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The Cultivation of Water Hyacinth in India as a Feedstock for Anaerobic Digestion: Development of a Predictive Model for Scaling Integrated Systems

Douglas G. Bray [1], Gaurav Nahar [2], Oliver Grasham [1], Vishwanath Dalvi [3], Shailendrasingh Rajput [3], Valerie Dupont [1], Miller Alonso Camargo-Valero [4,5] and Andrew B. Ross [1,*]

1 School of Chemical and Process Engineering, University of Leeds, Leeds LS2 9JT, UK
2 Defiant Renewables Pvt Ltd., Chinchwad, Pune 411033, Maharashtra, India
3 Department of Chemical Engineering, Institute of Chemical Technology, Mumbai 400019, Maharashtra, India
4 BioResource Systems Research Group, School of Civil Engineering, University of Leeds, Leeds LS2 9JT, UK
5 Departamento de Ingeniería Química, Campus La Nubia, Universidad Nacional de Colombia, Manizales 170002, Colombia
* Correspondence: a.b.ross@leeds.ac.uk

Abstract: A novel, integrated system is proposed for the cultivation and co-digestion of the invasive macrophyte water hyacinth (WH) with cow manure (CM) for the production of biogas for cooking in rural India. This study investigates the pre-treatment approaches and performs a techno-economic analysis of producing biogas in fixeddome digesters as a replacement for liquefied petroleum gas (LPG). Methodologies have been developed for the cultivation of WH collected from wild plants in the Indrayani River, Pune, India. Cultivation trials were performed in 350 litre tanks using water, which was nutrient fed with CM. Cultivation trials were performed over a 3 week period, and growth rates were determined by removing and weighing the biomass at regular time intervals. Cultivation results provided typical yields and growth rates of biomass, allowing predictions to be made for cultivation scaling. Samples of cultivated WH have been co-digested with CM at a 20:80 ratio in 200 L anaerobic digesters, allowing for the prediction of bio-methane yields from fixed-dome anaerobic digesters in real world conditions, which are commonly used in the rural locations of India. A calculator has been developed, allowing us to estimate the scaling requirements for the operation of an integrated biomass cultivation and anaerobic co-digestion unit to produce an equivalent amount of biogas to replace between one and three LPG cylinders per month. A techno-economic analysis of introducing WH into fixed-dome digesters in India demonstrated that the payback periods range from 9 years to under 1 year depending on the economic strategies. To replace between one and three LPG cylinders per month using the discussed feedstock ratio, the cultivation area of WH required to produce sufficient co-feedstock ranges within 10–55 m^2.

Keywords: water hyacinth; cultivation; nutrients; manure; anaerobic digestion

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Citation: Bray, D.G.; Nahar, G.; Grasham, O.; Dalvi, V.; Rajput, S.; Dupont, V.; Camargo-Valero, M.A.; Ross, A.B. The Cultivation of Water Hyacinth in India as a Feedstock for Anaerobic Digestion: Development of a Predictive Model for Scaling Integrated Systems. *Energies* **2022**, *15*, 9599. https://doi.org/10.3390/en15249599

Academic Editor: Giovanni Esposito

Received: 10 October 2022
Accepted: 13 December 2022
Published: 17 December 2022

1. Introduction

Globally, around 3 billion people still depend on solid biomass fuel (SBF), such as wood, crop residues, dung cake (DC) and coal, for cooking and other household activities [1]. Developing countries predominantly depend on biomass as a source of energy, e.g., approximately 592 Tg (1 Tg = 10^{12} g) of dry matter is burnt annually in India. An estimated 252 Tg of fuel wood, 99 Tg of agricultural residues and 106 Tg of DC are consumed per annum [2]. The decadal trend in household energy consumption patterns shows that 77.5% of rural households in India rely exclusively on solid biomass fuel for cooking. Biomass burning results in the emission of particulate matter (PM) that is below 2.5 μm diameter (PM2.5), with around 80–90% of their volume being in the accumulation mode (<1 μm in diameter or PM1) [3,4]. Liquefied petroleum gas (LPG) has been promoted as a clean cooking fuel by the government of India to mitigate the health effects of solid biomass burning during cooking. However, the switch from biomass to cleaner fuel has faced challenges: between 1981 and 2011, only 2% of rural households shifted from solid biomass fuel to cleaner fuels [5]. Since 2011, the data show significant uptake of LPG for household cooking purposes, although fuel costs are still a critical obstacle to its widespread adoption. Since 2014, the government of India has implemented policies to increase the access of poor rural communities to LPG [6]. The findings show that expanding LPG use offers great promise in rural India, but its affordability prevents a complete transition from traditional biomass to clean cooking fuels [7]. The national database of all LPG customers indicates that after a year of being connected, the mean cylinder refill rate, of a 14.2 kg LPG cylinder in Pradhan Mantri Ujjwala Yojana (PMUY) households is ~four cylinders per year, rather than the expected ~seven cylinders which would indicate full usage [8]. This low rate of LPG usage suggests the continued use of burning biomass for cooking. The price of LPG rose 66% between April 2020 and April 2022 [9], alongside this increase, recent geo-political events have deeply affected the global LPG markets, making affordable LPG even harder to access for many people in India [10].

