidity: 47.1 %
16:34:43.512 -> Humidity: 47.2 %
16:34:51.527 -> Temperature: 22.5 *C
16:35:15.571 -> Humidity: 47.3 %
16:35:27.574 -> Humidity: 47.4 %
16:35:33.575 -> Humidity: 47.5 %
16:35:43.606 -> Humidity: 47.6 %
16:35:57.599 -> Humidity: 47.7 %
16:36:01.647 -> Humidity: 47.8 %

```

Table 15 – Output on the serial monitor of the environmental temp/hum sensor

While designing the proof of concept in Chapter 3, the importance of a water temperature sensor for this project was established; to this effect, the circuitry involved in implementing this sensor is shown here (fig. 27). Nevertheless, and despite the reliable electronics involved in this implementation, the water sensor did not produce reliable enough data and had to be eliminated.

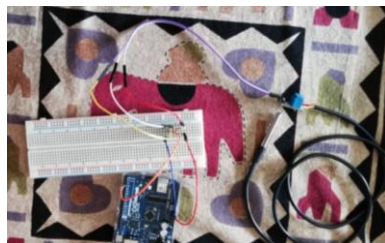


Figure 27 – Setup of the water temperature sensor

4.1.3.2 Actuators of the prototype

The prototype aimed to create processes to interface with the hydroponic system so that it could become a two-way system, where the information received from the system can then impact the variables being managed by the sensors. As such, the main actuators implemented into this project are three liquid pumps to move water, the common resource in hydroponics. The access to flow through the movement of liquids also allows for the introduction of new liquids, pH balancers and nutrition, into the environment, with an important impact on two variables: the EC and pH values of the reservoir tank, understood as follows:

- The EC values monitor the nutrition density by measuring particle volume in the liquid of the reservoir. When the reservoir levels become too low, more nutrient solution should be added to the reservoir.
- As for the pH values of the reservoir tank, pH measures the capacity of a plant to consume nutritional solution through osmosis. To maintain proper pH levels, the pH values must be monitored and changed, when needed, by inserting more pH solution in the correct direction. Note that pH values should remain between 5.6 and 6.5 (section 2.7.1).

Velleman 6V mini-pumps were used in this prototype. Because the Arduino is capped at 5V, the pumps could not be powered by the output. As an alternative solution, external power was found in a 12V source and a DC/DC adapter that could lower the voltage to the target 6V. Relays allow for control of the pumps' run time by shunting the power supply of all three relays together and connecting the positive output of the pumps with the output of the relay. The negative output of the pumps was connected with the negative output of the DC/DC adapter for parallel access to the pumps, so that each of the three pumps could be controlled individually. To monitor the pumps through Arduino, the output of three digital pins connects to each of the pump relays. These relays' common pin position is HIGH, a state that needs to be forced LOW to send power to the associated pump.

4.1.3.3 Schematic overview

The integrated circuit designed for this thesis is a fluid management system comprised of actuators for the three pumps that facilitate the precise control required for fluid flow. In this exposition of the testing stage, note that a breadboard was used to create access to the Vcc and GND pins on the Arduino throughout the circuit diagram, created to represent the system (fig. 28).

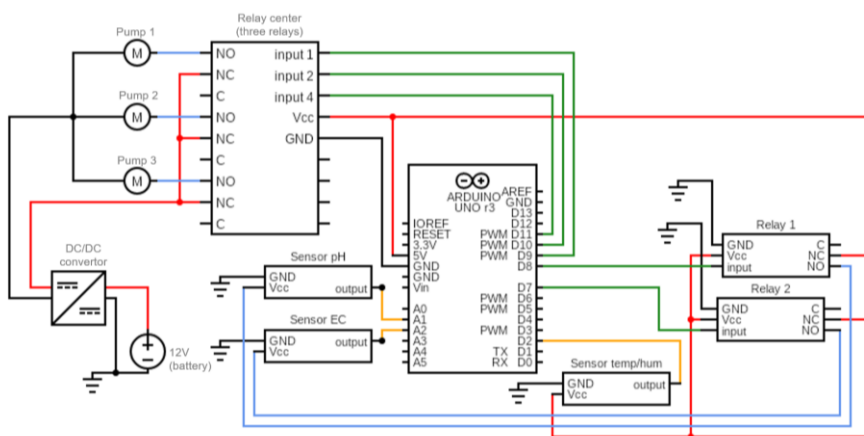


Figure 28 – Circuit diagram of the thesis prototype
 Source: Created with <https://www.circuit-diagram.org>

In figure 28, all of the elements are grounded (GND). The relay center, as illustrated, serves to integrate the three relays that manage the (de)activation of the three water pumps. The Normally Open (NO) relay outputs from the relay center are connected to the actuators for pumps 1, 2, and 3. Simultaneously, the Normally Closed (NC) relay outputs link to the positive terminal of the DC/DC convertor, where the energy from a 12V battery is converted to 6V. The Vcc of the relay center establishes a connection with the 5V pin on the Arduino, as do the NCs of relays 1 and 2.

The pins input 1, input 2, and input 4 of the relay center are connected to the respective D9, D10, and D11 pins on the Arduino, creating an interface for communication and control between the two components. To integrate the three sensors, digital pin 8 and digital pin 7 connect to the input pins on relays 1 and 2, respectively.

Digital pin 2 on the Arduino is connected to the output of the sensor for temperature and humidity. The NOs of relays 1 and 2 are connected to the Vcc pins of the pH and EC sensors while the analog input pins A1 and the A2 on the Arduino are connected to their respective output pins.

Through modeling this diagram, aimed to orchestrate an automated fluid management system, the operational efficiency has been optimized to maintain the desired environmental conditions. To contrast with the first setup of the prototype in section 4.1.1 (fig. 22), the final

setup of the IoT Node (fig. 29) maintains the compact qualities and shows how the system can be optimized.



Figure 29 – Photo of the IoT Node

4.2 Data Handler and communication protocols

After the data started flowing from the sensors, a bridge was then made between the IoT Node and the IoT Hub. It was necessary to setup a Mosquitto broker on Linux for a working MQTT broker on the Raspberry Pi, the WifiNINA and ArduinoMqttClient libraries on Arduino, are responsible to access the Wi-Fi and link up to the same internet service provider (ISP) as the Raspberry Pi and then to publish from the Arduino to the Rapsberry Pi through a broker topic, which in this case can be any of the following: *arduino/ec*, *arduino/ph*, *arduino/temp* and *arduino/hum*. These libraries serve to create the bridge between nodes for the technology to work. The easy console access to subscriber and publisher methods made for elegant visualization and parsing of the well-formatted information sent from the IoT Nodes, as per section 3.3.1 on MQTT.

