Taeda Tech Project – Soilless Cultivation for Rapid Biomass Feedstock Production

Project Report

Prepared for: DESNZ, Biomass Feedstock Innovation Programme

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NET ZERO INNOVATION PORTFOLIO

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Our project partners:

Executive Summary

The Taeda Tech Project set out to demonstrate a novel way of cultivating Short Rotation Coppice (SRC) willow, using aeroponics, to achieve biomass scale-up targets in line with the route to Net Zero [1]. This approach was chosen based on previously demonstrated gains when using aeroponics for small leafy crops and was targeting the ability to scale up planting material, by operating at the nursery stage. Led by the University of Surrey, the project ran over three years, between July 2022 and June 2025 and formed part of the wider Biomass Feedstock Innovation Programme.

The project required a holistic approach to achieve successful demonstration, from the development of the technology (a suitable aeroponic system), to developing the relevant processes to will best support SRC willow growth and ensuring that the planting material produced is viable in the field. Taeda Tech also embarked upon assessing the long-term impact of the innovation on the environment and on the socio-economic landscape; it also explored the application to crops other than SRC willow. To achieve these wide-encompassing objectives, the project required close collaboration between academia and industry.

In collaboration with LettUs Grow, the project team successfully developed an aeroponic system that can host large crops, woody crops included. The systems developed are now a scalable solution for aeroponic large crop cultivation. The project was able to demonstrate that growing willow in aeroponics can accelerate the supply of willow planting material by a factor of seven, compared to traditional propagation methods. By reasonably extrapolating findings from the research facility at the University of Surrey to a one-hectare scale operation, the innovation could produce over 3 million cuttings/ha/year, using a standard SRC willow commercial variety mix. Not only can aeroponics deliver more cuttings, but these are of superior quality. To ensure the feasibility of the innovation, field viability was also tested, with establishment rates comparable to field-multiplied willow and a biochemical profile that results in superior growth than their counterfactuals.

These results are tied into the work the team have put into identifying and optimising the operational parameters, from testing the crops in a glasshouse and a polytunnel, identifying the best watering regimes and developing a custom fertiliser solution for willow in aeroponics. The optimisation was supported by the agri-tech expertise provided by UK Urban AgriTech and willow expertise provided by Rothamsted Research. As part of the optimisation work the project has successfully developed a digital twin model which will be able to support decision making for SRC willow growth in aeroponics and has the potential to be adapted to other crops.

Data from the trials has been collated and analysed to assess the potential environmental and socio-economic opportunities and challenges should the innovation become widely adopted. While a single cutting produced from aeroponics has a higher greenhouse gas (GHG) impact than one grown in the field, the impact over the 20-year crop life cycle is comparable. Moreover, GHG savings are achieved due to rapid scale up of field biomass cultivation facilitated through aeroponics nursery cutting production. From a socio-economic perspective, the project has developed a detailed simulation exploring various deployment scenarios and, in all scenarios, the impact of adopting the innovation resulted in increased outputs from the renewable energy sector, increased Gross Domestic Product (GDP), and improved social welfare.

Alongside demonstrating the successful application to willow, the project has also explored growing other species in aeroponics. We have demonstrated that some species, such as alder, eucalyptus, *Miscanthus* and Sitka spruce, grow two to three times faster in aeroponics than in soil. While more work on other trees is required, these findings have profound implications for the potential of aeroponic nurseries to support achieving UK biomass and afforestation targets.

The Intellectual Property (IP) developed during the project, as well as the partnerships and stakeholders engaged, will be valuable in the commercialisation of the innovation. There is potential to not only commercialise the aeroponic system as a standalone piece but also to use the expertise and current assets as a Research and Development (R&D) service, and an all-inclusive aeroponics SRC willow package for growers. During the three years of the project, the team have been following policy and market developments and have remained agile in their approach. The project was complex and required multiple collaborations with numerous interdependencies. Given the length of the project, some changes and delays have occurred, however the project has been successful in meeting its objectives, within the three-year timeline while remaining under budget and ensuring excellent value for money.

While this project is ending, Taeda Tech acknowledges the potential for future works. This includes additional optimisation to reduce the cost of the systems and further refinement of operations to increase productivity and ensure a market-competitive willow product. Additional research and work are required to finalise and implement the digital twin developed during the project – an add-on optimisation feature of the innovation, which may evolve into a standalone product. More immediate applications of the innovation are focusing on the development of bio-chemical traits in plants and higher value crops, as well as applications to sustainable food supply chains. These are facilitated through an already established partnership. Taeda Tech and the team will continue to operate under the umbrella of the University of Surrey, making use of the state-of-the-art aeroponics facility on campus, and will continues to provide R&D aeroponics services, further developing the University's applied research capabilities. Technology development will continue in collaboration with LettUs Grow, alongside exploration of market opportunities and supply chain partnerships.

With the three-year funding opportunity under the Biomass Feedstock Innovation Programme, Taeda Tech was able to, for the first time, demonstrate the immense potential and advantages of aeroponics in supporting the development and scaling up of planting material for biomass production.

Contents

List of Figures

Abbreviations

BFIP	Biomass Feedstock Innovation Programme
CEA	Controlled Environment Agriculture
CGE	Computable General Equilibrium (model)
CO_2-eq	Carbon Dioxide (CO_2) Equivalent
FTE	Full Time Equivalent
GDP	Gross Domestic Product
GH	Glasshouse
GHG	Greenhouse Gas (emissions)
GWP	Global Warming Potential
ha	Hectare
IP	Intellectual Property
KPIs	Key Performance Indicators
LCA	Life Cycle Assessment
LuG	LettUs Grow
MS	Milestone
NIAB	National Institute of Agricultural Botany

NZIP	Net Zero Innovation Portfolio
PT	Polytunnel
Q	Quarter
R&D	Research and Development
SRC	Short Rotation Coppice
TRL	Technology Readiness Level
UKUAT	UK Urban Agri-Tech
UoS	University of Surrey
WP	Work Package

Project Team

Current and historic project staff, in alphabetical order.

Team Member Name	Areas of Work/Work Package	Organisation
Alan Foy	SRC Willow Trials, Technician	University of Surrey
Adesola Ali	Commercialisation	University of Surrey
Alexander Owens	SRC Willow Trials, Technician	University of Surrey
Avinash Agarwal, Dr	SRC Willow Trials, Plant Science	University of Surrey
James Suckling, Dr	Environmental Impact Assessment	University of Surrey
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Katia Zacharaki, PhD candidate	SRC Willow Trials, Plant Science	UKUAT
Laura Nelson	SRC Willow Trials, Technician	University of Surrey
Linqi Sun, PhD candidate	Socio-Economic Impact Assessment	University of Surrey
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1 Background

Taeda Tech Project is part of the Biomass Feedstock Innovation Programme (BFIP), which aims to support the production of sustainable domestic biomass [2]. The BFIP is funded under the Net Zero Innovation Portfolio (NZIP), which fosters innovation in carbon removal, energy storage, and low-carbon fuels and energy production [3].

Bioenergy is one of the priority areas of the NZIP and decarbonisation pathways recommended by the Climate Change Committee [4] [5]. If the UK were to act on these recommendations to expand the land area dedicated to biomass feedstock production for energy, it would encounter a bottleneck in the supply of planting material.

To alleviate this bottleneck, the project focused on means of accelerating planting material production. Specifically, it focused on Short Rotation Coppice (SRC) willow at the nursery stage, based on the role of perennials in the biomass feedstock mix [4] [5].

The delivery of the project was led by the University of Surrey (UoS), Guildford. Founded in 1963, the University caters to over 15,000 students and has a robust reputation for outstanding education and research, renowned for contributions to Hospitality and Leisure Management, Engineering and Sustainability. Taeda Tech has leveraged the University's areas of expertise and has sought support from UK Urban Agri-Tech (UKUAT), the main delivery partner. UKUAT is a non-profit industry association, formed in 2020, that brings together key players from the field of Controlled Environment Agriculture (CEA) in the UK. This collaborative project was developed to apply principles previously used in CEA to speed up the propagation of Short Rotation Coppice (SRC) willow for bioenergy production. The innovative aspect of our proposal was the use of aeroponics for the rapid propagation of SRC willow cuttings.

Aeroponics is a means of growing crops without the use of soil, by providing nutrients directly to the root system through spraying/misting. This provides advantages over soil-based agriculture by increasing the speed at which plants develop and by maximising controls to create closed-loop systems of water and nutrients (Figure 1).

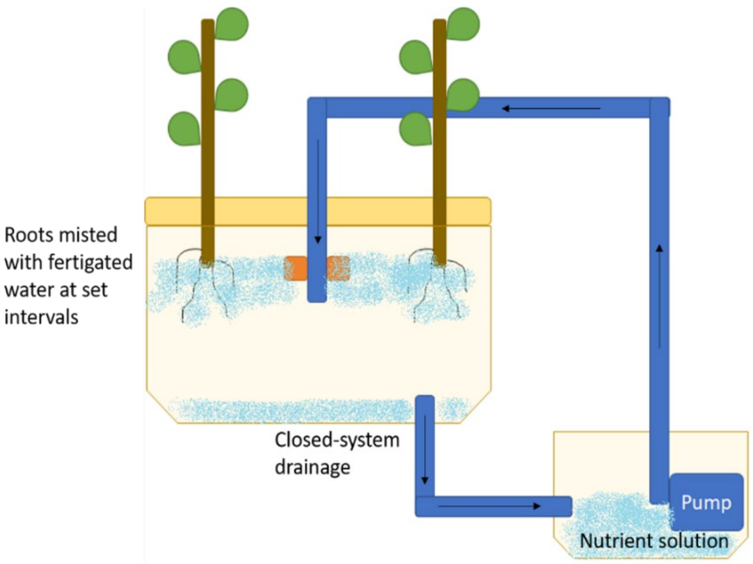

Figure 1 Schematic of aeroponic principles

Aeroponics has been widely used in growing small, leafy crops, such as lettuce, spinach and basil; however, using aeroponics for large woody crops had not previously been tried. Research during the feasibility study found no previous work on woody crops in aeroponics or commercially existing large aeroponics systems. Led by Dr Zoe M Harris, the project feasibility study took place between 2021 and 2022 and was part of the Phase 1 of the BFIP. Using Dr Harris's previous experience in aeroponic willow, from a 2019 small-scale trial, and core stakeholders' insights into the industry and standard field practices, a project plan for the Taeda Tech Project was developed, which aimed to demonstrate rapid and superior propagation of SRC willow planting material. The project was selected to be part of the Phase 2 BFIP which ran between July 2022 and June 2025, alongside other projects addressing different stages of the supply chain for feedstocks of interest [2].

2 Project Overview

Taeda Tech Project – *Soilless Cultivation for Rapid Biomass feedstock production* set out to demonstrate that the new aeroponic technology can be a commercially competitive means of rapid and superior cultivation of SRC willow cuttings. To achieve this aim, the project team adopted a holistic approach, ensuring that cost-benefit considerations also include any potential environmental and socio-economic impacts. It also acknowledged that applying aeroponics to SRC willow will be a continuous learning process, from which we can draw optimised practices and outputs, and applications for a wider range of possibilities, such as other woody species. The project would measure success based on the plant life cycle of SRC willow, from nursery to field (Figure 2), demonstrating that cultivating SRC willow in aeroponics is a viable approach.

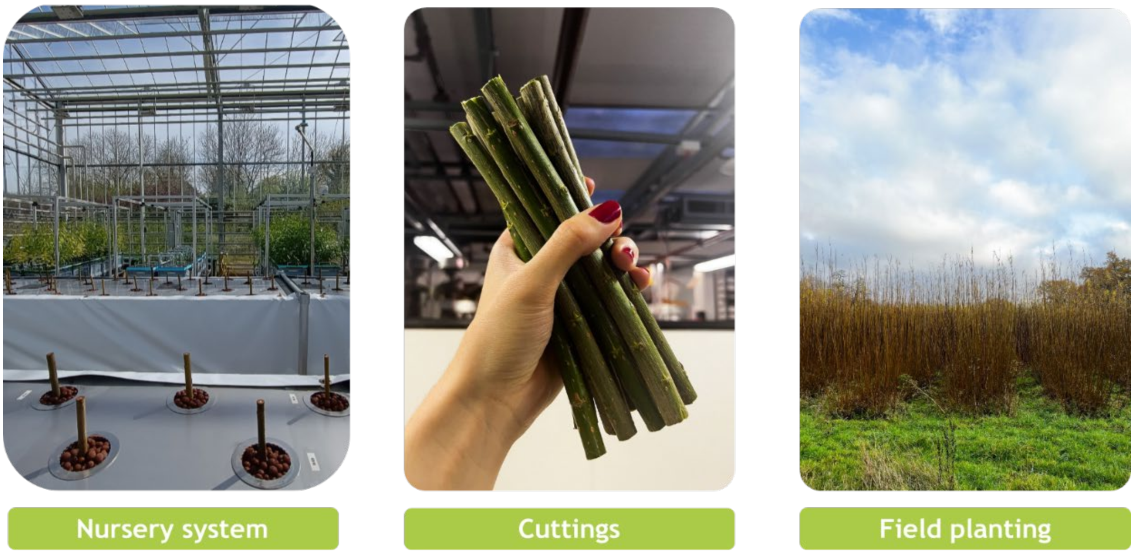

Figure 2 The three stages ensuring viability of SRC willow produced aeroponically: aeroponics SRC willow, cuttings production and field planting of the cuttings

To ensure a holistic delivery, the project's objectives were:

- To optimise the aeroponic system for maximised growth rate, and minimised resource usage, with the least environmental impact and at the lowest cost.
- To demonstrate rapid, superior growth of SRC willow using the aeroponics system.