One approach to reduce indoor air pollution and address the increasing cost of energy is to promote the use of anaerobic digestion (AD) for the production of biogas. Biogas is generated via AD, where micro-organisms break down the organic material in the absence of oxygen, forming methane-rich biogas. With there being nearly 300 million bovine animals and the reliance of 22% of the rural agricultural households on livestock for their livelihoods [11], the use of manure-based biogas digesters offers a potential solution to energy poverty in India [12]. The available quantity and quality of the feedstock is a key barrier to biogas adoption, as well as sub-optimal operation, leading to lower biogas quality and yield [13]. *Eichhornia crassipes* (Mart.) Solms or water hyacinth (WH) is an aquatic macrophyte that is widespread in India and has the potential to be a useful feedstock for anaerobic digestion. WH has a holocellulose content of ~56.9% by dry weight, a favourable C:N ratio of 20–35 and a moisture content of 90–95% [14,15]. WH has been utilised as a feedstock for AD in comparison with other biomass, producing greater methane yields than water chestnut [16], salvinia [17], giant reed and maize can [18]. However, there are significant variations in the methane yields, ranging within 103–252 mL CH_4/g Volatile Solids (VS) [19–24]. Brown et al. demonstrated that raw WH had a biodegradability of just 30%, suggesting that pre-treatment is important for the digestion of WH [25]. There have been a variety of pre-treatment methods which have been applied to WH. Acid hydrolysis via H_2SO_4 has been shown to improve the biogas yield by 131% with a vol% methane of 64% [26], as well as reduce the lag period in biogas production [27], however, this approach is likely to result in a greater production of H_2S [28]. Alkali pre-treatment, including NaOH or KOH addition, also results in an improved methane yield of up to 71%, which is a 10% increase [29], whereas thermal pre-treatments, such as steam explosion and hydrothermal treatment, have demonstrated an improvement in the methane yield by 38–85% [24,25]. The physical/mechanical pre-treatment of WH such as grinding and size reduction has also been shown to improve digestibility [29,30].

WH is one of the world's most invasive and damaging aquatic weeds [31] that is native to tropical America, and it is now widespread in almost 100 tropical countries [32] due to its high growth rate and ability to adapt to extreme conditions [31]. In optimal conditions, WH can double its weight in under two weeks [33–35] and reach growth rates of 50–72 g dry weight (DW)/m^2/day when it is supplied with excess nutrients, yielding ~18–26 kg/m^2 per annum [36–38]. This rate is significantly higher than that of other aquatic macrophytes, e.g., when it is grown in nutrient rich water, *Pistia stratiotes* demonstrated a growth rate of 28.3 g DW/m^2/day, yielding ~10 kg/m^2 per annum [36]. WH also demonstrates a high nutrient uptake, and it has the potential to remove 1.98, 0.32 and 3.19 tonnes/ha of NPK per annum [39]. The high nutrient uptake and growth rate, makes WH ideal for treating wastewaters and simultaneously generating renewable biogas that could be used for cooking fuel or power generation. The cultivation of WH may provide a more sustainable supply of biomass, reducing the reliance on cow manure (CM). The high growth rate of WH would provide a sustainable source of biomass that could be utilised in an integrated system with nutrient introduction from CM or digestate and carbon recycling via photosynthesis.

There are over 5 million small-scale biogas plants operating in India [40]. Despite this seemingly large number, a major barrier for the uptake of AD in India is the initial start-up costs, which far exceed the average monthly rural household expenditure [13,41]. India's National Biogas and Manure Management Program (NBMMP) provides a lump subsidy to assist with installation costs, and it has been used in around 40% of all the small-scale facilities that have been built [13]. A key product generated by AD is the digested slurry, known as digestate, which is formed from the breakdown of the biomass within the reactors. Digestate is a nutrient-rich and bio-available organic fertiliser. A study by Mukhuba et al. [42] showcased the fertiliser benefits and quality of the digestate when one is utilising CM as a feedstock, instead of using CM as a direct fertiliser. The use of digestate can significantly improve the financial feasibility of implementing AD in rural environments [41,43]. However, many AD users are unaware of the benefits of using digestate as a fertiliser. This was exemplified in a survey by Raha et al. [44] where 1/3 of the respondents were throwing digestate away.

The current work investigates the potential of cultivating WH in artificial tanks using animal manure as a nutrient input and co-digesting the biomass generated with CM for the production of biogas for cooking gas, replacing wood burning and improving indoor air quality. WH has been co-digested with cow manure, either raw or following pre-treatment by mechanical or chemical treatments, using KOH or a combination of the two of them. Pre-treatment by performing combined mechanical and chemical treatments has been shown to increase the biogas generation by 6.8–7.0% and increase the methane production by 7.0–8.0% as compared with that of raw WH biomass (data not published). Secondly, KOH has been shown to increase the biogas yield by up to 42% in the AD of reeds [45], and it has been shown to improve the enzymatic hydrolysis yields [46].

This study proposes a novel integrated WH cultivation and biogas generation design with the aim of producing enough biogas to displace the use of LPG for cooking, which in return will help to achieve sustainable energy security and reduce PM1 exposure in rural settings. The paper describes the cultivation of WH, anaerobic co-digestion experiments with WH and CM following different pre-treatment approaches and an Indian-based techno-economic assessment. The feasibility of an integrated system for rural deployment is discussed.

2. Materials and Methods

2.1. Biomass and Nutrient Sources

Fresh WH samples were collected from the Indrayani River, Pune in February 2020 for use as stock plants for cultivation experiments. These were placed in a large tank (see Section 2.3 for tank details) for storage until the cultivation experiments began. The plants were fed with 12.7 kg of CM every two weeks. The CM was procured from local cow sheds and utilised fresh as a feedstock and nutrient source. The CM was characterised to determine its nutrient contents of nitrogen (N), phosphorus (P) and potassium (K) via the methods detailed below.

2.2. Characterization of Water Hyacinth, Cow Manure, Digestate and Water

The biomass, CM, digestate and water were analysed for total N using the modified Kjeldhal methodology [47], as suggested by Baethgen and Alley [48]. Twenty mg of the dry solid sample (or one mL of the liquid sample) was shaken in 70 mL tubes with 5 mL sulphuric acid and 1.1 mL catalyst mixture (10:1 mixture of K_2SO_4 and $CuSO_4$) and heated at 200 °C for 4 h to convert all of the organic N into ammonium ions (NH_4^+). The solution was then cooled and diluted with 35 mL of de-ionised water. Finally, a 1 mL aliquot of solution was added to 5.5 mL of the buffer solution (0.1 M Na_2HPO_4; 5% Na-K tartrate;

5.4% NaOH) to increase the pH. Then, 4 mL of sodium salicylate was added along with 2 mL of sodium thiosulphate, and it was left for 45 min to produce a blue-green derivative that absorbs light at 650 nm. The solution was analysed within 2 h and quantified using external calibration.