While at this barebones level, this working project could send information from the reservoir to the Raspberry Pi, one of the objectives was to be able to collect data inreal-time and analyze it, not necessarily in real time but for a prolonged period through the creation of a database. In researching how to connect MQTT messages with Python to the database, an accessible solution was found.

4.3 Creating the Database Repository

Python was chosen to develop the scripts to bridge the Mosquitto Broker to the SQLite database. This choice was made because of Python's libraires having already built extensive frameworks for aid in data analytics and in community support, both of which were important in developing this prototype. Python also seamlessly integrates with the prototype system, a characteristic that works towards resolving interoperability issues and scalability.

Given these advantages, a Python script was designed and developed to subscribe to specific MQTT topics and stored the received messages in an SQLite database. The development of the code is described as follows:

- The libraries `PAHO.MQTT.CLIENT`, `SQLite3`, and `datetime` were imported. Through this combination, the code can apply MQTT communication and handle SQLite database interaction as well as obtain the current timestamp so that it can be applied in real-time processes.
- The MQTT was then configured with its broker address, in this specific case the ipv4 WiFi address that is linked to the Raspberry Pi, and port 1883 was specified – as is standard. SQLite was also configured by giving it access to the path to the database file and then the connection and cursor objects that were needed to navigate the .db file type were defined.
- After having achieved a stable connection, five database tables – reservoir, device_message (tab. 16), nutrient_solution (tab. 17), plant (tab. 18), and sensor table (tab. 19) – were then created.
- To add new data to the database, a function is used for message handling as well as database insertion. For these purposes, the function picks up the latest reservoir_id from the database and, depending on the topic, it inserts the information received through the broker into the appropriate table in the database. After completing this action, a function from the SQLite library is called to commit the changes made to the tables. Every time a new message is received, a timestamp is added to the sensor table which allows real-time processes to be applied.

The following tables were generated for the database through the MQTT broker from the devices and their data regarding nutrient solution, the plants in the hydroponic NFT system, and the sensors themselves (tabs. 16-19).

device_message_id	sensor	data	sensor_id
Filter	Filter	Filter	Filter
1	1 arduino/ph	6.6	NULL
2	2 arduino/ph	7.0	NULL
3	3 arduino/ph	7.1	4
4	4 arduino/ph	7.1	5
5	5 arduino/ph	7.1	6
6	6 arduino/ph	7.2	7
7	7 arduino/ec	12.00	8
8	8 arduino/temp	25	9
9	9 arduino/temp	25	10
10	10 arduino/hum	50	11
11	11 arduino/hum	50	12
12	12 arduino/temp	25	13
13	13 arduino/ec	12.00	14
14	14 arduino/ph	7.2	15
15	15 arduino/ph	7.1	16
16	16 arduino/hum	50	17

Table 16 – device_message table

nutrient_solution_id	type	n_uses	timestamp	reservoir_id
Filter	Filter	Filter	Filter	Filter
1	1 pH	30	2023-10-30 14:45:52.594767	1
2	2 EC	30	2023-10-30 15:21:27.391857	1
3	3 pH	30	2023-11-06 14:45:33.817522	1
4	4 EC	30	2023-11-06 14:45:33.817522	1
5	5 pH	30	2023-11-22 15:31:11.036697	1
6	6 pH	30	2023-11-22 15:34:13.495003	1
7	7 EC	30	2023-11-22 15:58:58.348588	1
8	8 EC	30	2023-11-22 16:01:08.717364	1
9	9 EC	30	2023-11-22 16:03:41.035176	1
10	10 EC	30	2023-11-22 16:05:53.074010	1
11	11 ec	30	2023-11-22 16:09:08.416127	1
12	12 ec	30	2023-11-22 16:09:58.175133	1
13	13 exc	30	2023-11-22 16:10:44.922355	1
14	14 pH	30	2023-11-22 16:13:17.750504	1
15	15 pH	30	2023-11-22 16:17:05.138206	1
16	16 pH	30	2023-11-22 16:20:54.589489	1

Table 17 – nutrient_solution table

plant_id	name	number	reservoir_id
Filter	Filter	Filter	Filter
1	1 chives	2	1
2	2 spinach	1	1
3	3 brocolli	1	1
4	4 mint	5	1
5	5 chives	2	1
6	6 spinach	4	1
7	7 mint	1	1
8	8 chocolate	2	1
9	9 chives	1	1
10	10 mint	2	1
11	11 chives	1	1
12	12 chives	1	1
13	13 chives	1	1
14	14 potato	1	1
15	15 chives	3	1

Table 18 – plant table

sensor_id	device_name	metadata
Filter	Filter	Filter
1	1 E-201C-Blue pH Sensor	2023-09-25 15:37:19.230387
2	2 E-201C-Blue pH Sensor	2023-09-25 15:46:13.082977
3	3 E-201C-Blue pH Sensor	2023-09-27 15:20:32.316239
4	4 E-201C-Blue pH Sensor	2023-09-27 15:24:34.286554
5	5 E-201C-Blue pH Sensor	2023-09-27 15:24:34.286554
6	6 E-201C-Blue pH Sensor	2023-09-27 15:24:34.286554
7	7 E-201C-Blue pH Sensor	2023-09-27 15:27:14.601040
8	8 DJS1C-Black EC Sensor	2023-09-27 15:27:14.601040
9	9 DHT22 Environmental Temperature Sensor	2023-09-27 15:29:22.532392
10	10 DHT22 Environmental Temperature Sensor	2023-09-27 15:29:22.532392
11	11 DHT22 Environmental Humidity Sensor	2023-09-27 15:31:02.851957
12	12 DHT22 Environmental Humidity Sensor	2023-09-27 15:31:02.851957
13	13 DHT22 Environmental Temperature Sensor	2023-09-27 15:31:02.851957
14	14 DJS1C-Black EC Sensor	2023-09-27 15:31:02.851957
15	15 E-201C-Blue pH Sensor	2023-09-27 15:31:02.851957
16	16 E-201C-Blue pH Sensor	2023-09-27 15:31:02.851957
17	17 DHT22 Environmental Humidity Sensor	2023-09-27 15:31:02.851957

Table 19 – sensor table

4.4 Graphical User Interface of the prototype

For the user to be able to interact with the data stored in the Database Repository, a GUI was created (fig. 30) in the IoT Hub, where the colors blue and green predominate the design. Ultimately, however, *functionality* is the focus that was applied in the making of the GUI.