- To explore the potential of the aeroponic innovation for advancing breeding programs.
- To identify the potential application to other crops (for example, hazel, forestry species, *Miscanthus*).
- To quantify the environmental and socio-economic benefits of growing planting material in aeroponics.
- To demonstrate a viable route to market and establish an appropriate commercial vehicle for the application.

2.1 Project Structure

Work Packages (WPs) were formed around the aforementioned project objectives, with synergies between WPs mapped out to ensure a unitary outlook for the project. Each WP was overseen by the most appropriate expert, with team members sourced from the UoS and UKUAT pools of expertise. Additional support and delivery were provided through partnerships where added capabilities and resources were needed to achieve each objective:

Technology Development (WP1): To demonstrate willow performance in aeroponics, the project first needed to develop novel systems to accommodate large crops such as SRC willow. The development and optimisation of the technology was led by the UoS in collaboration with partners Glideology and LettUs Grow (LuG). Our combined specialisms in engineering and procurement allowed the development of the aeroponic systems.

SRC Willow Trials and Optimisation (WP2): This WP managed the SRC willow trials and monitored plant response in aeroponics as well as performance in the field, on the premise that aeroponics acts as a facilitating technology to speed up the production of high-quality planting material. WP2 was split into two parts – one which focused on the practical cultivation of the crops and associated plant biology and operational optimisation, and a second which focused on gathering data to develop a digital twin to inform operations. The WP2 team core competencies required both practical and research skills, including firsthand plant science, SRC willow experience, data analysis and modelling. Plant trials were supported by partner expertise on SRC willow from Rothamsted Research, and field trials were supported the National Institute of Agricultural Botany (NIAB), Newcastle University and Biomass Connect (BFIP Lot 2).

Other Crops and Breeding (WP3): The application to other crops and to speeding up breeding processes was entrusted to WP3, with a strong focus on research and applied plant science in controlled environments. Led by UoS, external support was provided by partnerships with Aberystwyth University, Forest Research and NMC2.

Environmental Benefits and Trade-offs (WP4): This work aimed to quantify the environmental impact, the benefits and trade-offs of growing willow in aeroponics, using a life cycle thinking approach and a Life Cycle Assessment (LCA) methodology. This required robust technical and research capabilities from the WP4 team members and experience in producing LCAs, which was provided through UoS talent.

Socio-Economic Performance Evaluation (WP5): Assessing the socio-economic impact was led by UoS and engaged research staff with modelling capabilities. This WP developed forecasts which assumed different scenarios for aeroponically grown SRC willow, to measure impacts on the broader socio-economic system.

Commercialisation and Communication (WP6): The team required strong commercialisation, strategy and stakeholder engagement skills. This was led by UKUAT, with contributions from staff at UoS and external partner Capital Agri.

Project Management (WP7): Led by UoS, this WP was responsible for the project management activities and ensuring that data and findings were shared between the other WPs and integrated into their future works within the project.

Figure 3 shows the operational layout of the project and partners' respective areas of contribution. A detailed work breakdown structure and Gantt chart are provided in the Appendix A.

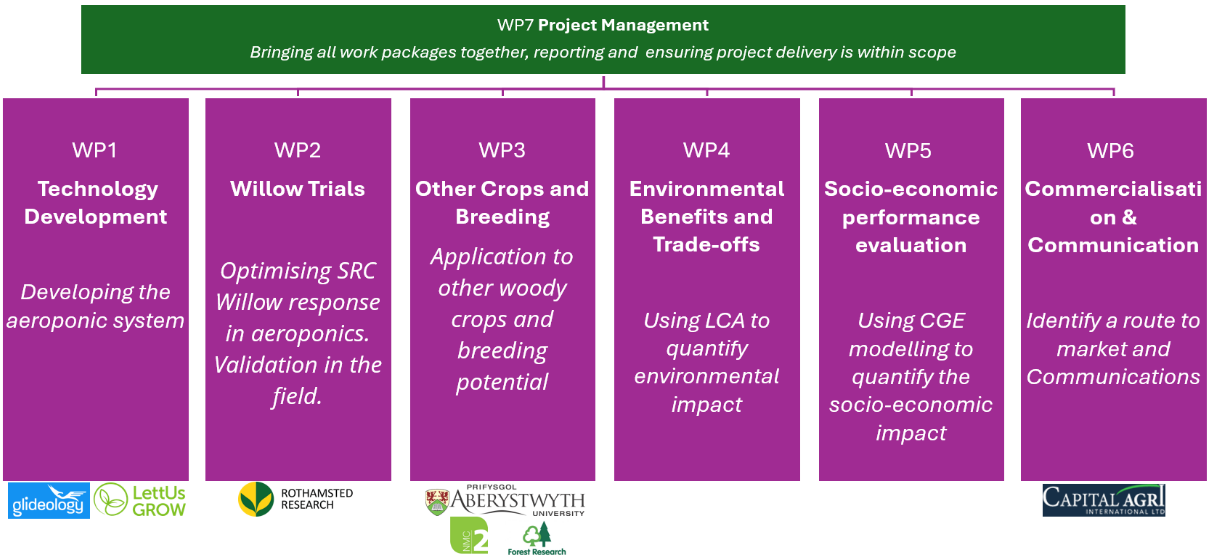

Figure 3 Taeda Tech Project WPs, their work focus and respective external partners

2.2 Project Timeline

The project's delivery was centred around repeated SRC willow cycles in aeroponics. These cycles would create feedback loops and allow incremental improvements in practices, technology, data and results, thus enabling us to demonstrate the viability of the produced plant material in the field (Figure 4). All other works, such as the system development, the impact assessment and commercialisation would complement the critical path activities demonstrating feasibility beyond the technical and adding credibility to the Taeda Tech offering.

The project was scheduled to start in April 2022 with considerations for plant seasonality, including field planting, and was planned for three years, allowing us to gather relevant data. The project start date was pushed back to July 2022, due to contractual onboarding delays, and in November 2024, the project was granted a three-month extension to June 30th, 2025. The extension was granted to allow SRC willow works completion as per the original plan, on the premise that plant physiology cannot be rushed, and field trials data is critical to validation. It was granted only to the works and activities related to SRC willow (WP2) and supporting project management activities, and was not granted for other crops, environmental and socio-economic impact analysis and commercialisation. Overall, the project did not encounter any other major delays and managed to stay within the planned and revised timelines, which accounted for adjusted timing of works discussed above.

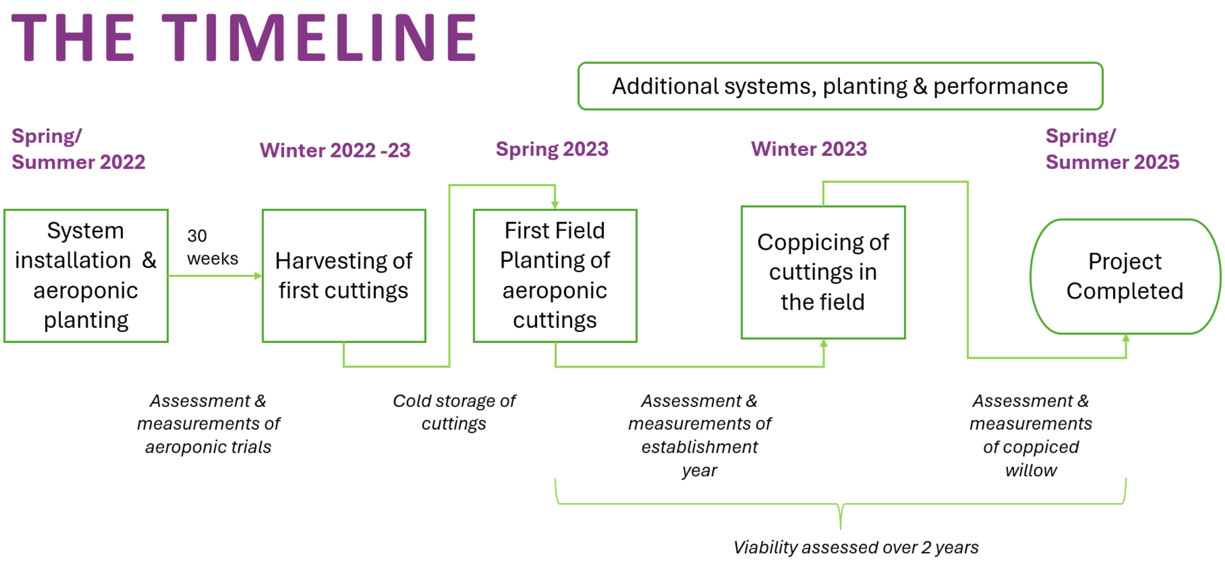

Figure 4 Project critical path considering seasonality of willow plants

The project had a distinctive thirteen quarter (Q) reporting period aligned with thirteen payment milestones (MS) due to the slight delay at the start and to align with reporting and invoicing around UK's financial year-end. To be noted that while the project has a timeline of thirteen reporting periods, the total project length did not exceed thirty-six months, or three calendar years.

2.3 Project Cost

Taeda Tech Project was successful at staying within budget. The estimated project cost at the proposal date was £3,999,495.33, and the expected project end cost is £3,672,476.73[1], with the project delivering the planned activities under budget, within the agreed timeline. The project was managed by UoS in accordance with DESNZ requirements, on a cost only invoicing agreement. All underspend has remained with the funding body. The project experienced notable fluctuations between the planned and actual costs early in the project (MS1-MS5; Figure 5) and the budget was reprofiled in Autumn 2023, effective from Q7/MS7 (Baseline 2; Figure 5).

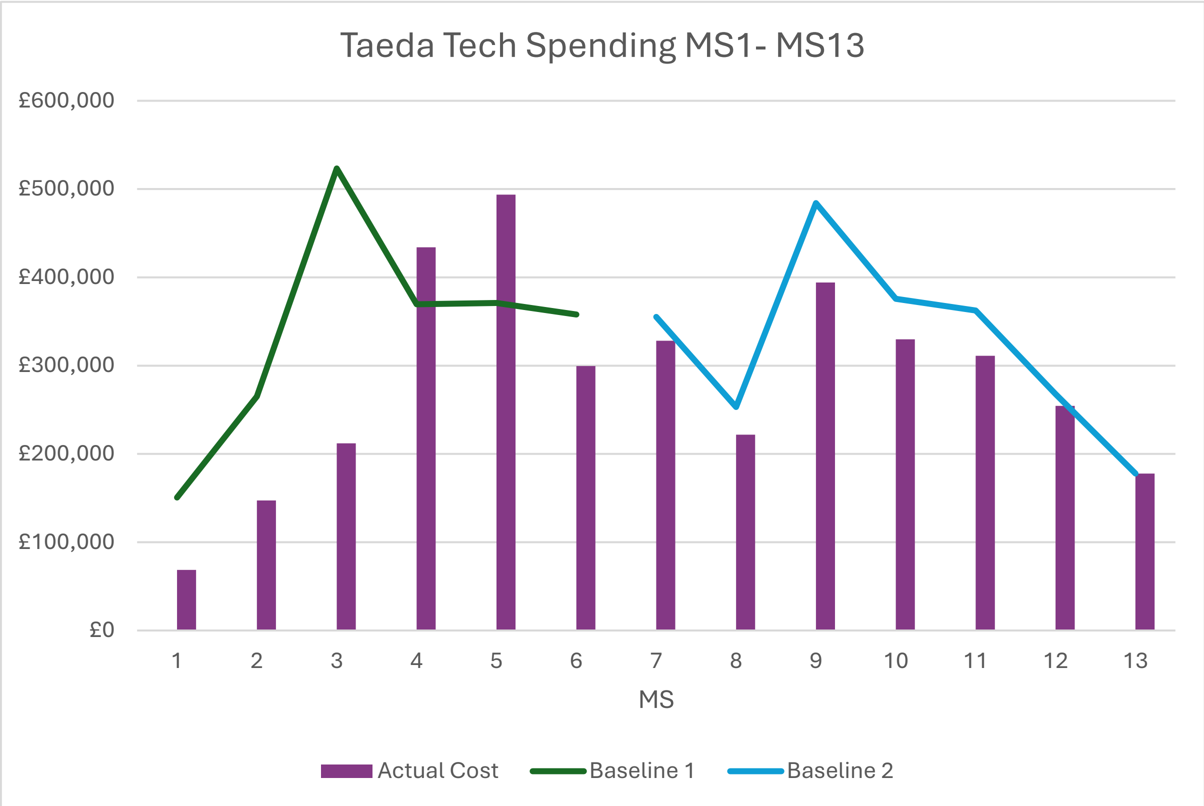

Figure 5 Project Planned (Baseline 1 and Baseline 2) versus actual costs

[1] Total cost is based on the assumed cost of the last quarter associated with MS13, which had not been completed and invoiced for at the time of writing this report. MS13 is not expected to exceed planned costs.

3 Technical Details

This section outlines the rationale and activities involved in the Taeda Tech aeroponic innovation development. Results and findings from production are detailed, including lessons learnt for best SRC willow operations, as well as implications for the wider biomass landscape.

3.1 The Innovation - Design and Development

Applying aeroponics to large woody crops and demonstrating potential benefits required a comprehensive approach. The project not only needed to develop a suitable aeroponic system, but also needed to research, test and develop suitable protocols and procedures that would be most beneficial to the plants. The project's innovation thus lies in the combination of the system, expertise of SRC willow plant management, and the optimisation modelling to enhance production.