The moisture, total solids (TS), volatile solids (VS) and ash were determined using a gravimetric analysis by drying the samples at 105 °C for ~2–3 h, and subsequently, they were ashed at 550 °C for 5 h [49].

To determine the elemental composition of P and K, the WH, CM and digestate were sent to a third-party laboratory for ICP-OES analysis and analysed according to the ASTM D1976-18 standard methods.

2.3. Cultivation Trials

Six metal tanks of the dimensions 1.22 × 1.22 × 0.31 m (461 L) were filled with ~350 L of water from a storage tank. The tanks were fitted with a frame with a net and pulley system to allow us to weigh the WH mat (see Figure 1). Approximately 35 plants (+/−5) of varying sizes (daughter plants) were removed and washed, and then added to the tanks to produce an initial WH mat of ~5.5 kg (+/−250 g). The mats were left to acclimatise in the tanks for 4 days. Each mat was weighed on the first and last day of the acclimatisation period (see Figure 1). Before weighing, the mat was held in mid-air for 1 min to remove the surface moisture. After acclimatisation, the water level was raised back to 350 L, and CM was added to the tank as a source of nutrients (18 g fresh weight (FW)/L of CM). The water was agitated to ensure all of the material was solubilised; the water was then collected for analysis. The mass of the WH mat was measured every four days using the pulley system (see Figure 1). The plants were harvested either when they were above 7 kg fresh weight or after two weeks if this was not reached, so that the mat weighed as close as possible to the starting weight of the plants. The water samples were also collected when we weighed and analysed them for the nitrogen content utilising the same method as previously described. The trials lasted three weeks.

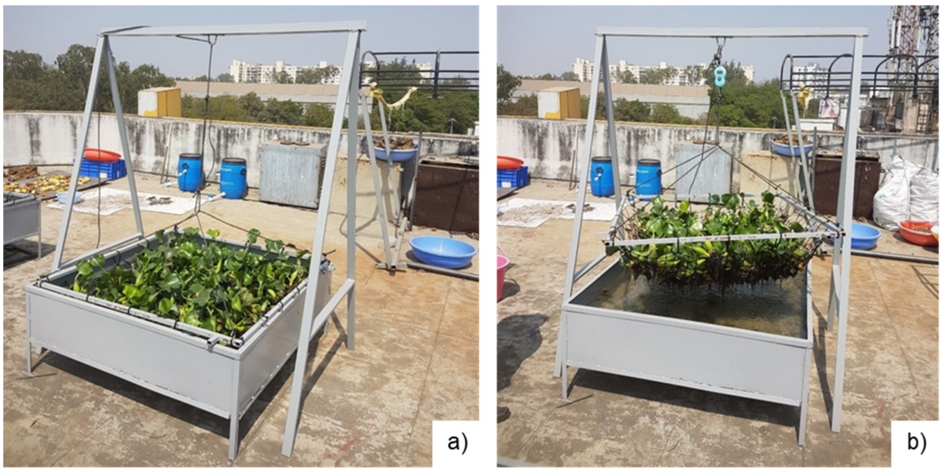

Figure 1. Artificial cultivation tanks with pulley system for weighing the plants: (**a**) during cultivation; (**b**) for draining and weighing.

The productivity of the WH was analysed for its response to the nitrogen concentration, temperature and plant density. To assess the response to these variables, the specific growth rate (r) in g/g/day was calculated for the periods between weighing via Equation (1):

$$r = \frac{M_{DW(2)} - M_{DW(1)}}{M_{DW(1)} \times (t_2 - t_1)} \quad (1)$$

where $M_{DW(t)}$ is the dry weight mass of the WH, and t is time in days. M_{DW} was calculated using a moisture content of 92% which was found during analysis of the cultivated plant. The daily temperatures at the growing location were accessed via NASA's power data tool [50].

2.4. Anaerobic Digestion Experiments of Cultivated Biomass and Cow Manure

The anaerobic digestion of the cultivated biomass was performed in a 200 L semi-batch reactor with an active digestion volume of 100 L (see Figure 2). The reactor was loaded at a 20:80 ratio of WH:CM on a wet basis, representing a 15:1 inoculum-to-substrate ratio on a VS basis. Further, the WH and CM additions were added to maintain the ISR ratio. The cow dung acts as both inoculum and substrate, whereas WH is solely a substrate. The head space was flushed with nitrogen, and the gas generation was measured using a pressurised gauge. The generated gas was passed through a water trap to remove the condensable material, such as water vapour and fine dung particles, and it was stored in an SUV tyre tube. The stored biogas was measured on alternate days using a biogas pump provided by SP ecofuel, Gujarat, India. The biogas flow was measured using a flow meter provided by PS Instruments, Mumbai, India.