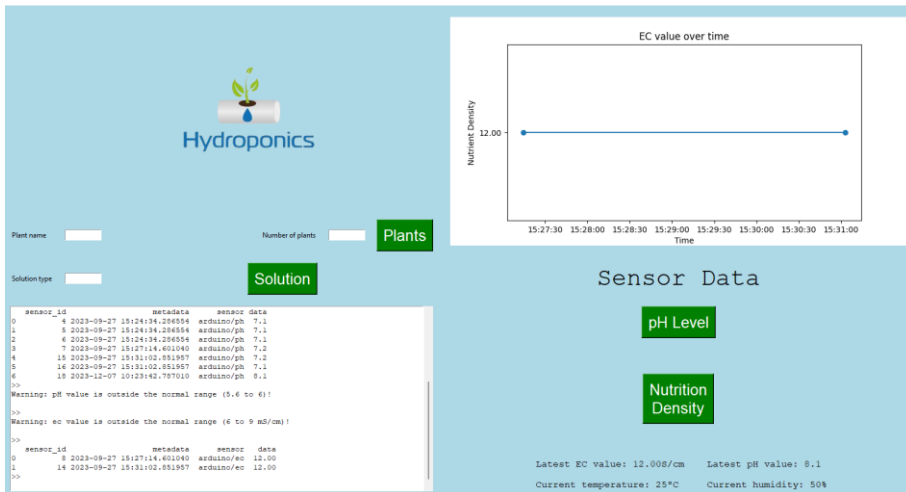


Figure 30 – GUI of the prototype

To create the GUI (fig. 30), Tkinter offered a framework that can be integrated with most Python libraries and allows for widgets to be used to their full effect. As a simple tool, this framework allows people with no previous experience building GUIs to be able to quickly get their project running, a description that corresponded well to the conditions of this project. On the other hand, disadvantages of the Tkinter framework are its lack of complexity, which, as mentioned, does not deliver the most appealing visual. But again, recalling that design is not the priority of the project, Tkinter can be used to manifest not only buttons and scrolled text, but also external images, input boxes, textboxes, and different frames for compartmentalization of data.

To add all the functionalities of the framework, some external libraries were imported for the project. Matplotlib was used for graph making; Pillow (PIL) was used for importing external images; Pandas was used for data manipulation and analysis that allowed the graphs to be built; ChatGPT API was used as to create a chatbot to aid the farmer/user in understanding the system and query collected data. As referred to in the development of the MQTT to SQLite parts in the previous section, the SQLite3 and datetime libraries provide access .db files and keep time within the system.

To handle the database information and triggers in the code that pair with the Matplotlib library for creating static, animated, and interactive visualizations, the graphs are updated with the information from the system sensors in a time-bound manner. Note the

importance of the Pandas library to merge tables of the database, and thus create time and data graphs to illustrate the levels of pH and nutrient solution.

Interaction between the user and the GUI can happen in several forms:

- The first way is inputting the plant type and number when maintenance is done. Every time a new plant is introduced into the NFT system, it should be added into the appropriate input boxes in the GUI, followed by the number of plants of that type added into the system. Every time a new solution is added into the system, be it nutrient solution or pH solution, the addition must also be updated in the database through the appropriate input boxes in the GUI.
- Another way for the user to interact with the system is to change the graph, altering between the visualizations of *pH over time* to *nutrient density over time* in quadrant I of the GUI. With this interaction, the user can analyze either kind of data over whichever timeframe they need.

To handle errors and technical tools, a logger was integrated into the framework through a *scrollingtext* widget. This way, the data itself and what is happening to the database can be shown while the user works with it in quadrant III of the GUI. The logger window's most recent information is thus dependent on the user. When the user inputs more plants in the system, the scrolling text will reveal the plant table. When introducing new solutions in the database, the user maintains access to the already existing entries of the *nutrient_solution* tables. The same logic applies to the pH and nutrient density graphs because the logger will show the information pertaining to those tables as well.

Textbox widgets hold the latest information gathered from the tables for an at-a-glance look at the information of the database. Also, to aid the user in making informed decisions about the project, an artificial intelligence assistant was added through the API of OpenAI's ChatGPT.

4.5 Decision-Support Unit

A decision-support unit is a useful tool that aims to aid in decision-making. Upon request of the user, these units can process data and find correlations that are accelerated through automation. Where it would take some time for humans to reach the same conclusion, this tool is commonly applied in Big Data to deal with the volume of data available from the system. As a scalable solution, it makes sense to implement a decision-support unit even at

this level. Leveraging artificial intelligence, in the context of this NFT hydroponic system, offers outside support for the small farmer as the LLM algorithms process and extract the information to gather insights. In the prototype for the NFT hydroponic system, especially for organizing the information that has been extracted on plant growth and behavior, tracking trends, and identifying areas that require attention or intervention. As a conversational agent, the LLM-driven decision-support unit enables natural language interaction to effectively answer queries from the user, in writing or through speech recognition. The relevant and accurate responses that LLM systems can develop to answer user queries, in turn, can provide support and even influence strategic decisions. Since LLMs can discover hidden patterns and trends or correlations, the insights may even be revealing to the user.

The initial selection of spaCy, the opensource library for natural language processing, recognized its lightweight and efficient qualities that made it suitable for deployment in this resource-constrained project. Designed for efficiency, spaCy is optimized for real-time processing, unlike ChatGPT, which must make requests to a model hosted on the OpenAI API. The original thought was that spaCy's capacity for training with domain-specific data might also be important, but the time resource needed to train a new spaCy AI would have been costly and the support tools to aid development are sparse.

Therefore, despite the latency and slightly less potential for customization, the focus was switched over to ChatGPT due to its ease of integration after two weeks. The decision support unit (fig. 31) is visible in the space alternatively designated for the logger in quadrant III of the GUI. In this example, the sequential questions pertain to the database file and, initially, to the current state of the hydroponic system's nutrient solutions. The follow-up question asks for decision-support about what to do next. In this case, for Bibb lettuce, that is not growing as expected, the AI responds with four suggestions, three of which – nutrients, pH and EC levels, and temperature/humidity – the prototype can be adjusted for in this implementation. The fourth suggestion about lighting will have to be resolved in the next iterations of this prototype, as will be projected in the considerations for further research and future work on the lighting and light sensor.

```

ChatGPT: Hello! How can I assist you today with your hydroponic system?
>>What are the current types of solution in our hydroponic system?
ChatGPT: The current types of solutions in your hydroponic system are pH and EC solutions.
>>My lettuce's growth is not as expected, what can I do?