The Technology Readiness Level (TRL) at the start of the project was TRL5 – 'Technology validated in relevant environment' and the TRL at the end of the project is in line with our target of TRL7- 'System prototype demonstration in operational environment'.

The development of the innovation was approached so that its core components could continue to be used or further developed into standalone products, such as the aeroponic system, the bespoke fertiliser or the optimisation model. The project focused on SRC willow multiplication and at the same time recognised the potential for wider and more diverse impact through modular development of each work strand. As an example, the aeroponic system as a standalone product can be considered a TRL8 - 'System complete and qualified'.

This section will present the approach taken for each of the work strands and results will be presented in the following section, Demonstration and Results.

3.1.1 System development

The aeroponic system focused on scalability, utilising control systems which allow operational ease and cost reduction, with low adoption barriers, to ensure a standalone product capable of rapidly multiplying larger crops. The end goal for the technology was to have a market ready product that can be used for large crops, independent of SRC willow operations. Four versions of the aeroponic system were assessed, with progress made from one version to the next (Figure 6).

a) 2022 – UoS-built aeroponic systems - A simple system, acting as proof of concept and focusing on plant experimental set-up (modularity).
b) 2023 – Glideology manufactured systems - focusing on experimental set-up (modularity) with improved root access and support for plants.
c) 2023 – LettUs Grow 1st version (LuG_v1) – co-designed with UoS, focusing on scalability, cost reduction and increased control.
d) 2024 – LettUs Grow 2nd version (LuG_v2) – co-designed with UoS, additional controls added for remote supervision, focus on scalability, cost reduction and improvements based on learning from previous versions.

The systems' technical performance was evaluated against:

- Response of SRC willow in the experiments, for example ensuring sufficient space for the root zone, root access to misting droplets and adequate plant support for a fully grown plant (in aeroponics, willow stems can reach around 5 meters before they are harvested).
- System's operability – including access for measurements, ease of management, fault-finding, maintenance and repairs.
- Technical reliability – looking to remove or reduce any component failures, water leaks, to increase controls and to ensure redundancies are built in for irrigation and power to reduce operational risks.

While the systems were assessed, informed design decisions for future models were made at the same time, to maintain an agile approach and rapid turnover of system iterations. The lasted model provided in 2024 (LuG_v2; Figure 6) is a scalable design with significant cost reductions achieved by considering design efficiencies and reduced number of components compared to previous versions.

Figure 6 Chronologic order of aeroponics systems, at installation (left) and during plant growth (right). From top to bottom: a) self-built, b) Glideology, c) LuG_v1, and d) LuG_v2

Alongside the aeroponic system development, additional works were undertaken to optimise output of SRC willow, including best practices addressing:

- Improved SRC growth, such as developing a custom fertiliser mix for aeroponics, identifying specific irrigation schedules, optimum operational environment, pest management, ideal time to harvest.
- Increased productivity per area through a planting density increase (higher planting density results in longer straighter stems which are preferential for cuttings production).
- Developing a digital twin (computer model representation of the system) to identify key contributing factors that affect willow growth and predicting plant growth and time of harvest.

3.1.2 SRC Willow Trials Development

In each version of the aeroponics system commercial SRC willow varieties were grown. Data collection and analysis ensured sufficient information was gathered on plant performance along its entire life cycle: in the system, at harvest and in the field. These data were fed back into the aeroponic operations, allowing for revised protocols as the systems were refined and optimised.

Five standard diverse commercial varieties of SRC willow were selected to demonstrate SRC willow growth in aeroponics (Tora, Resolution, Endurance, Cheviot, Hambelton). As field cultivation typically involves the use of a combination of varieties for increased pest and environmental resilience, it was necessary to demonstrate performance of the aeroponics across a range of varieties. Each system grew a mix of these five varieties, with cuttings randomly positioned to ensure unbiased cultivation results. Based on 2019 data from Dr Harris's previous experiments and using data modelling, the project estimated the time to harvestable size would be approximately 30 weeks, which informed early trial designs. 'Harvestable size' is based on the diameter of the cuttings required for use in a commercial step planter which is between 10-20 mm. Measurement of plant height and stem base diameter were recorded to measure plant growth and estimate growth rate (Figure 7). The 30-week modelled growth cycle has been validated during the project through repeated practical trials; however, it is worth noting that

Figure 7 Aeroponic SRC willow measurements to establish growth rate

some of harvests over the three years occurred later than 30 weeks, due to resourcing reasons, such as overlaps with winter holiday season.

Following clear proof of concept and performance of our five initial commercial varieties and to explore the breadth of the potential application, two additional approaches were taken:

1) Near-commercial varieties provided by Rothamsted Research were also tested in our system in 2023; however, due to operational challenges at the start of our experiments these crops experienced a severe drought and the outcome from this work was deemed inconclusive and discontinued.
2) Five additional commercial SRC willow varieties were added to the experiments, allowing coverage of the main varieties utilised here in the UK. Ester, Inger, Paramore, Wilhelm, Tryfan were selected as they have diverse genetic backgrounds from each other and the initial five varieties. Genetic diversity provides increased in-field resilience from pests, disease and harsh weather, as well as diversity of yields, carbon sequestration, soil microbiome and biodiversity. These additional varieties were planted in 2024, into the LuG_v2 system.

SRC willow response to aeroponics was tested in two environments: a 170 m^2 glasshouse (GH) with controlled heating and additional lighting, and a 100 m^2 open-sided polytunnel, with no environmental controls other than use of rolling sides which allow modifications to air flow and temperature. (Figure 8).

The lighting and heating regimes in the GH have been adjusted over the three years based on observations, including pest management and resulting cutting viability in the field. The project also optimised root management, with root pruning taking place to prevent system blockages, showing no detrimental effects on plant performance.

Figure 8 Growing environments at the University of Surrey. Polytunnel (PT, left) and Glasshouse (GH, right)

The SRC willow fertiliser mix has been improved over the course of the project, from a standard off-the-shelf macronutrient and micronutrient solution to the development of a bespoke formula. In developing the new formula, the team accounted for local water quality (acidity, hardness and presence of other elements) and plant response. The plant response was measured by observations (leaf colour, vigour), through biochemical analysis of leaf samples to measure rate of nutrient uptake, and through fertigated water sample analysis, which assessed the composition of irrigation water before and after application to the plants.

The planting density initially tested for SRC willow was of 10 trees/m^2. Further trials tested plant response and productivity at a lower and a higher density, of 8 trees/m^2 and 16 trees/m^2, respectively. While lower density trees have more stems and more cuttings per trees, the latest harvest confirmed that increasing the planting density results in more cuttings per area, with no detrimental impact on the plants. This is also observed in the field where a higher planting density results in longer straighter stems which are preferential for cuttings production.

After approximately 30-weeks, the SRC willow from the aeroponic trials was harvested and processed manually. Stem length, number of stems and biomass weight were recorded. Stems were cut into 20 cm cuttings which were categorised into 'yield': diameter 10-20 mm - suitable for currently used mechanical planters, and *'guard'*: 8-10 mm and 20-22 mm, viable, suitable for manual planting and potentially suitable for mechanical planters, given allowance of the planter and measurement error. The two categories are equally viable, and the projects' results will reflect the two categories combined.

3.1.3 Digital Twin - Optimisation Model Development

The digital twin optimisation model, a subdivision of WP2, is a computer representation of the physical aeroponic system, cultivation environment and willow growth and environment. The digital twin allows us to qualify interactions between factors which affect willow growth and estimate the biomass production, and therefore the number of cuttings. The ability to predict biomass accumulation and number of cuttings based on the changing environmental parameters (e.g. temperature, humidity, carbon dioxide concentration) means that the model can be used to make informed decisions about system and plant management, optimising cultivation approach to maximise the number of cuttings.

3.1.4 Other Applications

The aeroponic concept for SRC willow was also applied to other crops at a smaller scale, with successful results. The testing on other crops was designed to take place after initial trials on willow and following a desk review and stakeholder engagement which identified potential plant candidates. Successful species needed to be physiologically suitable for aeroponics and have market appeal. Experiments with other crops began in 2024 and focused on beach, hazel, Sitka spruce, alder and *Miscanthus* (Figure 9). The cultivation approach differed to the approach taken in the willow trials due to the differences in planting material. This included adaptation of aeroponic system to accommodate diverse starting material (seeds and cuttings), shorter experimental durations, and 'harvestable size' was determined by the specific end use. For example, for nursery trees, the industry standard is saplings of minimum 40 cm in height. Similarly to the willow trials, plant performance was assessed, including growth rates and the ability to be transplanted into soil. Results and discussion are presented in the following section.

Figure 9 Example of other crops in aeroponics. a) alder and b) eucalyptus

3.2 Demonstration and Results

To effectively demonstrate the impact of using aeroponics to grow SRC willow, a comparison was made to current in-field production. Taeda Tech project demonstrated that aeroponically multiplied willow has advantages over field multiplication practices, and whilst a wealth of data has been collected, the most pertinent results are presented below.

3.2.1 SRC Willow

Our aeroponic innovation has demonstrated increased production of cuttings. Extrapolating our findings to one hectare, aeroponics could produce more than seven times the number of cuttings compared to field multiplication. The project expects the results can be further improved with optimisation of the aeroponic system, cultivation approach and environment. To assess the progression of the innovation, the project has benchmarked itself against Key Performance Indicators (KPIs), reviewing the number of cuttings produced per unit area per unit time (cuttings/ha/year) and the cost of a cutting. Additional KPIs assessed field performance, specifically field establishment (percentage of cuttings surviving planting) and field yield (biomass obtained from an adult willow plant originating from an aeroponic cutting). This approach allows assessment across the entire life cycle of the plant. An overview of the innovation's KPI is presented in Figure 10.

To provide comparable results to current practices, the project has used one hectare (ha) as a reference production area. However, as the project does not operate on such a scale, the data gathered has been extrapolated using pertinent assumptions for a one ha operational area. These assumptions are related to possible layout, working space requirements (refined over the course of the project and based on system design), and scaling up operational costs for a one ha environment.

Cuttings/area/unit time ~ 3,141,632 [cuttings/ha/year]	**2. Cost of Cuttings** [£0.22/cutting] –production cost* polytunnel **3. Field Establishment** [>99 %] **4. Field Yield** TBC**[tonnes/ha/year]

Cuttings/area/unit time = ~3,141,632 cuttings/ha/year (based on January 2025 first rotation harvest from LuG_v2, polytunnel). This is our most sensible result so far. As a reminder assumption are:

a. 16 trees/m^2 = 76,800 trees/ha; working space accounted for – ASSUMED based on scaled up design.
b. 24 - cuttings/tree – average number VALIDATED in polytunnel (Jan 2025 harvest, LuG_v2)
c. All trees perform similarly - ASSUMED
d. All trees survive - ASSUMED
e. Cultivation enables 1.7 crops/year – VALIDATED

* Production costs for polytunnel assume 1 ha operations, fixed and variable costs included, assuming space rental

** Field Yield in tonnes/ha/year was not possible during the project, proxies were used for field performance.

Figure 10 Project chosen KPI to measure output of aeroponically multiplied willow

3.2.1.1 Cuttings/ha/year

Achieving an average of 1.7 harvests per year, based on our demonstrated 30-week cycle and at a planting density of 16 trees/m^2, the innovation could produce around three million cuttings/ha/year – assuming all trees survive and perform similarly. This is equivalent to seven times more cuttings than field multiplication.

Even at a lower planting density or assuming not all trees perform the same, aeroponics could still produce more than four times the number of cuttings. For reference, field-based multiplication allows for one harvest per year (52-week cycle) at a density of 40,000 trees/ha or 4 trees/m^2, capable of producing in the region of 416,000 cuttings/ha/year.

There are several variables which contribute to the above-mentioned annual production estimate:

- This estimate accounts for a potential system layout and working space, for example, allowing safe and suitable access for maintenance and harvest etc. The feasibility of which was discussed with LuG, the technology supplier.
- Results are based on the cultivation of a standard varietal mix. A commercial decision could be taken to focus on naturally higher yielding varieties which would result in higher number of cutting/ha/year but limit the range of varieties which would be offered.
- The demonstrated harvest period is 30 weeks, which can vary slightly between a summer harvest (where the period could be slightly reduced) and a winter harvest (extended beyond 30 weeks to allow overwintering and higher cutting quality).
- This production is based on results from the polytunnel, an environment which has produced a higher overall number of cuttings than the GH, at lower economic input (considering polytunnel installation and running costs).

In the planning phase, the project projected the innovation could produce up to a maximum of 25 million cuttings/ha/year. This assumed no working space for system access, resulting in 100,000 trees/ha, with each tree producing 150 cuttings from 10 viable stems, at an average of 1.7 crops per year. This estimation has proven inaccurate firstly because of the need for access, unless technological advancements are made where this is not required, for example automation; secondly, and mainly, because of the low probability that a willow tree will produce 10 stems all of which will produce 15 cuttings.

Details of the calculations and comparisons are provided in Appendix B.

3.2.1.2 Cost of Cuttings

Assumptions and extrapolations are required to calculate the cost of a cutting in a potential operational setting, given the innovation is currently being operated at research scale (100 m^2 polytunnel facility). The current production cost estimate of £0.22 per cutting is based on the production potential of three million cuttings/ha/year from a rental polytunnel operation with conservative fixed and variable production costs. Given field-multiplied willow is currently selling on the market for £0.25 per cutting, the aeroponic production cost per cutting likely remains higher than those for field operators. There are however quality considerations which may justify a premium price of aeroponically multiplied willow, such as higher establishment and preferential post-cultivation traits such as reduced pre-processing and improved combustion properties (see section 3.2.1.4 for details). As operations, systems and assumptions have been refined during the project the production cost per cutting was reduced from £3.96 at the first harvest, to £0.69 mid-project and finally to £0.22 at project completion. More work is required to further decrease the cost of a cutting by reducing production costs, specifically system costs and labour, but also by increasing output.