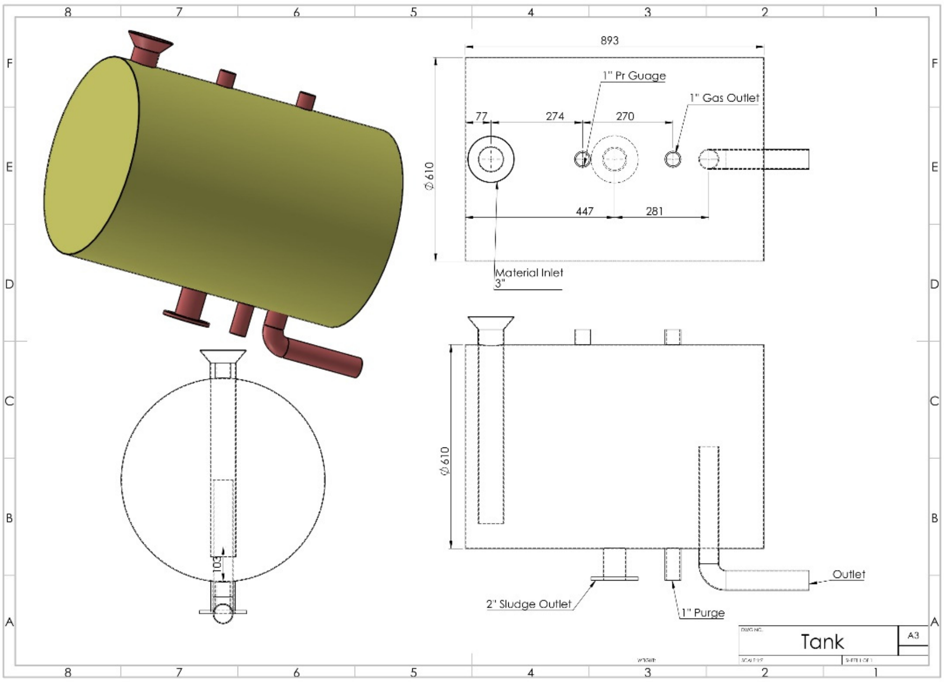

Figure 2. Schematic of the anaerobic digestion experimental setup.

This AD reactor was designed to replicate the behaviour of the rudimentary-type reactors that are often used in rural Indian locations such as Deenbandhu fixed-dome digesters [51]. The WH plants were added following the combined mechanical and chemical treatment, the mechanical treatment alone or no pre-treatment. The mechanically treated plants were shredded into a paste using a chipper shredder provided by Bhide and Sons, Sangali, India; this shredder is designed for farming applications. The chemically pre-treated plants were soaked in 3% potassium hydroxide (KOH) for two hours. The plants that were loaded without having undergone the pre-treatment were minimally cut using hand-held tools to a particle size of around 10 cm.

CM was added to the mixture as a source of inoculum and nitrogen; the volatile solids (VS) were determined by drying at them 105 °C, and subsequently ashing them at 550 °C [25]. The inoculum-to-substrate ratio (ISR) of 15:1 on a VS basis was maintained in the digester. For the runs that were fed with the chemically pre-treated WH, the pH was adjusted to 7 with diluted phosphoric acid due to the higher pH of the feedstock following the KOH pre-treatment.

The gas composition was analysed using a gas chromatograph (GC, Agilent 7890 B Gas Chromatograph, Germany). The gas analysis was performed using argon as a carrier gas, and detection was achieved by means of a thermal conductivity detector. The average yield of methane that evolved in the test reactor was used to predict the expected yields in a typical fixed-dome digester for the techno-economic analysis.

2.5. Techno-Economic Analysis

A techno-economic analysis was performed based on small-scale digester scenarios using the biogas yields from the anaerobic digestion trials. The digesters were costed using information provided in [43], detailing that the Deenbandhu fixed-dome digesters with 50–300 kg/day of loading would cost INR 23,000–64,000 when it is adjusted for inflation to the 2022 prices [52], accounting for both the material and labour. Various scenarios were considered based on the estimated current LPG use value as per the biogas generation showcased in the AD trials and the digestate value. Subsidies are available for digesters generating over 1 m^3 of biogas from the Indian Ministry of New and Renewable Energy (MNRE) from the New National Biogas and Organic Manure Programme (NNBOMP) [53]. The subsidy provides INR 7500–25,000 for plants generating 1–25 m^3 biogas, with greater subsidies being available for certain states and regions depending on their remoteness and level of development [53]. The chipper shredder upfront costs were not considered as it was assumed that this machinery was required for animal feed on rural farms.

Under the scenario where digestate is sold, it is assumed that a drying process was incorporated, whereby a 50% weight reduction has been achieved. A survey presented by Dey et al. [41] informs that small-scale AD operators were selling their digestate at INR 4 /kg. However, Samar et al. stipulate that the market price of digestate is INR 3 /kg [43]. Accordingly, a sensitivity analysis has been performed on the influence of the digestate value on the economic outlook. Income is not generated by the sale of biogas, rather, a proxy income stream is achieved by the offset of LPG purchasing. The costs of the LPG, CM, WH and KOH used in the feedstock pre-treatment are presented in Table 1. The cost of CM was estimated to be INR 1 /kg, and the cost of the water hyacinth cultivation was assumed to be INR 0.5 /kg. The cost of the cultivation tank was not included as it was assumed most villages would have a farm pond which could be used for cultivation or access to wild biomass from rivers or ponds. The INR 0.5 /kg is associated with the harvesting and maintenance of a fully stocked pond. The payback period has been used as the main method for the comparison of economic performances, and it is also an important factor for potential users from rural and often low-economic regions. It is calculated, as shown in Table 1, as the subsidised total installed cost divided by the annual profit.

$$Payback\ period\ (yrs) = \frac{Total\ installed\ cost - subsidy}{Annual\ LPG\ expense\ offset + annual\ digestate\ sales - annual\ OPEX} \tag{2}$$

Table 1. Cost assumptions for techno-economic assessment.

Object	Quantity (kg)	Cost (INR)	Reference
CM	1	1	[43]
LPG cylinder	14.2	949.5	[9]
KOH	1	100	[54]
WH	1	0.5	-

3. Results

3.1. Cultivation Trials

WH was cultivated in tank trials with CM as a source of nutrients, and it was compared with a control, which contained water alone (the composition is described in Table 2). The CM was selected as an appropriate nutrient source due to its high availability and low cost; the N content of the CM was at the lower end of that which was suggested by literature, 0.16–0.56 FW% [55]. This was likely due to the poor diet of the cows, however, this is reflective of rural cows. The CM does not fully solubilise in the water due to the presence of insoluble undigested fibrous material from the cow's diet. As a consequence, the levels of soluble nitrogen are lower than the total nitrogen levels supplied by the CM, and this resulted in starting water nitrogen concentrations of 13 mg/L in the fertilised tanks and 3.2 mg/L, in the control tanks due to elevated levels of nitrogen in the locally collected water.

Table 2. Composition of cow manure, water hyacinth and digestate (cow manure and water hyacinth feedstock).