ChatGPT: To improve the growth of your lettuce in a hydroponic system, you can consider
the following factors:

1. Lighting: Ensure your lettuce is receiving adequate light. Lettuce typically
requires 12-16 hours of light per day. Consider adjusting the distance of your grow lights
or increasing the light intensity if needed.

2. Nutrients: Check the nutrient levels in your reservoir. Make sure the nutrient
solution is balanced and contains essential nutrients for lettuce growth, including
nitrogen, potassium, and phosphorus.

3. pH and EC Levels: Monitor and adjust the pH and EC levels of your nutrient
solution. Lettuce generally thrives in a pH range of 5.5-6.5. Ensure the EC levels are
appropriate for the growth stage of your plants.

4. Temperature and Humidity: Maintain optimal temperature and humidity levels for
lettuce growth. Lettuce prefers temperatures around 60-70°F (15-21°C) and humidity levels
between 40-70%.

```

Figure 31 - Integrating the AI chatbot into the GUI, example

This artificial intelligence tool leverages OpenAI's ChatGPT 3.5 Turbo. Queries are directed then processed, and the AI was trained to respond in the most suitable way for the user according to its directives. This project established the initial prompt as the directive, "You are an assistant to an NFT hydroponic system. Any questions out of the scope of this project, you are to answer that you are unable to answer their question." In addition to this information, all the tables from the database were imported through the SQLite3 library and added to the information available to the AI.

After the AI has its directives and collected data stored in the system, the logger can be used to chat with it, allowing the user to ask questions about the collected data and any required assistance regarding NFT systems, hydroponics, or any other related subject, based on the information available to the decision-support unit.

The processes applied to the Python script that created the GUI as well as the connection between the decision-support tool function with the OpenAI library, which can enable access to a number of functionalities, most importantly, access to OpenAI's API. With this key, created from their platform, a communication bridge is established with a customized version of Chat GPT's 3.5 Turbo. A conversation history variable is thus created which can be updated with the data in the Database Repository as well as the initial prompt needed to confer "personality" to the AI. The conversation history is only affected when the user engages with the AI via the data logger; otherwise, the process is silent. When a query is made through the API, a short wait-time is needed for updating this variable with the data from the Database Repository and the corresponding answer from OpenAI's AI. This allows for more complex services

to be afforded to the user, apart from the ones given by the GUI, and merits further development, as discussed in section 5.1.2 on Future Work. The free version of OpenAI's Chat GPT allows for a limited number of characters for the initial prompt as well as for the conversation history. This means that the paid version is more appropriate for the project, allowing for a greater amount of data to be processed as well as for a working history to be appropriate for the development of the AI.

4.6 Testing the Prototype

While the prototype was in fact created, and although it has achieved its intended purposes, the automated NFT hydroponic system with decision-support unit is not without its flaws, as revealed in the results of the testing phase (tab. 20).

Test	Review
Do the sensors communicate with the IoT Node	Yes
Can the sensors be calibrated?	Yes
Are the liquid pumps activated when the pH falls outside the required threshold?	Yes
Are the liquid pumps activated when the EC falls below the established threshold?	Yes
Does the system collect data (pH, EC, etc.) at predefined intervals?	Yes
Is maintenance necessary in predefined intervals?	Yes
Can the system grow plants?	Yes
Is the system fully autonomous?	No
Does the system actively compare incoming data against predefined rules and take appropriate actions?	Yes
Is the envisioned maintenance enough with the to keep the system functioning?	Yes
Can the IoT Node communicate with the IoT Hub effectively?	Yes
Can the Data Handler manage the MQTT topics and save the information in the Data Repository?	Yes
Is data cleaned previously before creating ATS and DTS?	Yes
Does the system cover all the specifications of a Hydroponic NFT?	No
Can the User Interface effectively display data from the Database Repository	Yes
Can the operator insert new data into the Database Repository through the User Interface?	Yes
Does the User Interface employ graphical representations for data analysis and decision support?	Yes
Does the decision support unit provide solutions for different scenarios?	Yes

Table 20 – Results of the testing stage of the prototype implementation

The questions used for this testing stage (tab. 20) were created based on the objectives of the present thesis. The questions themselves reflect areas that either became important to solving the problem statement or became obstacles that had to be solved to reach the final solution, thus validating the research question. Despite the dominant affirmation supporting

the implementation of the prototype, negative responses are shown due to the system needing maintenance periodically to recalibrate sensors and replenish buffering solution to keep them healthy, thus not being totally autonomous, and it being unable to cover and actuate on all specifications (light, environment temperature and humidity, etc.), due to the level of control of the involving environment as we cannot isolate the variables completely. This underscores the necessity for additional investigation, thereby affirming the need for the subsequent chapter.

5.

CONCLUSIONS AND FURTHER RESEARCH

In the pursuit of precision agriculture, the integration of cutting-edge technologies has emerged as a cornerstone of progress. Among these, the fusion of sensor systems and IoT holds tremendous promise for revolutionizing hydroponics within the framework of Agriculture 5.0. Standing at the precipice of a new era in agriculture, characterized by heightened efficiency, resource optimization, and sustainable practices, the full potential of sensory networks must be engaged. Throughout this dissertation, these systems, driven by IoT, have been shown to offer real-time data acquisition and analysis, enabling growers to fine-tune their operations with unprecedented precision.

This chapter offers a considered pause to reflect on the main results of the study and the ethics involved in creating hydroponic environments.

5.1 Main Results

After all, implementation is not without its problems – some defective hardware, incompatible software – and interoperability can clearly become both a frustrating and a difficult endeavor. The learning opportunities drawn from prototyping the project relate specifically to the circuitry sensors and actuators themselves, the programming required, and their related protocols as well as market management, delivery processes, and budgeting.

5.1.1 Sensors, actuators, and GUI

Three sensors were used and IoT was leveraged for real-time monitoring and control of the pH, EC, temperature, and humidity. Other key parameters can also be achieved, as pointed out in Chapter 2 on the state of the art, for light, barometric pressure, ground chemical concentration, drone equipment, video cameras, agricultural information management systems, GPS, and communication networks. Although time constraints required a careful initial selection, several sensors were eliminated even in the experimental phase. For example, the water temperature sensor had to be eliminated because the libraries that were associated did not work due to a manufacturing error of the DS18B20 device, which led to serial monitor output to be N/A.