3.2.1.3 Field Establishment

Aeroponically-multiplied cuttings have an excellent response in the field, with >99% establishment rate, which is comparable to field-multiplied cuttings. These findings have been consolidated over the past two years from data gathered at multiple trial sites (Figure 11) and we have learned that optimised and appropriate nutrition is necessary for high establishment rates.

Figure 11 Field trial locations across the UK: Newcastle University (NCL) and NIAB in black, and Biomass Connect sites in grey

Over the course of the project, it became apparent that management of the aeroponic cultivation stage impacted the in-field cultivation success. For example, trials managed with manual nutrient dosing, which were provided ample amounts of nutrients, produced more cuttings but these had a lower establishment rate compared to cuttings from trials using automated nutrient dosing systems and optimised nutrient recipes. Following biochemical analysis of aeroponically-multiplied willow material, we learned that providing the willow with high nutrient concentrations results in a higher starch content which contributes to plant decay, thus impacting survival rates.

Equally, material which is not exposed to hardening (vernalisation), harvested and planted fresh in summer (July 2024), had a lower establishment rate than material which had been kept in cold storage over winter. Vernalisation is an essential process in plants that normally grow overwinter, where molecular and hormonal changes take place, allowing plants to store and later utilise resources to reestablish themselves successfully in spring [6].

It is essential that the multiplication stage is well managed, and a lower field establishment may occur if this is not the case. However, with optimised input, such as fertiliser, acidity regulators and cold storage, cuttings achieve >99% success rate in field establishment.

3.2.1.4 Field Yield

Due to the SRC willow management for biomass production, with harvesting taking place after a minimum of 2 years [7], and the project timelines, we have not been able to gather data on the actual yields to be comparable to field yields for SRC willow. Therefore, we have taken physiology measurements of our field cuttings at one-year post-planting and compared the field-multiplied cutting performance with aeroponically-multiplied cutting performance as a proxy for field yield. Aeroponically-multiplied cuttings had visibly preferential traits, appearing larger and healthier. This was confirmed with our measurements showing aeroponically-multiplied cuttings have significantly higher biomass, stem length and number of stems, in four of the five tested genotypes, at one year after planting (Figure 12).

Biochemical differences are the main driver for superior field performance, and aeroponic multiplication allows for the controlled expression of these traits. Compared to field-multiplied cuttings, the aeroponically-multiplied cuttings have higher energetic content and nutrient reserves, as well as good levels of hormones to allow higher establishment and growth rates. Analysis findings also show that the wood derived from these cuttings is of a higher quality, capable of more efficient combustion and therefore better suited to bioenergy production. These benefits and traits can be further refined, but they are an excellent indicator of the premium quality of aeroponically produced SRC willow cuttings.

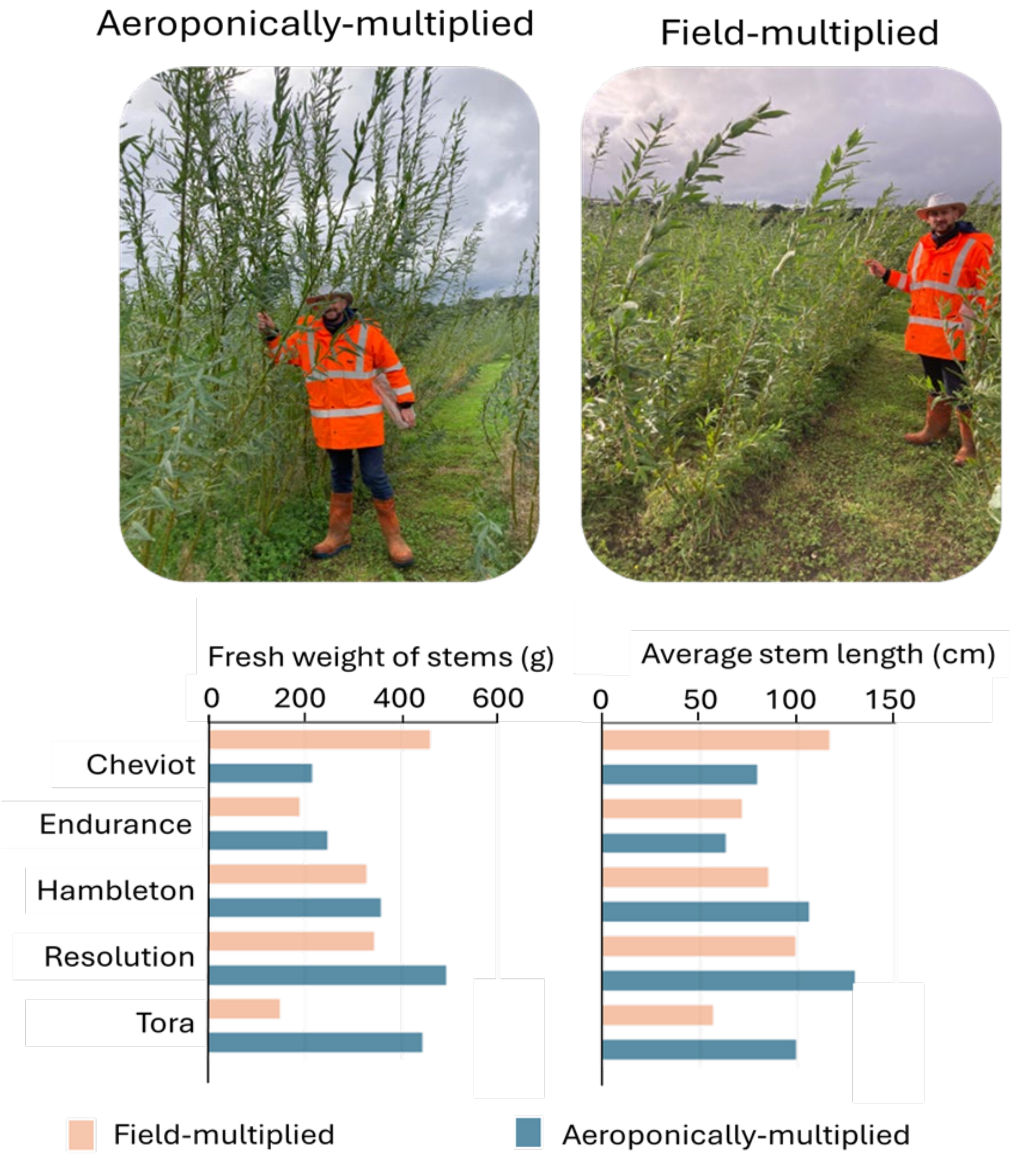

Figure 12 Comparison of performance between aeroponically-multiplied and field-multiplied willow

3.2.2 The Digital Twin

The digital twin model is a computer representation of a real-life system (Figure 13), in our case a predictive tool which can be used to optimise operations and maximise number of cuttings generated in our system.

The model relies on data from the experiments and from the environment. Two key datasets have been used to build the model – photosynthesis estimations and measurement of total biomass produced (separated into roots, woody, leaf). These data were coupled with environmental data to provide estimated biomass production, allowing a forecasting of predicted yields based on seasonal and environmental variations.

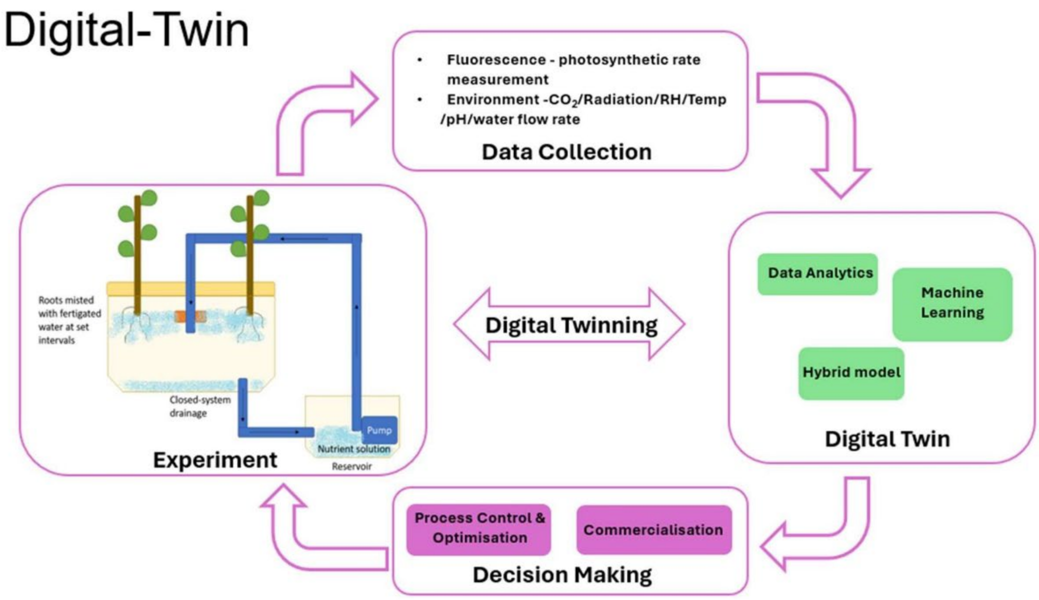

Figure 13 Digital twin as a decision-making tool

The model performed well across both environments, with the ability to predict biomass accurate to 20-60g in the polytunnel (Figure 14) and accurate to c.55g in the GH.

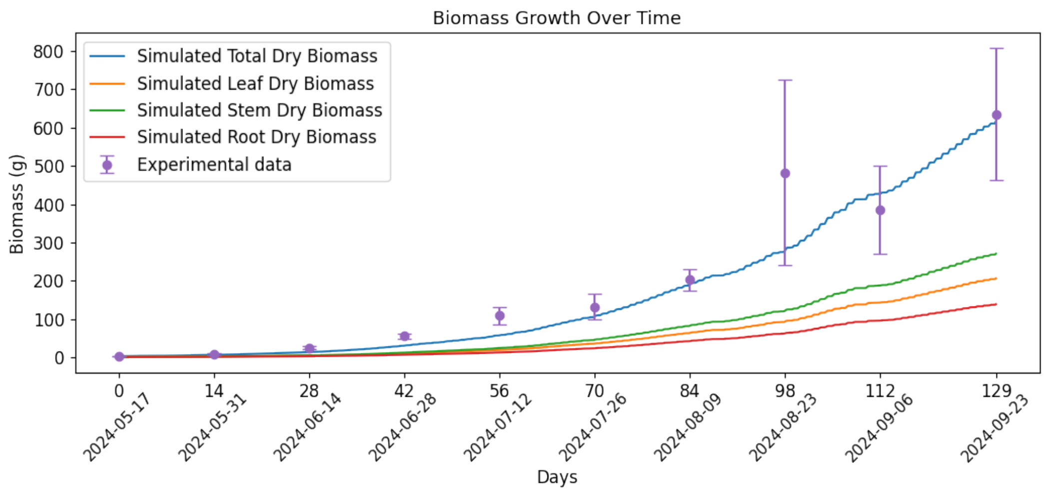

Figure 14 Dry biomass simulation in the polytunnel, from May 17 to September 23, 2024

The model was also tested to assess its future predictive capacities. A target amount of biomass and target number of days were set and the model asked to suggest the optimal cultivation environment. The outputs of test provided sensible results, which would need to be replicated in practical operations to fully validate the model performance, this is a strong indication of the validity of this approach.

The digital twin outputs can provide valuable guidance for controlling environmental parameters in operational setups which create optimal conditions that support higher biomass yields. However, the construction of the digital twin requires complex computational simulations coupled with experimental data collection; therefore, it is still at an early stage of development. In future, the optimisation algorithm could be further extended with economic and emissions constraints to enable more holistic operational decision-making. This allows the underpinning digital twin model to be coupled with a user-friendly interface as a standalone operational decision-making software.

3.2.3 Other Crops

The project demonstrated that aeroponics can be used for the propagation of other crops, with successful results for alder, eucalyptus and *Miscanthus*. The project has shown these species can be grown two-to-three times faster in aeroponics compared to soil controls (Figure 15). Sitka, another species tested, also grew faster in aeroponics, however Sitka might be a too slow growing species to justify aeroponics use at this point. Alder and eucalyptus saplings can reach a marketable size of 40 cm in 24 weeks in aeroponics, compared to 80 and > 52 weeks, respectively, in soil control. The crops were grown in a controlled environment, where light and temperature were tightly regulated.