	Cow Manure (AR*, FW %)	Water Hyacinth (AR*, FW %)	Digestate (AR*, FW%)
Moisture	83.2	92.2	-
TS	16.8	7.8	-
VS	14.1	6.4	-
Ash	2.7	1.3	-
N	0.20	-	0.04
P	0.24	0.07	0.01
K	0.61	0.08	0.04

*AR: As received; TS: Total Solids; VS: Volatile Solids; N: Nitrogen; P: Phosphorous; K: Potassium.

To determine the total amount of biomass that could be cultivated from this system, the plants were harvested back to the original weight, ~3.5 kg FW, after reaching 7 kg or after two weeks, as suggested by Ho and Wong [56]. During the 21 day growth trial, the tanks with added CM were harvested twice, whilst the control was only harvested once (see Figure 3). This suggests that over a two-week period and after providing 13 mg of N/L, the cultivation tanks produced ~6.35 kg FW/m^2 or 0.5 kg DW/m^2, which are similar to the values in the literature of WH yields [57].

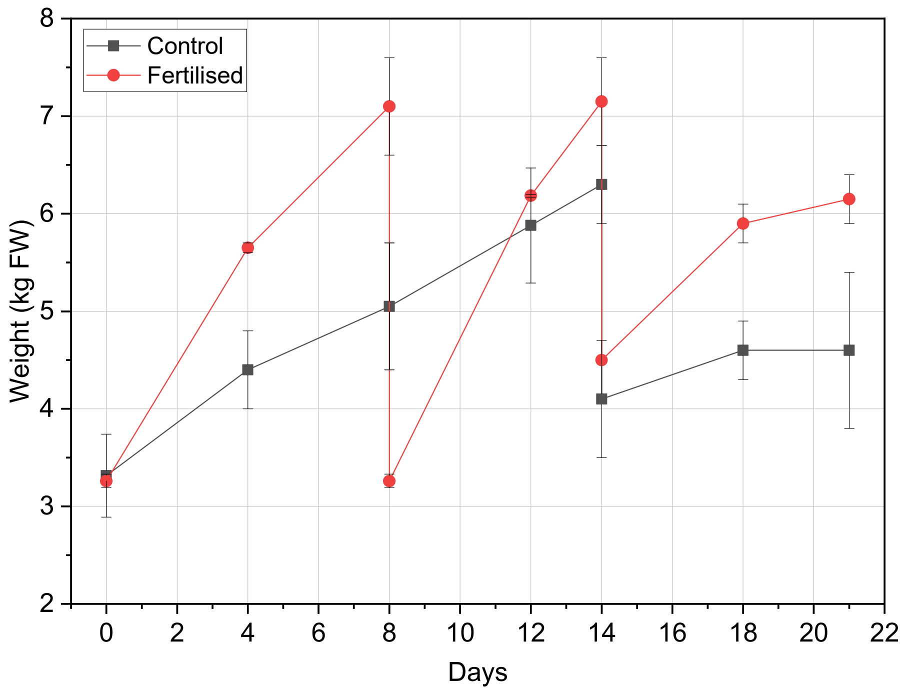

Figure 3. Changes in weight of water hyacinth over time during cultivation in artificial tanks. Error bars relate to the variation of weight between replicates.

The maximum growth rates, which were demonstrated in the large tank trials, reached 39.3 and 14.6 g DW/m^2/day for the fertilised tanks (13 mg N/L) and the control tanks (3.2 mg N/L), respectively. The associated specific growth rate values (*r*) were 0.224 and 0.082 g/g/day, respectively. The specific growth rate tended to reduce over time, most likely due to a combination of increasing mat density and reducing nitrogen concentration. The average specific growth rates from both of the trials were 0.11 and 0.038 g/g/day, respectively. These fall within the range found in the review that was carried out by Wilson et al. [57] which was from 0.01 to 0.12 g/g/day.

The negative correlation between the mat density and growth rate, which has been previously demonstrated in the literature [57,58], was also observed in these cultivation trials. Figure 4 reveals that both the control and fertilised tanks exhibit lower growth rates at higher densities. Equation (1) was used to calculate the specific growth rates between each biomass weighing, providing the growth rates that are exhibited in Figure 4 and correlated with the mat density. The relative steepness of the best fit gradient for the fertilised data compared to the control tank data indicates that nitrogen loading is more influential on the growth rate at lower densities. The variations from the trend seen in both of the data sets can be explained due to other productivity influences such as nutrient availability and environmental forcings [57] such as temperature.

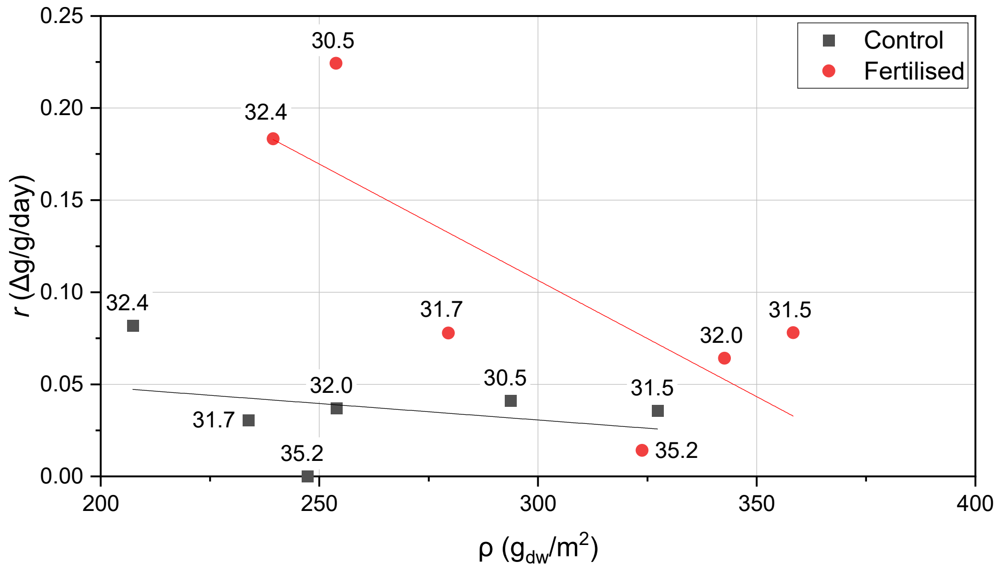

Figure 4. Specific growth rate (*r*) of water hyacinth against mat density (ρ) for fertilised trials (R^2 = 0.09) and control (R^2 = 0.60); data labels of mean max temperature (°C).