When procuring the hardware, it is common for some sensors to come with insufficient information on how to use them, leading to exhaustive consulting and troubleshooting to understand how to get them to work. This is what happened to the DS18B20 temperature sensor, which did not work with any official or researched libraries. According to the results of research from the University of Alaska [195], [196], [197], many cloned or fake DS18B20 sensors do not meet the specification of genuine Dallas/Maxim temperature sensors – the original manufacturers – which may correspond to the lack of readings.

The EC sensor proved to be problematic during calibration. Despite using 2-point calibration with standard solutions of 12.88 mS/cm and 1433 μ S/cm, having twice followed the calibration steps to completion, these attempts were unsuccessful. The sensor did not recognize the 1433 μ S/cm. As such, the values given by this sensor have proven to not be reliable and caution is recommended in the continuation of this project. Also note that, because conductivity is affected by temperature, using a conductivity meter with a built-in temperature sensor and algorithms to compensate for temperature changes could ensure more accurate measurements. The fact that the projected water temperature sensor did not work may justify the lack of temperature correction and, hence, the lack of calibrated values from the EC sensor.

The AI for the GUI presented a series of complications related to trying to leverage ChatGPT in its free version. Managing the budget and sticking to a commitment to zero extra costs beyond hardware, water, and electricity meant that the number of questions a user could ask had to be limited to three per minute. The original intent had been to use spaCy, the open-source NLP, but the time involved was prohibitive and not the main focus in the development of the project.

5.1.2 Future Work

Other areas for improvement relate to health and safety; for example, although this **prototype reservoir is red**, transparent is recommended for better visualization and control of unforeseen water contamination. Consideration of other aspects such as **insulation, light, and ambient heaters** would have required a dedicated, enclosed space for building and testing the prototype.

Scalability is an essential consideration of any project, and the list of problems is long, covering obvious limitations like **system size and capacity and resource management** of the water, nutrients, and electricity itself. The prototype has been conceived with just four net pots, but the same space, per the research in section 4.1, could house up to ten, depending on the size of the plants themselves.

Cybersecurity has not, in fact, been considered for this project. As a counterpoint and given the reality of the international plant-based drug trade, this is likely an area that has benefitted from serious investment, especially in hydroponics, to protect any illegal growth and subsequent trade. Cybersecurity threats and data breaches can pose a significant risk to the system and compromise its effectiveness. Data management and security should also be addressed by implementing robust data collection and processing systems and adopting best practices for cybersecurity. Further integration of **data analytics or other precision agriculture tools**, as discussed in section 2.6, could, however, require a significant learning curve for more advanced biochemical knowledge.

The **Artificial Intelligence** side of this project opens many avenues of study that should be considered in the future. Instead of LLMs we could consider other types of AI. When thinking of scalability, an AI network (e.g. by using federated learning approaches) that shares information from each node and can learn about the specific problems facing a small farm could also be offered to provide decision-support for solutions that are not so broad but specific to the NFT hydroponic system that has been developed.

Each of the areas indicated merit further consideration given the appropriate opportunity for further research. From a technology development perspective, building a more modern GUI and developing environmental actuators in a ventilated room with a dynamic light source could be particularly interesting.

5.2 Concluding Remarks

The NFT hydroponic system that has been created – selected from four hydroponic systems for its ease of conception and maintenance – aims to improve yield and resource efficiency. We have implemented a sensorized and automated system so that the NFT hydroponic system can optimize the use of valuable resources, like water and nutrients. To reduce labor costs, the automation of the hydroponic system effectively aims to reduce the need for manual labor. For real-time monitoring and control, we have used IoT and CPS technologies to allow for real-time monitoring and control of key parameters, like pH and EC, enabling prompt corrective action of the nutrient and pH solution.

These technologies, in turn, have an additive impact on the environmental sustainability of NFT hydroponic systems. From our planned actions, we feel gratified that the intended outcomes seem to fit the parameters of Agriculture 5.0. Although automation can be costly and complex, we hope to have proposed a system that could in fact be used by small farmers invested in nutrient dosing, pH and EC control, and environmental monitoring.

We have also been mindful of the broader implications of sensor-driven hydroponics leveraging IoT within the context of Agriculture 5.0. We have found that these technologies facilitate data-driven decision-making, enhancing adaptability to environmental fluctuations and minimizing waste. Moreover, we have examined the potential for leveraging artificial intelligence and scalability, envisioning a future where sensor-driven hydroponic systems can be deployed across diverse geographical and climatic landscapes.

We first prepared the prototype with sensors and were about to deliver the final thesis when we were instead encouraged to continue and effectively deal with the actuators, the GUI, and adding the artificial intelligence. Some months later, having learned how to effectively work with these elements and create a functioning system, the learning curve has been rewarding.

In review, this thesis has covered vast amounts of learning and feels like an appropriate conclusion to our academic journey in electrotechnical engineering. In the planning and initial research stage to become familiar with hydroponics, we were reassured of our interest in the project proposal due for example to its inclusion in the SDG.

Developing the state of the art took us into uncharted territory, where we discovered academic and policy benchmarks in Agriculture and found that, as Agriculture 4.0 is further advancing and the transformations into Agriculture 5.0 become more evident, the crux of time

offers an exciting potential for building on our proof of concept. Many aspects of the research were striking since we were unfamiliar with precision farming, such as the importance of open-source software in projects like GRIN-Global, the free platform jointly developed by the Global Crop Diversity Trust, and the strategic role of the Portuguese Plant Germplasm Bank were inspiring in our quest to promote social and economic equity through technology. Applying the policy and technology research that currently supports the application of technology which has been the focus of this integrated Master's degree, we were further motivated to apply the knowledge garnered as an FCT student.

As we moved into the phase dedicated to proof of concept, our task was met with the unique challenges of making our theoretical knowledge a reality and the best ways to plan ahead so that our objectives become clear. We learned to prepare the high-level diagrams required, which has been apt preparation for representing engineering creations succinctly and in the appropriate educational medium.

Identifying the requirements and prototyping encouraged us to consider the step-by-step process of building the prototype, breaking it down into parts that can be explained appropriately. Building and representing our circuit for sensors and actuators with an Arduino, in brief, has effectively monitored sensor outputs, transmitting them to the Mosquitto broker on the Raspberry Pi. Local triggers on the Arduino activate the system actuators to ensure the balance of critical values in our hydroponic system. For data analysis and management, the GUI interacts with the database and communicates with the decision support system.

The experience of writing up the research and building the prototype has brought my sense of organization and written clarity to a fore. So much has been learned but we have paid attention in the final thesis to avoid over-burdening the reader. Having chosen a meaningful topic to study – one that has taken us down the rabbit hole on how to harness technology for food growth – has been gratifying. As an activist for education the breadth of this topic this has been a good fit and has allowed us to come in contact with different areas of study throughout the thesis. We feel particularly motivated by the social and economic impacts of technology.