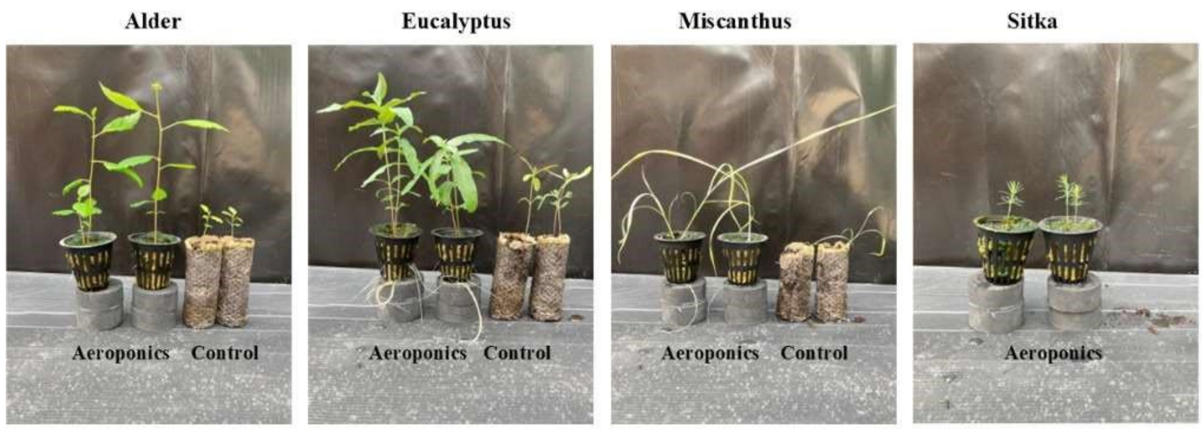

Figure 15 Eight weeks old seedlings of alder, eucalyptus, Miscanthus and Sitka in both aeroponics and soil conditions. NB Sitka seedlings in soil (control) died in the process, therefore no picture of control is shown

The growth rate gains are significant, as seen in Figures 15 and 16, and the project acknowledges that the transplanting process and understanding survival rates post transplanting require further investigation.

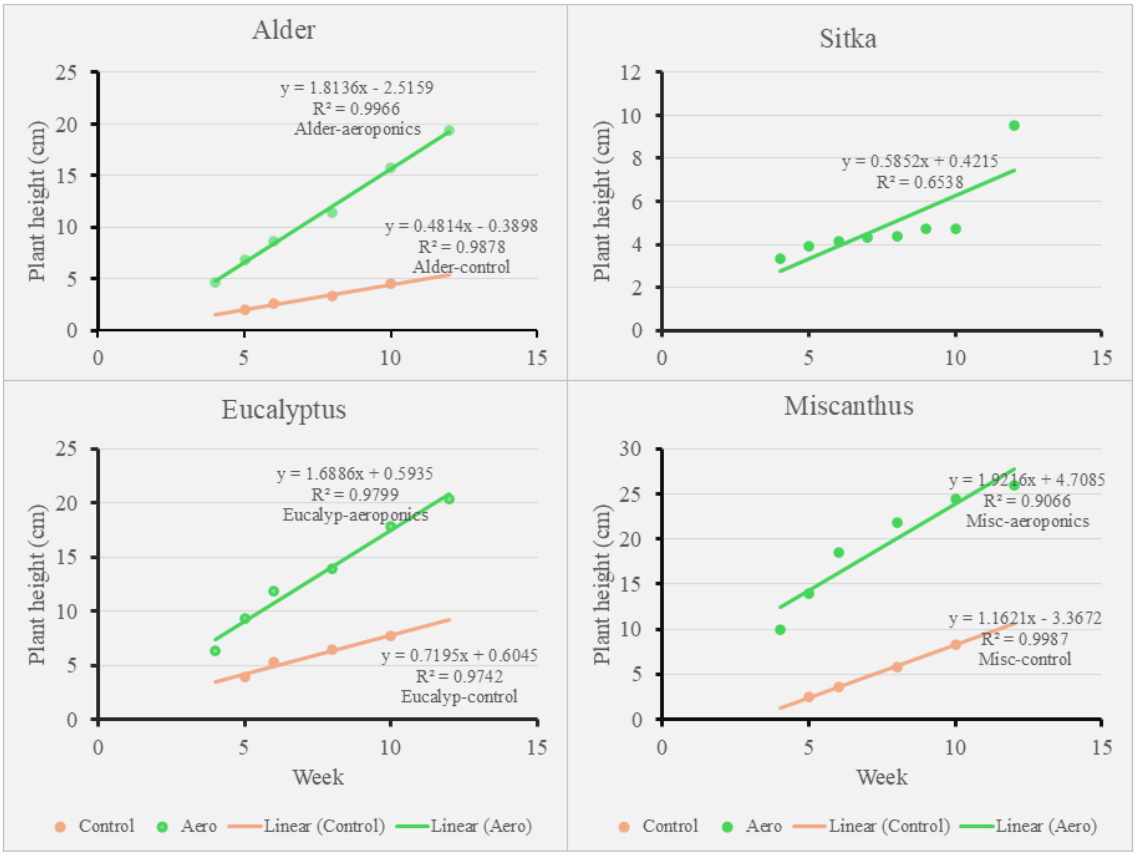

Figure 16 Growth rate of Alder, Eucalyptus, Miscanthus and Sitka for 12 weeks in aeroponics and soil (control) conditions, with regression function. NB: No data/results for Sitka in soil (control) due to poor germination of seeds

While the willow trials have progressed over several years and continue to be developed, work on other crops remains in its nascent stages. The project's findings on the plant performance in aeroponics are reassuring and could support additional production of woody crops for afforestation, bioenergy and biomass material.

Using aeroponics for SRC willow, alder, eucalyptus, *Miscanthus* and Sitka provides an opportunity for testing a wider variety of plant material. The knowledge developed during the project and disseminated through our scientific publications will support further research, development and demonstration, contributing to enriching the variety of species used in aeroponics and their applications.

3.3 Impact on Sustainable UK Biomass Supply

The following section will discuss the implications of multiplying SRC willow in aeroponics and the potential impact of this approach on biomass supply in the UK. It is important to note that where a comparison to conventional field multiplication is mentioned and aeroponics is noted as having advantages, the project does not intend that aeroponics should replace conventional field or nursery practices. Rather it is well positioned to supplement these approaches to accelerate production of planting material, adding flexibility to commercial operations due to the ability of the innovation to allow rapid crop switching within minimal effort (compared to land preparation, replanting, dependence on seasonality etc., which may be found in field operations).

3.3.1 Production Gains

Using aeroponics for multiplication of SRC willow can make a significant contribution to the UK supply of sustainable biomass by providing a larger volume of higher-quality SRC willow cuttings. A standard field multiplication bed has a planting density of c.40,000 stools/ha, which can produce sufficient planting material to populate c.26 ha of SRC willow (Figure 17; where plating density for energy crop production is c.16,000 stools/ha). At an average of 1.7 crops per year, one ha of aeroponics could outperform conventional field multiplication by around seven times, with one ha of aeroponics providing planting material for roughly 200 ha of SRC willow for bioenergy. Details of calculation provided in Appendix B.

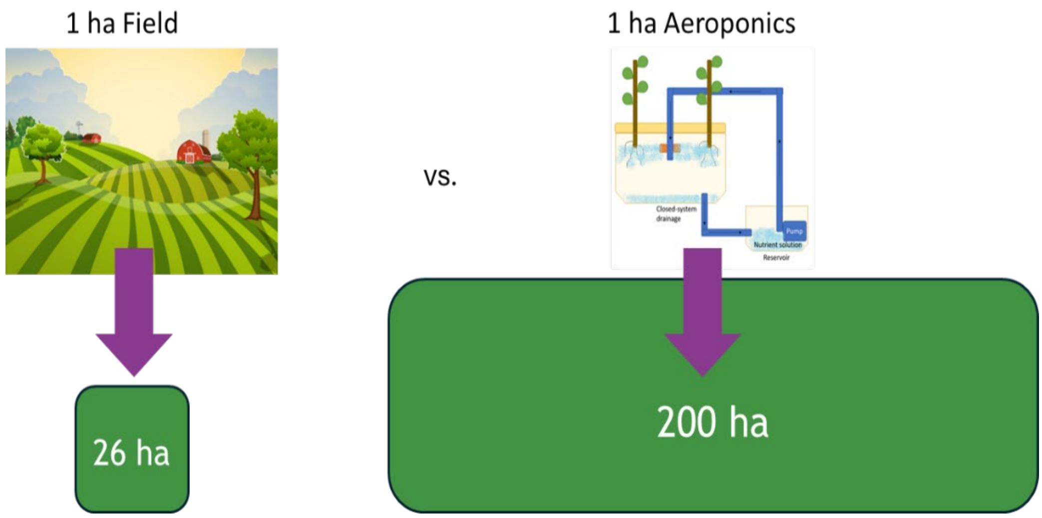

Figure 17 Capacity of aeroponically-multiplied willow to accelerate SRC willow planting area

Aeroponic production allows for rapid crop switching based on market demand, by allowing changes of the cultivated variety without the need for large field scale operations. The stools are not 'locked in' for several years in the ground. This allows for a flexible response to demand in a way that conventional field operations cannot. The innovation thus has considerable potential to support the UK in upscaling perennial bioenergy crop use, alleviating the bottleneck that was identified in Phase 1 of the project. Increasing UK-grown production reduces reliance on imports, as well as the costs and logistical challenges associated with UK's exit from the European Union; and provides a steady supply of materials to accelerate planting.

The work on other forestry species further demonstrates the ability of aeroponically-multiplied trees to contribute to sustainable biomass supply in the UK. As part of the UK afforestation targets, 30 thousand ha of forestry must be planted per year, between 2025 and 2050 [4]. Meeting such a target is not feasible with current UK stock and current supply chain challenges associated with importing. Though in its initial stages, the project has demonstrated the rapid growth of key species, essential in meeting the planting target, with considerable potential to contribute to UK biomass supply.

3.3.2 Greenhouse Gas Emissions Impacts

Aeroponics can produce considerably more cuttings than conventional field production, but to ensure production remains sustainable, an environmental impact assessment was performed. Life Cycle Assessment (LCA) is a standardised methodology for assessing the impact of a product, service or activity considering its entire life cycle, from production-to use-to end of life [8]. There are 15 possible impact categories used to quantify the potential environmental impact of a product or a service, including global warming potential (GWP), eutrophication, biodiversity loss and land use change. In accordance with the BFIP and the Net Zero strategy, Taeda Tech has selected GWP as the most pertinent category, for which impact is measured through greenhouse gas emissions (GHG) and expressed as carbon dioxide equivalents (CO_2-eq) – a means of converting the GWP effect of all other GHG into the equivalent amount of carbon dioxide that would have the same effect [9].

The GHG emissions of producing SRC willow can be analysed in three parts. The first is the production of the willow cuttings themselves. The second is the production of 1 kg of biomass from the field over a 20-year cultivation cycle (a standard SRC willow crop timeline). The third is the speed at which other fuels might be replaced when introducing aeroponically-multiplied willow.

Firstly, if we analyse the production of the cutting in isolation, the GHG emissions from producing cuttings in aeroponics are greater than those from the field. The LCA showed that growing cuttings in the field generated approx. 5 gCO_2-eq/cutting. By comparison, cuttings produced using our technology generated between 328 to 546 gCO_2-eq/cutting, in either a GH or polytunnel setting (Figure 18). The ranges presented for aeroponics depend on whether there is any climate control used, such as heating and lighting. If reported in isolation of any other information, this might be perceived as a negative attribute of the technology. Note: for the aeroponics, this value is made up of the energy, infrastructure, equipment, consumables and waste. For field production, this value includes preparation of the land (mechanical and chemical) and harvesting activities (fuel and machinery).

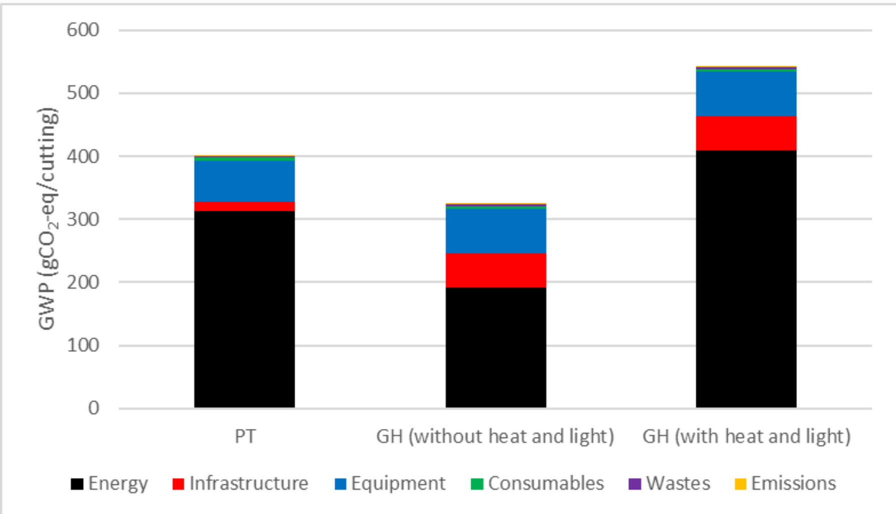

Figure 18 GWP for aeroponic production of SRC willow cuttings in the polytunnel (PT) and the glasshouse (GH). Field production not represented in this graph

Secondly, when looking at biomass production and the LCA is extended to include a 20-year cultivation cycle of SRC willow in the field, the results change markedly. The large relative difference in GHG emissions from producing cuttings, becomes much smaller when averaging impacts over total biomass produced in a cultivation cycle. Per 1 kg of dry matter, SRC willow derived from field multiplication beds would have an impact of 63 gCO_2-eq/kg, while the impact from our technology is between 85 and 100 gCO_2-eq/kg. With this more appropriate assessment approach, the cultivation impacts are more comparable (Figure 19).