During days 18–20 of the trial, the growth rate significantly dropped, as shown in Figure 3. Figure 5 illustrates the growth rates in both the control and fertilised tanks against the average daily maximum temperatures of the respective growth period (mean max temperature). The growth rates during days 18–20 are circled in Figure 5. It is clear that during this period, the maximum temperature was significantly greater than it was during the previous 18 days. It is highly likely that the high temperatures reached caused the drop off in WH growth. This would agree with the literature such as Wilson et al. [57] for which the growth rate is negatively impacted at temperatures above 35 °C. Nonetheless, the severity of the drop in the growth rate is surprising, and other factors should not be eliminated from this analysis. The results showed no significant particular trend between the maximum temperature and growth rate for the rest of the dataset, which highlights the influence of other growth factors such as mat density.

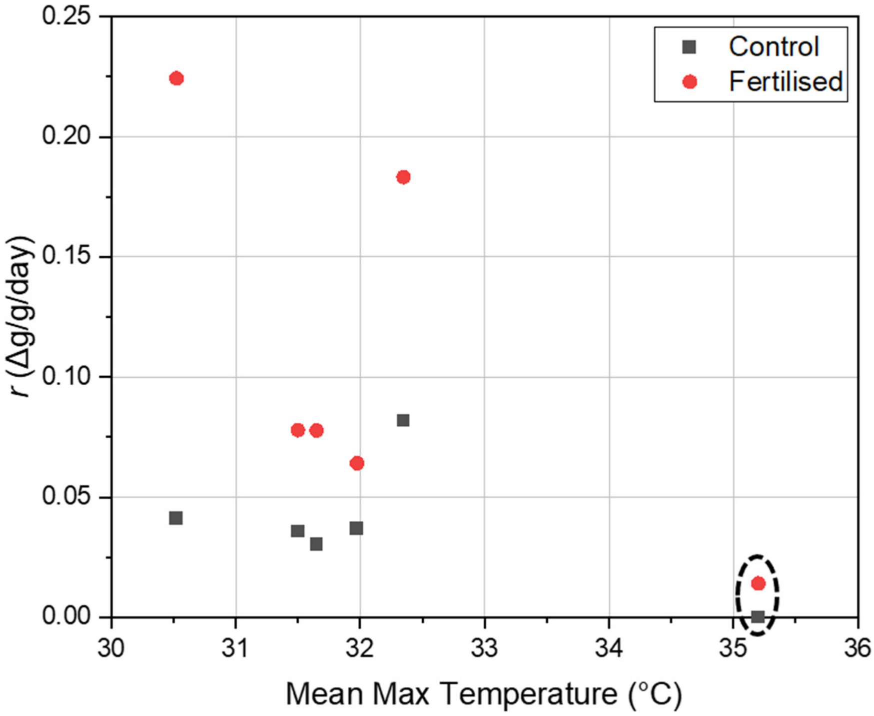

Figure 5. Growth rates against mean maximum daily temperatures of growth period.

3.2. Co-Digestion of Cow Manure and Water Hyacinth

The anaerobic digestion tests in the 200 L reactor were performed at a constant ratio of 20:80 ratio for WH: CM. The tests were performed with untreated biomass, mechanically treated biomass and a combined mechanical and chemical pre-treatment. The levels of biogas measured in the 200 L tests is described in Table 3.

Table 3. Biogas and biomethane yields from co-digestion of cow manure and water hyacinth following different pre-treatments.

Pre-Treatment Method	Biogas Yield (L/kg VS)	Methane Yield (L/kg VS)	Methane Content (%)
Mechanical and Chemical	339.5 ± 44.5	197.0 ± 26.0	58.0 ± 0.1
Mechanical	317.5 ± 40.5	182.0 ± 23.0	57.3 ± 0.1
No Pre-treatment	251.4 ± 32.3	145.9 ± 18.9	58.0 ± 0.1

The co-digestion of raw WH, without the pre-treatment produced the lowest levels of biogas, with a mean biogas production of 251 L/kg VS and a mean methane content of 58 Vol%, which represents 27.4 L CH4/kg of the material added (WH and CM). These values are typical of the amounts of biogas that can be produced easily from the co-digestion of cow dung and water hyacinth in a fixed-dome digester. It was noted that the WH did not fully digest, and it was suspected to be floating on top of the material in the digester. The co-digestion following mechanical the pre-treatment was slightly higher, with a mean biogas production of 318 L/kg VS and a mean methane content of 57 Vol%, which represents 33.3 L CH_4/kg of the biomass added. The feeding of the biomass was significantly easier after the mechanical pre-treatment, and the biomass appeared to be better mixed with the CM. The combined mechanical and chemical pre-treatment using KOH resulted in the highest digestion yields, with a mean biogas production of 339 L/kg VS and a mean methane content of 58 Vol%, which represents 35.6 L CH_4/kg biomass. The increased complexity of using the chemical and mechanical pre-treatment may only be available at selected sites, but it represents the maximum yields that were expect from the pre-treated

WH. The levels of biogas from the untreated WH represent the lowest levels of biogas that would be expected.

3.3. Techno-Economic Analysis

A simple techno-economic analysis was performed to determine the feasibility of WH cultivation for biogas generation and the subsequent utilisation of the biogas to replace LPG. The production of the biogas required was equivalent to the LPG calorific content under the current usage scenario described in Table 4. The analysis considered four scenarios, which were devised based on how much LPG was consumed, ranging between one and four cylinders per month. The subsidy available from the NNBOMP, which is also displayed in Table 4, would provide INR 7500 for the daily biogas production of 1–2 m^3 and INR 12,000 for the daily production of 2–6 m^3.

Table 4. Scenarios considered for LPG consumption and biogas (60 vol% CH_4) requirement to meet demand.