Reflecting on the futurist John Naisbitt's accomplishments and his message of empowerment and integration, we imagine a world of technology where STEM meets the Arts and Humanities in STEAM projects that consider the diverse impacts of each development at the prototyping stage. In essence, application of some of the aspects developed here may serve

not only to catalyze advancements in hydroponic technology but also to cultivate a conscientious and sustainable agricultural paradigm for generations to come.

5.3 Debating Ethics in Hydroponics for Agriculture 5.0

The role of ethics in a hydroponics project, especially in the context of Agriculture 5.0, with its integration of advanced technologies and sustainable practices to enhance agricultural productivity, includes some key issues. Not in any particular order, these include environmental sustainability, food safety, transparency, economic and social equity, accessibility, affordability, ethical research, and long-term impact assessment.

Hydroponics offers the potential to minimize environmental impact compared to traditional agriculture. Ethical considerations involve **implementing sustainable practices** such as efficient water and nutrient management, minimizing energy consumption, and reducing the use of pesticides and chemical fertilizers. The project should strive to protect ecosystems, conserve natural resources, and promote biodiversity.

To maintain high standards of **food safety and quality**, hydroponics systems should prioritize measures to prevent contamination and ensure that crops are safe for consumption. Strict adherence to hygiene practices, regular testing for contaminants, and proper waste management are essential ethical considerations.

Providing **accurate and transparent information** to consumers includes clearly labeling hydroponically grown produce to inform consumers about the cultivation method, its benefits, and any potential differences compared to conventionally grown crops. Openly sharing information about the project's practices, whether the source of seeds and nutrients or any additives used, is an ethical responsibility.

Hydroponics projects should further consider the impacts on local communities and strive to promote **economic and social equity**. From providing fair employment opportunities and supporting local farmers to ensuring that the benefits of the project reach all stakeholders, efforts should be made to avoid displacing traditional farming communities and, eventually, involve them in the transition to hydroponics.

Ethical considerations should also be given to making hydroponically grown produce **accessible and affordable** to a wide range of consumers. Although hydroponics can be resource-intensive in terms of capital investment and energy requirements, efforts should be made to optimize costs and explore avenues for community engagement and involvement.

Ongoing research and development are essential for the advancement of hydroponics in Agriculture 5.0. Through conducting ethical research, the welfare of plants, animals, and the environment can be respected. An emphasis on open-source practices, sharing knowledge, and collaborating with experts would best promote responsible innovation that avoids potential ethical pitfalls.

Finally, the **long-term impact** of hydroponics projects on both the local ecosystem and the broader agricultural system must be assessed. Monitoring and assessing the project's ecological footprint, the potential effects on soil health, water resources, and biodiversity can drive adaptation and mitigation strategies which could then be implemented to address any negative consequences that may arise. By incorporating these considerations, hydroponics projects can contribute to a more sustainable and responsible agricultural system.

5.3.1 A professional perspective

Despite the numerous ethical implications of innovation and technology their consideration is vastly underrepresented in the literature [198]. During my studies for the Masters in Electronics Engineering and Computer Science (EECS) at FCT Nova, I was fortunate to study with Sociologist António Moniz in his elective course on "*Sociologia das Novas Tecnologias de Informação*".

Despite his current position in Germany, he kindly accepted the invitation to talk with me about the implications of my hydroponics project. Taking the position of Devil's advocate in a guided interview that I set up in advance, we met online via Zoom on the morning of 19 September 2023 for almost a half-hour debate. I had forwarded him the results of the ChatGPT query, "Is hydroponics good for humankind?", which highlighted 11 topics. As introduced in section 5.3, my own concerns about the sociologic impact of hydroponics proved to be related to the results of the query (tab. 21).

THE SOCIOLOGICAL IMPACT OF HYDROPONICS	
MY INITIAL CONCERNS (section 5.3)	CHATGPT RESULTS
Implementing sustainable practices	Resource Intensiveness Biodiversity and Genetic Diversity
Maintaining high standards of food safety and quality	Food Security and Resilience
Providing accurate and transparent information to consumers	Consumer Perception and Trust
Ensuring economic and social equity	Economic Inequality
Making produce accessible and affordable	Cultural and Traditional Values
Ongoing research and development	Dependency on Technology Ethical Considerations
Elevating awareness of the long-term impact	Environmental Concerns Loss of Soil-Based Agriculture

Table 21 – Matching concerns about the sociological impact of hydroponics

By way of an introduction and for contextualization of this discussion, I would like to begin with his final statement: “There are few people working on the sociological point of view. [Correct.] This is the problem because lots of engineers, lots of things, but then about these aspects that you have asked for help with, on other issues they’ve got nothing, nothing... [Right. You were the teacher who, at the moment of our class, inspired me on this point because I believe it is also very important that we be aware of the impact of what we are creating.]”

Two primary topics dominated the conversation – the sociological impact of automation and the impact of hydroponics on the labor market for agriculture. Exploring the evolution of agriculture, particularly beginning with Agriculture 2.0 and its transition from traditional wheat cultivation to hydroponics, we delved into the shift towards hydroponics and the further possibility of applying hydroponics for mass cultivation, marking a significant advancement in agricultural practices. Nevertheless, we addressed the consequences of increased mechanization and automation in agriculture, leading to a decline in manual labor opportunities, which seriously impacts the workforce.

Midway through our discussion, we touched upon the concerning disappearance of crucial species like bees and insects, potentially influencing horticulture and even floriculture. This segue brought to light Portugal’s notable economic presence in horticulture, where it serves as a prominent subdivision of the economic sector dedicated to agriculture although it

cannot compare to India, for example, a developing country that dedicates the majority of its farmland to exports [199].

This refocused the discussion on the lack of willing people to be involved in manual labor in Portugal, particularly in the production of perishables like lettuce, where the labor involved in quickly handling a delicate product requires care and attention, with an efficient farm-to-fork process and minimal lag time. We explored the potential benefits of greenhouse production in various regions, including northern European countries and Spain. Of particular note was his point that the integration of hydroponics allows for a remarkable increase in production efficiency, with 100 square meters of land eventually translating into 500+ cubic meters of production space. He suggested consulting food production statistics related to horticulture from the UN Food and Agriculture Organization (FAO) for further research on global agricultural trends.

Again, he emphasized that it is not enough to develop the technology, but rather to understand that it will be implemented in an environment where there may be negative and positive aspects that we must consider to be sure that we are developing it more one way than another (fig. 32).