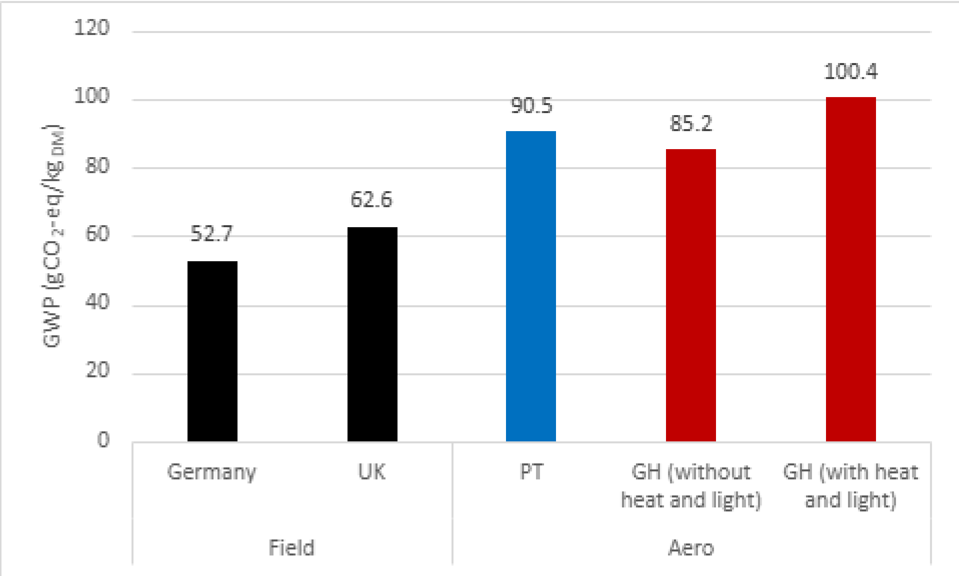

Figure 19 Impact for 1KG of dry matter of SRC willow dry biomass

The LCA showed that planting the cuttings to land and growing the SRC willow for 20-years were by far the greatest determinant of impact in all the analysed cases (field-multiplied, aeroponic PT or aeroponic GH). The production method, field or aeroponic, is much less important. The single biggest determinant of impact is the yield of biomass from the field. A 10% increase or decrease was found to be a more important factor than any changes in how the cuttings were initially multiplied (e.g., whether heating and lighting was used in the GH).

Thirdly, if we consider the acceleration potential of planting more cuttings into the field sooner using aeroponics and the subsequent fossil fuel use offset this would enable, further advantages are realised. Using willow for bioenergy production results in a reduction in the use of fossil fuels, for example SRC willow can be used in place of gas for either heat or electricity production. GHG savings are achieved regardless of whether the cuttings are produced aeroponically or in the field.

However, GHG emissions savings are most marked when factoring in the potential to accelerate production of biomass using aeroponics. The cumulative GWP savings from replacing gas with aeroponically multiplied willow are 2.04x10^5 tCO_2-eq, when compared to replacing gas with field-multiplied willow. The potential to plant 200 ha per year from one ha of land using our technology compared to 26 ha means a given mass of biomass can be produced years earlier. Therefore, it is possible to replace gas or other fossil fuels sooner. Regardless of whether aeroponic material came from the polytunnel or a heated GH, using aeroponics to accelerate biomass production resulted in lower net GHG emissions compared to using field-multiplied cuttings (Figure 20).

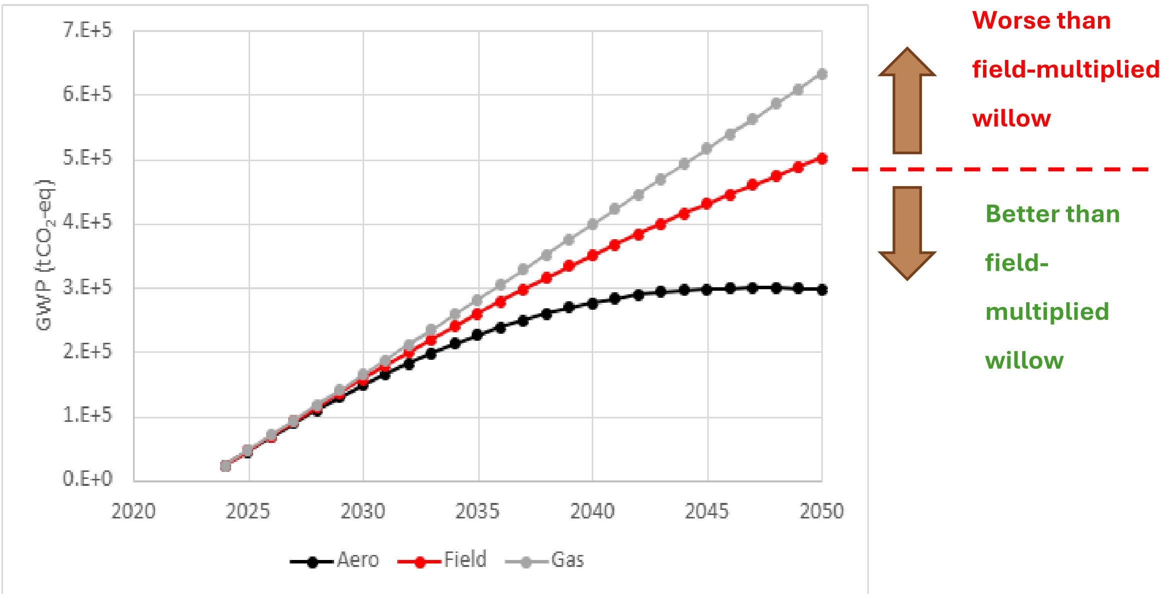

Figure 20 Total GHG emissions of energy production with scaling up accounted for, up to 2050

Land use change is typically a significant driver of the environmental impacts associated with bioenergy expansion, however in our analysis we found that land use change was not an influential factor in bioenergy expansion considering our approach. Our analysis suggested that even if a “bad” land use change transition is undertaken (e.g. replacing forest with bioenergy crops), planting SRC willow more quickly offsets the net release of carbon which would be expected from this transition in the long run. However, it is still recommended that good land management practices are followed to minimise land use effects.

Accounting for the temporal aspects provides additional insights into the sustainability of accelerated multiplication. While on a cutting-to-cutting comparison, aeroponically-multiplied willow may appear disadvantageous to field-multiplied cuttings, the ability to produce more material, faster and contribute to the renewable energy mix, makes the innovation a viable candidate to decarbonise the UK.

Environmental impacts may extend beyond the GHG emissions discussed above. Part of the project explored these other impacts and links to wider sustainability frameworks, in particular, the UK's Environmental Improvement Plan [10] and United Nations's Sustainable Development Goals [11]. Stakeholder insights showed that the strongest potential benefits were considered to be from SRC willow's ability to mitigate run-off of nutrients into waterways, or potential improvement of biodiversity if used sympathetically in an agricultural landscape, or its ability to grow on agricultural land increasingly vulnerable to flooding (and hence decreasingly suitable for arable crops).These benefits could be achieved at both an accelerated rate and at a larger scale with the support of aeroponic multiplication.

3.3.3 Socio-Economic Impacts

The project has also evaluated the wider socio-economic benefits of adopting the aeroponic innovation. The work undertaken by socio-economic impact team included the development of a Computable General Equilibrium (CGE) model and the development of a pertinent list of use scenarios. The scenarios include diverse options for biomass price, amount of biomass used in the energy mix, and different policy outcomes resulting in various planting targets.

The simulation results, after running the CGE model and the scenarios developed, show that using the aeroponics technology for SRC willow can bring significant socio-economic benefits with positive correlations to Gross Domestic Product (GDP), renewable energy sector outputs, employment and social welfare. Specifically, cultivation in the polytunnel can bring greater benefits due to lower costs and therefore greater gains.

3.4 Technical Takeaways from SRC Willow Operations

Running several cycles of harvest-regrowth and looking at the field response has provided insights into what an optimal operation would look like, from the data gathered to date. Below is a summary of the most important take-aways:

- Overall plants from the GH and the polytunnel have produced comparable numbers of cuttings. However, an open-sided polytunnel stands out as an optimal operating environment, due to the lower capital and operational expenditure (no heating and additional lighting). This set-up can produce more cuttings at a lower cost.
- The latest aeroponic system has demonstrated that plants respond well at a planting density of 16 plants/m^2. The results showing 3 million cuttings/ha/year at 16 trees/m^2 are based on a trialled variety mix (four standard commercial varieties in the polytunnel: Endurance, Hambleton, Ester, Wilhelm). The higher density findings align with field multiplication practices, where cuttings are grown at a higher density to encourage longer straighter stems for a step planter.
- All 10 varieties can grow and produce cutting material in aeroponics, at a greater rate compared to the field. Commercial decisions may influence selection of genotypes toward naturally higher yielding varieties, for cost reasons, but a varietal mix is preferential to cater to in-field requirements.
- Recommended management practices include an early spring initial planting followed by a summer harvest and a winter harvest. The time to harvest may depend on the geography and the characteristics of the year (a hot long summer and mild winter are likely to result in a higher number of cuttings). Two harvest per year are attainable from our aeroponics system for SRC willow.
- For best performance, the plants require a custom fertiliser mix, which Taeda Tech developed, and an irrigation cycle which can be adjusted based on annual climate variations (for example, more frequent irrigation in a hot summer). The same is valid for the pH (acidity) requirements. The nutrient recipe, pH levels and irrigation schedules can be customised for each

operation based on location climate, water quality and water hardness for optimal harvest results.

- Pests are an ongoing risk to operations, especially aphids. The team have developed protocols for responsibly managing willow pests. The expertise will form part of an offering to a potential grower/operation.
- To become viable planting material, the cuttings require hardening (vernalisation) before planting, so cold storage is required for summer harvests.

The project has made considerable progress since the initial testing in 2022 and acknowledges that additional optimisation is still possible, for example through the digital twin, which is currently in development.

4 Commercialisation

The project has demonstrated the technical viability of the innovation and has learnt that the commercial viability relies on the existence of end demand and complete supply chains. While the innovation is well placed to meet perennial biomass scalability needs, nationwide scalability is dependent on a series of factors outside of the projects' control, for example crop appeal to farmers, land use allocation, energy producers' ability and willingness to process perennial material. Repeated discussions with stakeholders during the project have reinforced these requirements for SRC success, within which the aeroponic SRC willow innovation would operate. When these external impediments are resolved and demand for SRC willow increases, the innovation will be an essential ally in meeting Net Zero targets.

Technically, the innovation is sound and scalable with the technology independent of geographical constraints. Production, as demonstrated and discussed above, is superior to conventional field propagation and the potential impact of using the innovation has been mapped out with positive outcomes for both environmental and socio-economic assessments.

The systems and controls have been designed to be user friendly with low adoption barriers. Taeda Tech and LuG have maintained usability and affordability as primary parameters, with the knowledge that traditional biomass producers may be hesitant towards new technologies. The project has been able to reduce the production costs of a cutting and LuG have worked towards lowering the cost of the system. While both parties have been successful, further work on cost optimisation is required to ensure adoption of the innovation for SRC willow cuttings is commercially competitive.

Due to a lack of immediate market entry opportunities for perennial crops in the bioenergy sector, Taeda Tech has sought other opportunities to ensure legacy. At the time of writing, specifics of commercialisation are under development, with the most immediate and likely commercial applications cantered on the aeroponic system and applied research expertise (science as a service), which would be delivered in close partnership with LuG.

Repeated and pronounced stakeholder interest has been received for potential applications to other crops. To explore these opportunities, Taeda Tech has tapped into the NZIP Acceleration support provided by the Carbon Trust, who have performed an assessment of key potential markets for the commercial application of aeroponics to other crops. Their findings demonstrate that Taeda Tech has excellent alignment and potential with 1) the paper and pulp industry, due to the need for high quality fibres, and 2) with high value chemicals industry (bio-based chemicals) due to already existing demand, consumer pressure and current and forecasted industry growth, which are independent of policy support.

The project also sought validation from an independent market research company (Team Services). This piece of work established that Taeda Tech's capabilities for fast growth, rapid genetic trait expression and biochemical manipulation have excellent alignment to the needs of the pharmaceutical market.

With a strong partnership with LuG, delivering through the aeroponic systems and the science and a service model, Taeda Tech is well positioned to apply these commercial opportunities to a wider set of sectors to create an impactful legacy. Taeda Tech anticipates that the biomass and bioenergy landscape may strengthen over time so that the SRC willow innovation and its potential can be fully realised.

5 Secondary Project Benefits

5.1 Dissemination Activities

To ensure wide-reaching impact the project engaged in a variety of dissemination activities, designed and delivered with different audiences in mind.

To raise awareness of the potential of aeroponics to the public, the project utilised social media posts, held open day events at our facilities on the University's campus and made use of UoS channels, including connections with established media outlets, such as local radio and television. For example, the project garnered the interest of local and national news channels, such as the BBC on the implications of aeroponics and the future of farming.

The project also commissioned a short documentary to showcase the project in a public friendly manner, but which can also be presented in shorter, easily digestible sections focusing on each area of work.

For industry engagement and dissemination, the project organised mini-conferences at the trials sites. It has also participated at events and conferences catering to specific industries that have synergies the application of the innovation, for example:

- Agri-tech (UKUAT Annual conferences)
- Low carbon farming (Low-Carbon Agriculture and Biomass Connect events)
- Biomass conferences (invited speaker at Argus Biomass and EUBCE)
- Horticulture shows (IPM Essen)

For specialist audiences, the project is planning the publication of scientific papers, covering work done by each WP. The papers are currently in preparation, with estimated publication timelines between March 2025 and December 2025. This is due to data being collected up to March 2025 and June 2025 for those works that could be extended, and we estimate over 10 scientific papers will be produced from the project works (Appendix C).

Also, for the specialist audiences, the project hosted a series of lunchtime webinars between April and June 2025, which allowed each team to present their work in detail to academic peers and engage in deeper, more technical conversations.

Special contributions to dissemination were provided by UKUAT who supported the project in the agri-technology space; Biomass Connect in the biomass and bioenergy space; and LuG in the vertical farming and agri-technology space.