Scenario	LPG Cylinders per Month	LPG Consumption (kg/day)	Bio-CH_4 Requirement (m^3/day)	Biogas Requirement (m^3/day)	Subsidy Available (INR)
1	1	0.47	0.55	0.92	-
2	1.5	0.71	0.83	1.39	7500
3	2	0.95	1.11	1.85	7500
4	3	1.42	1.66	2.77	12,000

The installation costs, which are presented in Table 5, were calculated as a factor of the loading in accordance with Samar et al. [43], and they are in the range of INR 35,488–102,104. An inventory for the WH, CM, water and KOH pre-treatment was generated for each LPG replacement scenario, as displayed in Table 5.

Table 5. Daily inventory of water hyacinth (WH), cow manure (CM), water and KOH for digester operation.

Scenario	WH Loading	CM Loading AD ∣ Cultivation	Water Addition	KOH Addition	Installation Cost	Subsidised Installation Cost
	(kg/Day)	(kg/Day)	(kg/Day)	(kg/Day)	(INR)	(INR)
1	5.5	21.9 ∣ 3.6	48.7	0.16	35,488	35,488
2	8.2	32.8 ∣ 5.5	68.3	0.25	51,052	43,552
3	10.9	43.7 ∣ 7.3	91.1	0.33	68,069	60,569
4	16.4	65.6 ∣ 10.9	136.7	0.49	102,104	90,104

Table 5 displays the scenarios utilising the mechanical and chemical pre-treatment, shredding and alkali treatment, however, whilst these pre-treatment approaches produce the highest gas yield, they may not be representative of the average end user, therefore, three approaches were compared for each scenario. The first approach involved the mechanical and chemical pre-treatment, as previously described, the second one used the mechanical treatment alone, and the third one used the co-digestion of water hyacinth with no pre-treatment. The mechanical pre-treatment was assumed to use a hand-turned chaff cutter that is normally available in most villages, and so the capital and running costs of this device were not included.

Two market strategies were assessed for comparison. The first one proposes that the CM is readily available to the AD user, and it has no associated purchase cost, and it would ordinarily be used as fertiliser. These fertiliser requirements would instead be met by the digestate slurry which, therefore, also has no associated income potential. This scenario assumes that the WH biomass can be collected from local waterbodies or cultivated in small ponds, and thus, it is available for free. The results of the economic forecast, in payback years, are presented in Figure 6. The differences in the biogas yield for the different pre-treatment approaches results in a range of outcomes for each scenario, however, it indicates that the combined mechanical and chemical pre-treatment has the highest payback period, ranging between 3.4 years to replace one point five cylinders per month and 7.2 years to replace one cylinder per month. In comparison, the mechanical pre-treatment ranges from 2.4 to 3.6 years, and no-pre-treatment has a range from 2.8 to 4.5 years depending on the assumed biogas yield and LPG replacement.

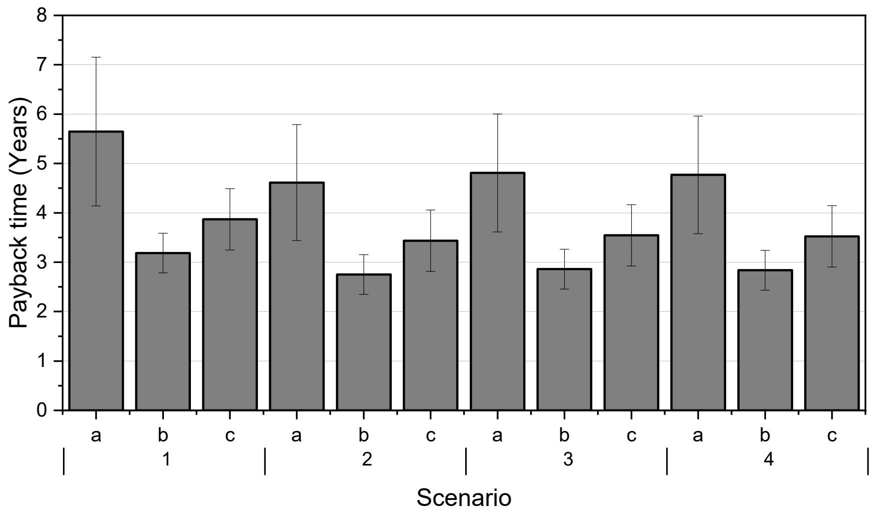

Figure 6. Payback period for each LPG replacement scenario, where digestate is utilised by AD user and cow manure has no purchase cost. Error bars demonstrate the impact on economic performance based on variations in feedstock costs. (a) Mechanical and chemical pre-treatment; (b) chemical pre-treatment; (c) no pre-treatment.

Figure 6 shows that a family using one point five LPG cylinders per month would experience the shortest payback period. This is the case for a number of reasons. Firstly, there is very little influence of the economies at that scale on the total installation cost under the scale range analysed, which provides a superior outlook for greater facility sizes. The minimum payback period is 10 months shorter when a household is replacing one point five cylinders compared to one LPG cylinder per month because the latter scenario just misses out on the subsidy provision that is provided above 1 m^3 biogas per day. Lastly, the fixed nature of the subsidy at a daily biogas production rate between 1 and 2 m^3 means that the monthly two LPG cylinders replacement scenario receives a lower subsidy per unit of biogas generated, which slightly increases the payback period compared to that of the one point five monthly cylinder replacement scenario. The market strategy assumes that there is no further economic benefits provided by using digestate instead of CM as a fertiliser or soil amender in terms of crop productivity or additional fertiliser purchasing, which are not accounted for in this analysis.