Figure 32 – Screenshot of our debate on the sociological impacts of hydroponics
Source: Zoom, 19 September 2023

On the creation of e-garbage, his response was, “In ten years, but not yet”. Looking into the future, he insisted that calculations should be made to avoid the production of new e-garbage although we agreed that this argument could be described as “*muito naturalista*”, or very environmental. Finally, and to conclude by paraphrasing Sociologist António Moniz, not

many people are working on this aspect, which could enrich a thesis. It is not enough to understand the technology.

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APPENDICES

A1: The historical geography of hydroponics

Before moving forward, the history of hydroponics is elucidating, with subtle changes in scale, spacing, and harvesting over time and across the world. From his 13th century travels in China, Marco Polo described the floating gardens he admired. These esthetic creations, floating platforms, derived from farming practice in Asia, where hydroponic rice crops long before had proven greater resistance against infestation and disease. In the Americas, the Aztecs developed a deep-water culture (DWC) system, an aquaponic version of hydroponic farms to adapt to their floating raft crops to the swamplands.

Around the Mediterranean, the practice was developing before the common era (BCE) (fig. 33).

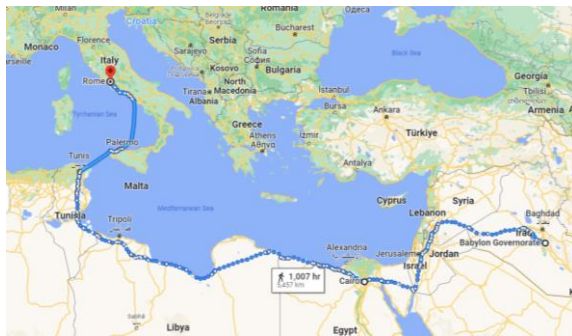


Figure 33 – Where the Mediterranean meets hydroponic farming Babylon-Cairo-Rome

King Nebuchadnezzar II, in the Middle East, built one of the seven ancient wonders of the world, the hanging gardens of Babylon. For this first documented case of hydroponics from 500 BCE, central reservoirs drawing on the lower Euphrates river in southern Mesopotamia were intricately connected to the root system with a carefully planned water delivery system of stone shelves to address concerns related to nutrients and aeration. Taking a 15-day walk to the southwest, just under 2,000 km away, hieroglyphs along the Nile also document the practice of using the flooding river to grow crops hydroponically. Just across the bustling economic center defined by the Mediterranean Sea, the Romans, under the emperor Tiberius, implemented a more complex hydroponic system with water running over a translucent stone for a greenhouse effect to provide humidity, heat, and light.

A2: Hydroponics in the early literature

Despite the widely known practice over time, the first modern academic reference to the term *hydroponics* came from the early 20th century at the University of California, Berkeley, where William Frederick Gericke showed that a solution of nutrients and water could substitute soil.

This soilless plant cultivation had been described in earlier moments with important advances throughout history:

- In the mid-1800s, Jean Baptiste Boussingault developed growing mediums and confirmed a list of nine essential elements, the addition of inert materials – charcoal, quartz, and sand – and the proportion of nitrogen required to grow healthy plants.
- In the 1600s, Sir Francis Bacon's book *Sylva Sylvarum* (1627) was published posthumously and, in 1699, John Woodward published his findings that distilled water did not contribute enough nutrients. Together these publications reflect the advanced harvesting techniques, like waterproofing and greater crop yields, that were prevalent at the time.
- Leonardo da Vinci had understood the principle, proposing that “[t]o develop, plants need mineral elements that they absorb from the soil by means of water. Without water, the plants do not survive, even if the soil has the mineral elements they need”.

Since the coining of the term *hydroponics*, this agricultural technique has not only led to increased crop yields and faster cycles of growth but also to the reduction of resource waste in the past century. In addition to the advantages for cultivating food, soilless growth guarantees greater conservation of CO₂ in the soil. In particular, in 1965 at the Glasshouse Crops Research Institute in Littlehampton, England, Allen Cooper pioneered the nutrient film technique for hydroponics. With the contributions of IoT and artificial intelligence, Agriculture 4.0 is a reality for hydroponics.

A3: Background on Cyber-Physical Systems

To better understand the pivotal role of CPS technology, we can look to Henrik von Scheel of the Arthur Lok Jack Global School of Business. Named "the most influential management thinker of our times", he is also known as "the originator of the 4th Industrial Revolution" [200], which he came to describe as a collision of Megatrends. These trends represent, in his terms, the "sequence of 5 metamorphosis stages of paradigm-shift, that change everything (...) the fusion of the digital, virtual, and physical worlds (also called the cyber-physical systems)" [201]. The stages (fig. 34) are:

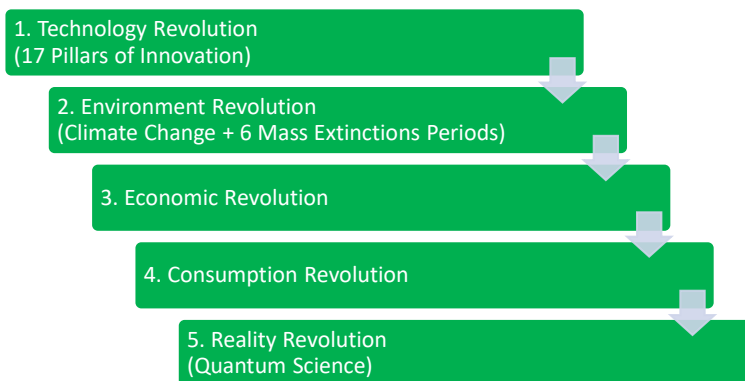


Figure 34 – von Scheel's 5 metamorphosis stages of paradigm-shift with Industry 4.0
Source: Adapted from [201]

The Klaus Schwab's 2016 publication for the World Economic Forum (WEF) [202] drew attention to von Scheel's forecasting as part of the team of German scientists [32], [203] and, the next year, 2017, the European Patent Office registered a 54% increase in patents filed related to the Fourth Industrial Revolution [63]. Figure 35 shows the sequence of the former Industrial Revolutions over time with a question mark postulated by the WEF for the year of the Fourth Industrial Revolution, albeit with an emphasis on CPS.