5.2 Intellectual Property

Intellectual property (IP) refers to all output generated from the project, be it material, such as the aeroponic hardware, data insights or fertiliser recipes. All the IP generated from the project belongs to UoS, except for IP developed in relation to the aeroponic system, which is shared between UoS and LuG.

5.3 Workforce and Talent

Across all the jobs created within the innovative space, the Taeda Tech team developed a unique combination of skills, built around aeroponic R&D for large crops. As such, talent and expertise have become one of the project's core assets, which Taeda Tech and UoS will leverage in developing their commercial offering.

While some changes occurred in the staffing profile and skills, the project maintained the equivalent of 12-13 jobs with UoS, including academic, technical and professional services, as well as roles through our principal partner, UKUAT. The project supported the research of three PhD candidates, their findings feeding back into the project delivery. Team roles and their allocation to the project are detailed in Appendix D.

To deliver on the more practical, labour-intensive support (e.g. at harvest), the project created several temporary roles developing technical skills in undergraduate and graduate students. These posts enabled familiarisation with working in a collaborative R&D environment, aeroponics operations, controlled agriculture and data collection.

Most of the team will be moving on after the end of the project, yet core competencies will remain with UoS. More importantly the knowledge and expertise have been captured in detailed protocols and reports for future use.

5.4 Partnerships

The delivery of the project would have not been possible without the support of our many collaborators and partners. The project developed a series of contractual partnerships for the delivery phase. The legacy and synergies of these partnerships can support the innovation further through contributions to securing future funding, and in amplifying the impact of the project's work.

UKUAT have been our strategic partner for the project, working closely with the UoS team on several aspects, from governance to plant science and communications. Their team members were considered a part of our core team and collaboration with UKUAT will extend beyond Taeda Tech, to a series of other projects centred around aeroponics applications.

LettUs Grow are our technology delivery partner, with whom the project is shares some of its IP. Therefore, the relationship is due to continue as we explore the commercialisation of the technology, independent of the willow production. LuG are well positioned within the industry to lead in the development of the supply chain and the route to market for the technology.

As leading willow experts in the UK, Rothamsted Research have supported Taeda Tech with advice on willow management and best practices, including identifying suitable field sites. They have worked closely with the team on exploring the breeding potential of experimental varieties which Rothamsted developed. Rothamsted Scientific Services, formerly part of Rothamsted Research, have made considerable contributions to the planning and early execution of the project, with valuable insights into operational practices for semi-controlled environments, such as the GH and polytunnel. As well as providing technical support to our trials which were hosted at the Rothamsted site.

Aberystwyth University, Forest Research and NMC2, are all partners who contributed to exploring the application of the technology on other crops. Their engagement was aligned to their specific area of expertise: Aberystwyth worked closely on aeroponic application to *Miscanthus*, NMC2 focused on hazel research and potential markets, Forest Research have also provided insights into forestry species.

Contractual research engagements with NIAB and Newcastle University were built around their ability to host the field trials, enabling verification of cutting viability in contrasting geographies (Central and West England – NIAB, and North England – Newcastle University). Both organisations have provided their expertise in field management and supported the project in collecting the field trial data.

Additional collaborations were developed during the project, such as with Carbon Trust and their NZIP accelerator program, initiated through DESNZ. On exploring commercial potential, the project has contracted Team Services, for a consultancy piece on pharmaceutical market analysis.

The project also developed other beneficial collaborations (non-contractual) with the wider BFIP projects, including Biomass Connect – a demonstrator and knowledge sharing organisation, which supported with engagement as well as field sites. From the same BFIP cohort, the project has established strong relationships, notably with Willow Energy and Envirocrops, who have offered meaningful insights for our data collection and interpretation.

6 Project Management

6.1 Structuring and Scheduling

The project was structured around the critical path activities made up of the SRC willow plant life-cycle, from cutting to harvest and field practices (Figure 4). Work was entrusted to specialist teams, the WPs (Figure 3). The rationale and detailed work focus for each WP are discussed in the Project Overview section.

The project was led by a project management triad (Project Lead, Project Manager and UKUAT commercialisation lead), which shared responsibility for risks and resources management. These were dynamically monitored and addressed while a monthly all-team-meeting ensured that planning for future works accounted for any interdependencies and information flow across the project's many areas of work.

While the project delivery followed an overall project-in-controlled-environments approach, in accordance with the funding body's requirements, aspects of the work benefited from agile management, specifically the development of the technology and the SRC willow trials.

The aeroponic systems development was designed around incremental improvements over the course of three years, with agile product iterations which applied learnings from the previous version and from the plants' response. The willow trials followed a similar approach, working around the crop's cyclicity and responding with improvements and adjustments. These lessons learned response applied, amongst others, to developing irrigation schedules, fertiliser recipes, harvesting timelines and the digital twin development. Work on other crops was to be informed by the willow activities, perform a desk-based review of possible crops and experiments from 2024. While these works were marginal at the project planning stage, they have gained more weight during the first two years of execution, with multiple stakeholders expressing interest in the potential of aeroponics for other tree species. As such, the other crops trials followed a similar iterative approach.

More linear approaches were suitable for the development of the site - where the project had to deliver custom built structures to bypass height limitations imposed by a tall crop such as willow. This has been a one-off activity delivered in the first year of the project which enabled future works, from 2023. Data collection has been ongoing for the duration of the project for the willow optimisation model (the digital twin), for the socio-economic and for the environmental impact assessments. Data was integrated and final results produced towards the end of the project.

Commercialisation works have also been ongoing throughout the project, starting with stakeholder identification and engagement, and development of a communications strategy. These works continued with refining the potential offering based on the trial results and stakeholders' responses in the later project stages.

6.2 . Key Risks and Issues

The project was complex and spanned widely, resulting in a risk profile that was equally diverse. Regular monitoring and frequent communications helped mitigate the traditional project risks of time, cost, and quality. Taeda Tech's more specific risks lay around technology, personnel, and markets. Specifically, the new systems were at risk of not functioning correctly, so previous iterations were kept functional to ensure data collection. Only one significant system challenge occurred during the project due to the delayed delivery of the 2023 system, and the need to establish experiments within the season. This resulted in a condensed timeline for installation and testing which gave rise to faulty irrigation and impacted subsequent plant growth in only one of the systems in the glasshouse. Other than this initial installation issue, there have been no other major system malfunctions during the project. Another risk was related to personnel, specifically finding, developing, and retaining talent. Mitigating actions included using the network of partnership to scout talent and providing sufficient remit for independent work and benefits to incentivise creativity and encourage staff retention. Risks related to market shifts have been twofold, in both cases out of the project's control. Firstly, repercussions of Covid, the war in Ukraine and the Suez Canal crisis have impacted the timely delivery of our second-year systems due to supply chain issues, when the project had to implement a recovery strategy to realigning works to the project plan. Secondly, stagnating- if not shrinking- demand for SRC willow has jeopardised, the feasibility of using aeroponics for biomass production. Market shifts for perennials, and specifically SRC willow, are not conclusive enough to support the immediate application to multiplying SRC willow. As such, pivot opportunities and additional applications have been explored (for example, the application to other crops and the related science as a service commercial offering).

Lastly, willow's susceptibility to certain pests, while known to the team, has been problematic especially in the GH environment where increased humidity, year-round warm temperatures and lack of natural predators created a hospitable environment for pests. Pest management measures and operational protocols were developed to ensure the survival of trials and that viable data could be collected. These were all successful due to diligent implementation from the site team.

6.3 Lessons Learnt

Despite the risks and challenges discussed in the previous section, the delivery of Taeda Tech has been made possible through robust and adaptable project governance and project controls. Some of our main lessons learnt from project management revolve around the importance of a well-balanced leadership team, maintaining agility in delivery and timeliness and frequency in communications. While the project acknowledges external communication could be improved, the successful delivery of a diverse range of works was possible through connected and empowered teams internally and through timely and open communications with DESNZ. The lessons learnt will be applied in future design and delivery of research and demonstration projects at UoS, and more widely, as team members engage in other projects.

7 Successes and Barriers

Successfully demonstrating willow and other crops in aeroponics and developing the hardware for the innovation are likely the greatest achievements of the project. Taeda Tech has been able to demonstrate that an innovative approach to growing SRC willow can result in a higher number of cuttings, on a smaller land footprint, with a greater degree of quality control, whilst doing so in a sustainable closed system, at a comparable cost. Accelerating the supply of SRC willow cuttings into the field will not only enable faster reduction in carbon emissions, through fossil substitution, but will enable wider environmental benefits such as soil carbon sequestration, soil quality improvements and support for beneficial biodiversity on a landscape scale.

Elsewhere, developing the expertise within the team by bringing together various skillsets, and applying them to aeroponic cultivation of large crops is something Taeda Tech sees as a success, with the expertise becoming the project's biggest asset. There is considerably more knowledge now on aeroponics for large crops than there was three years ago, and the project has contributed to this through the partnerships established, the dissemination, and the training of people.

While trial results showed from the beginning of the project that willow thrives in aeroponics, being able to increase our production in the number of cuttings, as well as establishing other efficiencies, optimisations and cost reductions is worth celebrating. Also worth celebrating is the fact that our 2022 first planted trials are still running in their original system, with the plants still performing well.

Demonstrating that the innovation can support the increase of SRC planting material with no detrimental social, economic and environmental costs has validated our assumptions.

The project also encountered a small number of barriers, which are worth mentioning. One the most persistent barriers for the biomass space is the lack of co-ordinated and full supply chain support. Currently, there is a general lack of interest in the production of local biomass in the UK as farmers are not incentivised to invest in biomass, nor are end users incentivised to make purchases locally. Given the higher cost of the operations, a higher price per cutting is difficult to justify on the current market. Guaranteed establishment and increased rigour of the cutting may allow us to attract a premium price, but the lack of sufficient support for the broader biomass or bioenergy industry leaves Taeda Tech in a challenging position. UK-sourced biomass, be it aeroponically-multiplied or field-multiplied, is not sufficiently competitive with imported waste wood derived biomass.

The use of technology to cultivate our cuttings – including infrastructure, pumps, climate control and use of nutrients – mean the environmental impacts associated with an aeroponically-multiplied cutting are higher than a field-multiplied cutting. From a marketing perspective, this may attract negative attention. However, the gains that come with more rapidly establishing biomass feedstocks in the field offset these higher inputs. This is not an insurmountable barrier, but rather a perceived risk in adoption that will require careful messaging of the value proposition and the context.

Given the end goal is to reduce our global GHG emissions whilst increasing the supply of renewable energy, a robust business case can be made for aeroponically-multiplied willow, given the production gains and ability to accelerate the low carbon transition.

8 Conclusions and Next Steps

The three-year timeline and funding opportunity have allowed the project to meet its objectives and contribute to Net Zero solutions. Taeda Tech has been able, for the first time, to demonstrate the advantages of aeroponically multiplying willow. The volume, time and quality gains of aeroponically produced cuttings, along with their environmental and socio-economic benefits place the innovation as an essential ally in meeting UK's low carbon energy targets.

Our current processes have shown that aeroponically multiplied willow can produce over seven times more cuttings than field-grown counterfactuals. Considering quality and performance gains alongside the cost reductions achieved to date, aeroponics has been demonstrated as an excellent supplementary method for propagation. The impact of this acceleration in the lead up to Net Zero has considerable benefits when compared to using only field multiplication for SRC willow. These contributions and assessments are based on processes developed to date and additional optimisation and gains can be achieved through digital modelling and further design and operational improvements to address any cost barriers.

Aeroponically-multiplied material could resolve the supply chain bottleneck that the recommended expansion to biomass crops will encounter, supporting the UK to meet the 700,000 ha planting target required by 2050 [5].

In addition to demonstrating the ability of aeroponics multiply to SRC willow, Taeda Tech findings can pave the way for further applications aligned with the Net Zero targets. Short rotation and traditional forestry species demonstrated excellent potential for aeroponic multiplication, with selected species reaching a marketable size two-to-three times faster compared to soil counterfactuals. This acceleration has garnered the market and stakeholders' interest, for woody species applications but also for higher value crops, where aeroponics can support the R&D efforts in pharmaceutical and high value chemical sector.

Faster growth, rapid genetic trait expression, biochemical manipulation and root zone access are some of the advantages that will allow Taeda Tech's legacy team to explore additional applications of the innovation tested and demonstrated for SRC willow. Next steps will be focused on immediate retention of talent and application of findings as not to lose momentum gained so far. UoS is supporting the Taeda Tech team who will remain a standing brand name for aeroponic R&D and will operate as a programme encompassing multiple aeroponics projects. With the support of the University, the leading academic team are already exploring and engaging with further bids and grants which will focus on further applications of the technology.

While the applicability of aeroponics to perennials is now demonstrated, the team are looking forward to continuing to work closely with stakeholders, the other BFIP projects and wider industry to help unlock momentum and create the conditions for rapid scale-up of biomass planting. The expertise developed during the BFIP provides Taeda Tech with a platform for further and wider research, development and application of aeroponics to support sustainable biomass production.