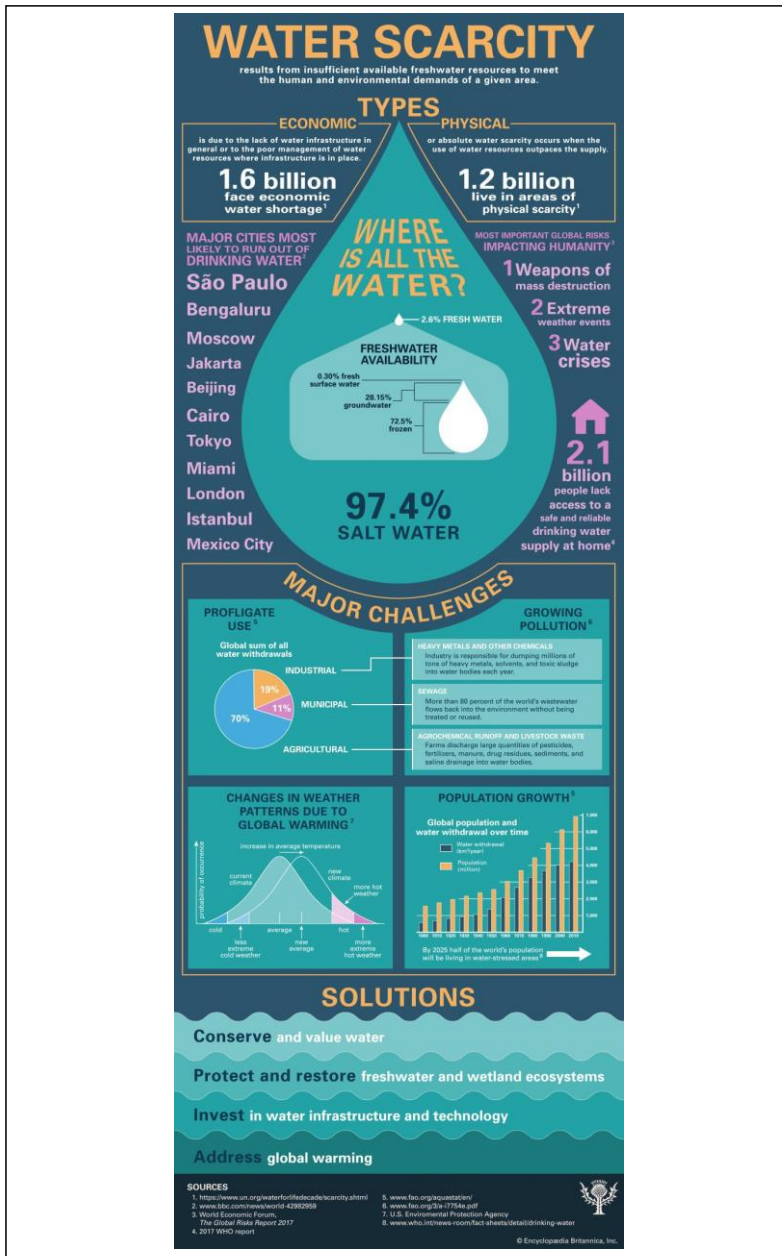
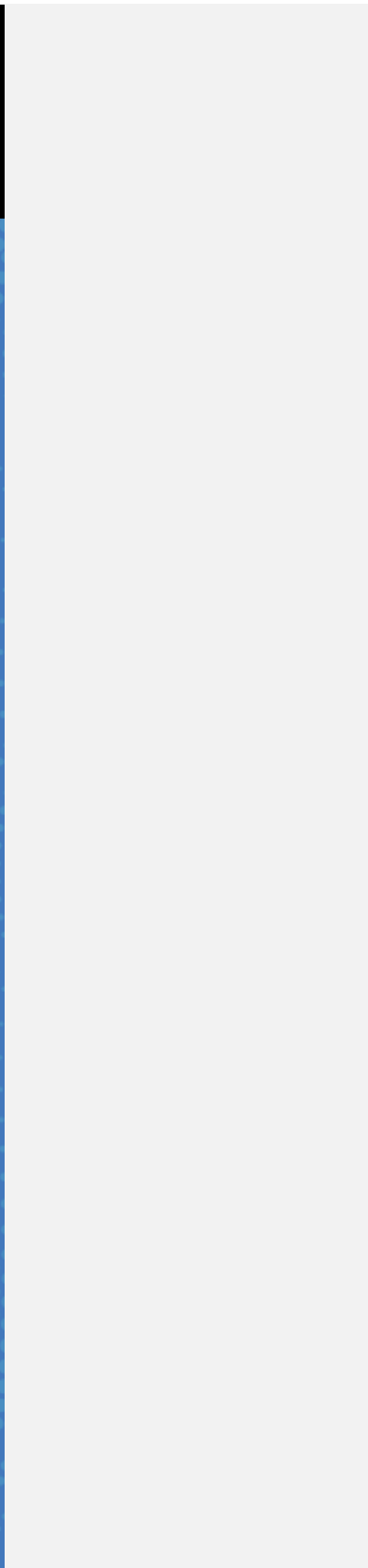
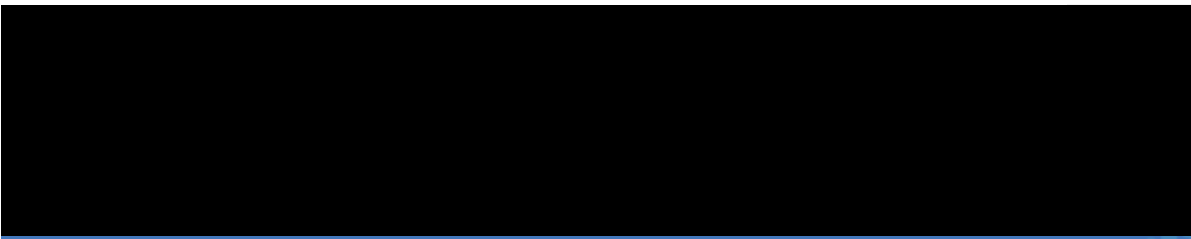
Revolution	Year	Information
	1 1784	Steam, water, mechanical production equipment
	2 1870	Division of labour, electricity, mass production
	3 1969	Electronics, IT, automated production
	4 ?	Cyber-physical systems

Figure 35 – Navigating the next industrial revolution per the WEF
Source: [202]

Note that prior to the WEF publication, in Europe, the global economic crisis in 2009 had led the Germans to developing their concept of *Industrie 4.0* [138] starting in 2011 at the industrial trade fair Hannover Messe, where the slogan was *Technology creates new markets, new contacts, new customers, new networks* [204] or even as early as 2006 with the government's High-Tech Strategy [32], [203].

A4: Economic and physical types of water scarcity [160]





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2024

HYDROPONIC IoT MONITORING SYSTEM
FOR DECISION-SUPPORT IN SMALL FARMS