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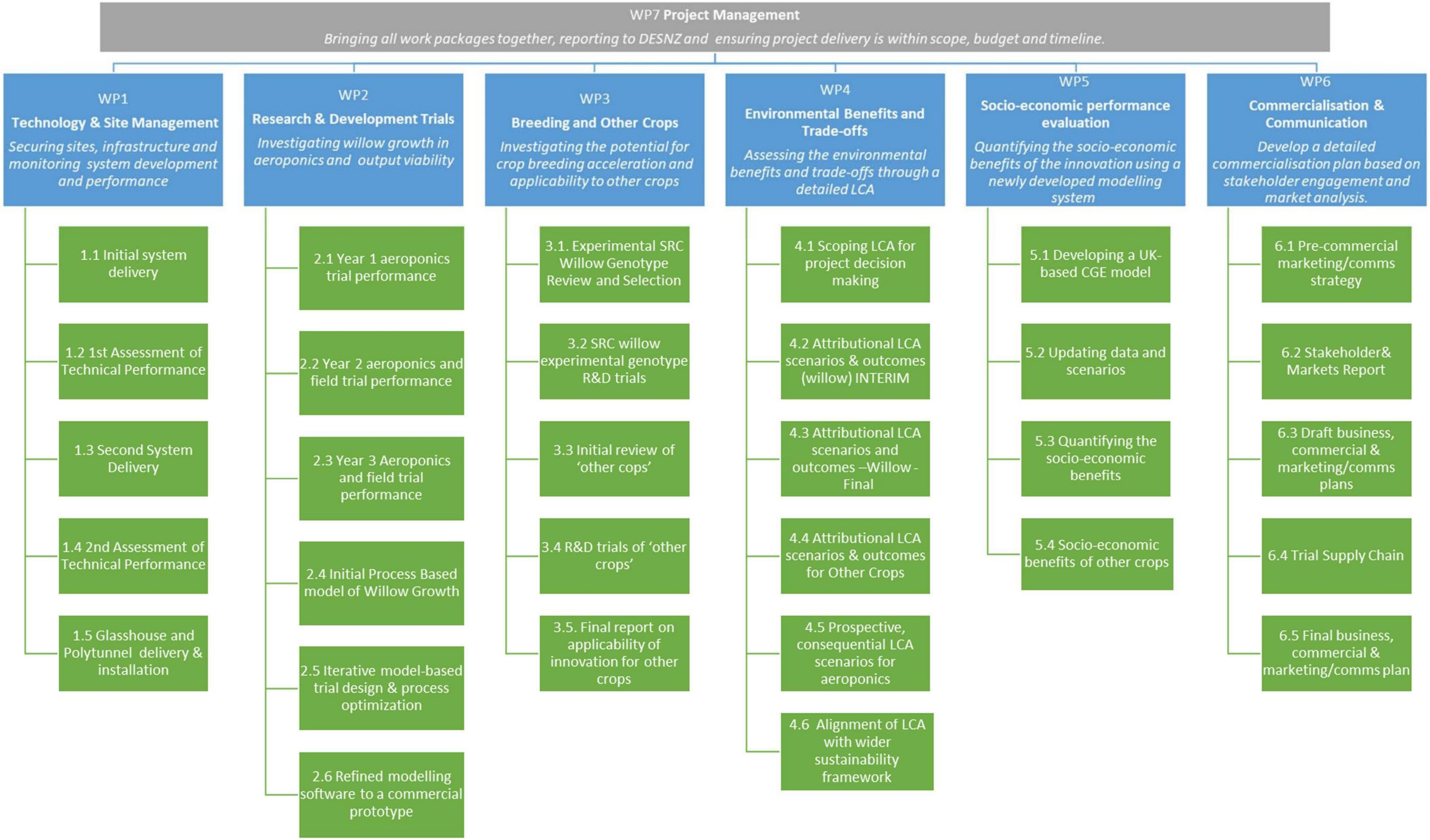
10 Appendices

10.1 Appendix A

Project Gantt Chart

	Updated 22/01/2025 with extension works _ SS															
	Work in Progress		Year 1 - 2022-2023				Year 2 - 2023-2024				Year 3 - 2024-2025					
	Deliverable		1	2	3	4	5	6	7	8	9	10	11	12	13
	New deliverable deadline/ New Deliverable	Week	1 2 3	4 5 6	7 8 9	10 11	12 13 14 15	16 17 18	19 20 21	22 23	24 25 26 27	28 29 30	21 32 33	34 35	36 37 38
		Month	M J J	A S O	N D J	F M	A M J J	A S O	N D J	F M	A M J J	A S O	N D J	F M	A M J
WP1 - Technology & Site Management															
D	1st system delivery & install	WP1	1.11	1.12	1.13										
D	1st assessment of system technical performance	WP1		1.21	1.22										
D	2nd system delivery (Revised version)	WP1			1.31	1.32	1.33								
D	3rd assessment of system techical performance	WP1						1.41	1.7	1.8	1.9	1.10	1.011		
D	Glasshouse & polytunnel delivery & installation	WP1	1.51	1.52	1.53	1.54									
WP2 - Research & Development Trials															
D	Year 1 aeroponics trial performance	WP2	2.11	2.12	2.13	2.14	1/2 of 2.15	2/2 of 2.15							
D	Year 2 aeroponics and field trial performance	WP2					2.21	2.22	2.7	2.8	2.9				
D	Year 3 Aeroponics and field trial performance	WP2									2.9	2.10	2.011	2.012	2.013
D	Initial process-based model of willow growth	WP2			2.41	2.42									
D	Iterative model-based trial design & process optimiza	WP2					2.51	2.52	2.75						
D	Refined modelling software to a commercial prototyp	WP2								2.85	2.95	2.105	2.115		2.135
WP3 - Breeding and other crops															
D	Experimental SRC willow genotype review & selectior	WP3			3.11	3.12									
D	SRC willow Other varieties	WP3				3.21	3.22	3.23	3.7		3.9	3.1	3.011		
D	Initial review of 'other crops'	WP3					3.31	3.32	3.7						
D	R&D trials for 'other crop'	WP3													
D	Final report on applicability of innovation for other c	WP3								3.8	3.9	3.10	3.011		
WP4 - Environmental Benefits and Trade-offs															
D	Scoping LCA for project decision-making	WP4		4.11		4.12		4.13		4.8	4.9				
D	Attributional LCA scenarios & outcomes (willow) INTE	WP4				4.21	4.22	4.23	4.7						
D	Attributional LCA scenarios & outcomes (willow) FINA	WP4							4.7	4.8	4.9	4.10			
D	Attributional LCA scenarios & outcomes for Other Cr	WP4					4.41				4.9		4.11		
D	Prospective, consequential LCA scenarios for aeropor	WP4			4.51		4.52		4.7		4.9		4.11		
D	Alignment of LCA with wider sustainability framewor	WP4			4.61		4.62		4.7		4.9		4.11		
WP5 - Socio-economic performance evaluation															
D	Developing a UK-based CGE model	WP5	5.11	5.12	5.13	5.14	5.15	5.16							
D	Updating data & scenarios	WP5	5.21	5.22	5.23	5.24	5.25	5.26	5.7						
D	Quantifying the socio-economic benefits	WP5							5.7						
D	Socio-economic benefits of other crops	WP5							5.7	5.8	5.9	5.10	5.011		
WP6 - Commercialisation & Communication															
D	Pre-commercial marketing/comms strategy	WP6	6.11	6.12	6.13										
D	Stakeholder & markets report	WP6	6.21	6.22	6.23	6.24	6.25	6.26							
D	Draft business, commercial & marketing/comms plan	WP6							6.7	6.8					
D	Set up & testing of a trial supply chain	WP6										6.10			
D	Final business, commercial & marketing/comms plan	WP6								6.8	6.9	6.10	6.011		

Project Work Breakdown Structure by Areas of Work



10.2 Appendix B

Calculations for cuttings per hectare per year production of aeroponic willow and comparison to field multiplied cuttings.

Polytunnel production highlighted based on most feasible cost-benefit business case.

Input data	Input data	Input data	Input data	Input data	Aero production 1 ha No working space	Aero production 1 ha No working space	Aero production 1 ha No working space	Aeroponic production 1 ha Operational space	Aeroponic production 1 ha Operational space	Aeroponic production 1 ha Operational space	Aeroponic production 1 ha Operational space	Field application	Field application	Field application
Environment	Trees/ m^2	AVG cut/tree	AVG cut/ m^2	1 ha = m^2	Trees/ ha	AVG cut/ha	AVG cut/ha/year	1 ha growing space = m^2	Trees/ ha	AVG cut/ha working space	AVG cut/ha/year [2]	1 ha aero >>field SRC ha	1 ha field	**Aero over field improvement**
PT	16	24[2]	378	10,000	160,000	3,776,000	6,545,067	4,800[3]	76,800	1,812,480	**3,141,632**	196	26[4]	**755%**
PT	8	28	226	10,000	80,000	2,260,000	3,917,333	4,800	38,400	1,084,800	**1,880,320**	118	26	**452%**
GH	16	15	233	10,000	160,000	2,330,000	4,038,667	4,800	76,800	1,118,400	**1,938,560**	121	26	**466%**
GH	8	16	128	10,000	80,000	1,277,727	2,214,727	4,800	38,400	613,309	**11,063,069**	66	26	**256%**

[2] Calculation includes 1.7 average number of harvester per year.
[3] Average number of cutting per tree in line with production from previous harvest and systems, at an average of 1.7 crops per year.
[4] Available planting space from a 480m2 system design extrapolated to 1 ha
[5] Data from stakeholder engagement to verify field practices.

10.3 Appendix C

Anticipated Academic Publications

This table detailed the planned publications as a result of the work conducted on the Taeda Tech Project. Title, authors and journals are still to be finalised. Additional papers, not yet listed here, are expected to be developed.

Paper Title and Authors	Intended Journal	Submission date
National-level evaluation of the economic and environmental advantages of retrofitted biomass-coal co-firing power plants. *Linqi Sun, Xiaogui Zheng, Alan Foy, John M Stormonth-Darling, Pranav Pankaj Sahu, Mohammed Khandaker, Zoe M Harris, Lirong Liu*	Applied Energy	Dec 2024 *In resubmission*
National-level evaluation of the socio-economic benefits of the aeroponic technology using in cultivating Short Rotation Coppice willow. *Linqi Sun, Xiaogui Zheng, Alan Foy, John M Stormonth-Darling, Pranav Pankaj Sahu, Mohammed Khandaker, Zoe M Harris, Lirong Liu*	Journal of Cleaner Production	Jun 2025 *In preparation*
A review of the application of aeroponic technique for growing forest seedlings and other crops: A UK case study. *Okanlawon Lekan Jolayemi, Pranav Pankaj Sahu, Zoe M Harris*	Journal of Plant Interactions	Jul 2025 *In preparation*
Aeroponics cultivation— a rapid propagation technique for woodland creation and establishment. *Okanlawon Lekan Jolayemi, Mohammed Khandaker, Alan Foy, Laura Nelson, Pranav Pankaj Sahu, Kerrie Farrar, Zoe M Harris*	Frontiers in Plant Science	Jul 2025 *In preparation*
Enhancing the quantity and quality of woody biomass produced in willows through sustainable soil-less cultivation approach. *Pranav Pankaj Sahu, James Suckling, Avinash Agarwal, John M Stormonth-Darling, Mohammed Khandaker, Alan Foy, Laura Nelson, Katia Zacharaki, Ce Huang, Simona Stangaciu, Zoe M Harris*	Nature	Q3-Q4 2025 *In preparation*
A comparative biochemical compositional analysis of the willow grown under soil and soil-less agriculture cultivation system. *Pranav Pankaj Sahu, John M Stormonth-Darling, Alan Foy, Laura Nelson, Katia Zacharaki, Zoe M Harris*	Biofuel Research Journal	Q3-Q4 2025 *In preparation*
Development of a novel predictive model for the cultivation of aeroponic willow. *Yuqing Xia, Xiaoyang Wu, Mohammed Khandaker, Alan Foy, Laura Nelson, Zoe M Harris, Tao Chen*	*tbd*	Q3-Q4 2025 *In preparation*

Assessment of Heating Demands and Biomass Energy Potential for Greenhouse Willow Cultivation Across Different Regions of the UK. *Xiaoyang Wu, Yuqing Xia, Mohammed Khandaker, Alan Foy, Laura Nelson, Zoe M Harris, Tao Chen*	*tbd*	Q3-Q4 2025 *In preparation*
Life cycle assessment of using novel aeroponics technology to upscale short rotation coppice willow production. *James Suckling, Pranav Pankaj Sahu, Avinash Agarwal, John M Stormonth-Darling, Alan Foy, Laura Nelson, Mohammed Khandaker, Katia Zacharaki, Zoe M Harris*	International Journal of Life Cycle Assessment	Q3-Q4 2025 *In preparation*
The impact of Biostimulants on the growth and morphology of aeroponically cultivated willow. *Vicky Palumbo, Pranav Pankaj Sahu, Avinash Agarwal, John M Stormonth-Darling, Katia Zacharaki, Alan Foy, Laura Nelson, Mohammed Khandaker, Ce Huang, Yuqing Xia, Zoe M Harris*	*tbd*	Q4 2025 *In preparation*

10.4 Appendix D

Core team jobs created, by organisation.

Organization	Role/ Job title	Area(s) of work	FTE
UoS	Site Manager/Experimental Officer	• System and facilities management • Willow trials management	2
UoS	Research Fellows	• Willow plant science and trials development optimisation model (digital twin) • Other crops • Quantifying environmental impact	3.8
UoS	PhD Candidates	• Crop optimisation - environment. • Crop optimisation - biostimulants. • Quantifying the socio-economic impact	0
UoS	Project Manager	• Project management	1
UoS	Commercialisation Officer	exploring and developing commercialisation options	1
UoS	Work Package Leads	• Academic lead for willow and other crops • Academic lead for the optimisation model • Academic lead for environmental assessment • Academic lead for socio-economic impact	0.35
UKUAT	Work Package Lead	• Leading on engagement and commercialisation	0.4
UKUAT	Technical Support	• Technical support on data management • Technical support on plant science	0.4