The second market strategy assumes that the initial procurement of WH biomass is included at a cost of INR 0.5 /kg and that users purchased CM for both nutrient provision in WH cultivation and feedstock for AD, but they were able to utilise digestate to offset the cost of fertiliser or sell their digestate to local farmers as a fertiliser. In this case, the economic forecast looks considerably more attractive than when digestate is used to replace the user's diverted CM fertiliser. This is evident when we are comparing the payback period results in Figure 6 to those in Figure 7. Figure 7 shows that digestate value is a critical factor in the payback period: at INR 0.5 /kg, by offsetting half of the assumed cost of the CM as a fertiliser, the payback period ranges from 3.1 years for the mechanical pre-treatment to 9.4 for the combined mechanical and chemical pre-treatment. If this value is increased to INR 1 /kg, the payback time ranges from 1.9 to 3.3 years. This concurs with the findings of Dey et al. [41] and Raha et al. [44] about the potential benefit of selling digestate as a fertiliser and overturning the lack of knowledge. The value of digestate suggested by Dey et al. and Raha et al., was INR 3 [41] and 4 [44], however the high water content of digestate suggests that a lower value is more appropriate. Whilst Table 2 suggests that the NPK of the digestate is up to 24 times low than it is for the CM, this is diluted by large quantities of water.

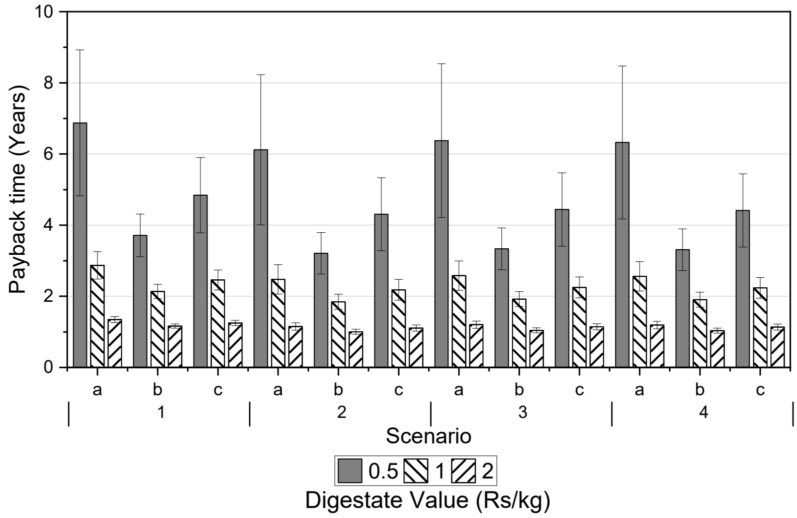

Figure 7. Payback period for LPG replacement scenarios where digestate is sold between INR 1 and 4 /kg. Error bars demonstrate the impact on economic performance with lower and upper biogas production shown in the anaerobic digestion trials. (a) Mechanical and chemical pre-treatment; (b) chemical pre-treatment; (c) no pre-treatment.

One aspect, which is not attributed in this analysis, is the time that is put into the cultivation of the WH and the operation of the anaerobic digester. These activities are assumed to be performed by the AD user rather than a paid professional. This means that time must be spent away from other potentially economic activities, which is difficult to account for, and this could be expanded upon in future work. Figure 8 demonstrates the space requirements with a range from 11 to 55 m^2. The larger cultivation areas are unlikely to be cultivated in small ponds, and therefore, they would likely have an associated costs, likely for tank fabrication.

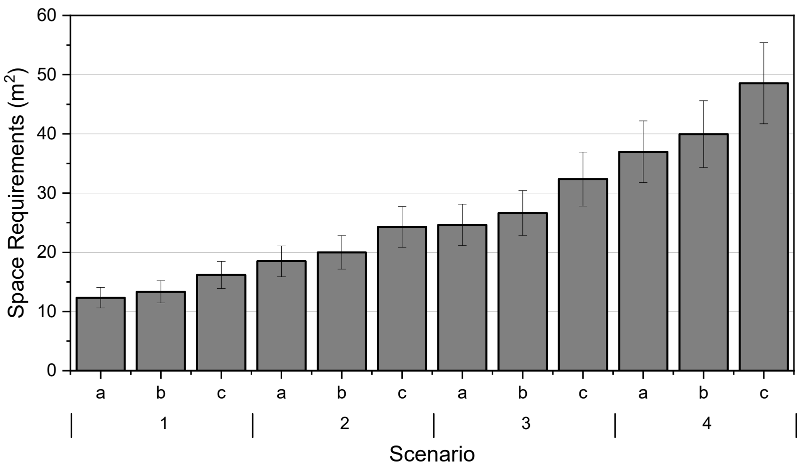

Figure 8. Space requirements for water hyacinth cultivation for each LPG consumption scenario. Error bars demonstrate the variation in growth rates displayed in cultivation trials. (a) Mechanical and chemical pre-treatment; (b) chemical pre-treatment; (c) no pre-treatment.

A potential limitation of these results is that the growth data presented are for a limited period during the year. Further cultivation trials must be carried out in order to provide a more accurate representation of the mean annual growth rate potential. It is assumed that the cultivation tanks would be made from recycled material and do not hold any financial cost. However, if this is not the case, then additional purchasing costs would increase the payback periods discussed previously. Furthermore, if a digester is developed in a location close to a natural source of WH, this could meet or support the loading demands of the digester during the natural growing season.

4. Conclusions

The concepts presented in this study have the potential to contribute to the UN's SDG7, providing clean, affordable and reliable energy by promoting the development of small-scale anaerobic digestion for cooking. The concepts proposed in this paper propose the use of an additional feedstock for the production of biogas from anaerobic digestion. The digestate produced, after anaerobic digestion, provides a suitable organic source of nutrients to support agriculture, but further tests are required to assess any biological hazards for their safe reuse as a fertiliser. This study has demonstrated the potential for the artificial cultivation of WH for producing feedstock for anaerobic digestion which can be used to generate biogas when it is co-digested with CM for use in family-size digesters. The methods developed have allowed for the successful cultivation and measurement of WH growth rates which generally fall within ranges in the literature, with average specific growth rates of 0.038 and 0.11 g/g/day for unfertilised and fertilised growing tanks, respectively. The anaerobic digestion of the WH and CM at a respective 20:80 ratio in a 200 L pilot reactor provided biogas yields of 218–384 L/kg VS with a 58% bio-methane content by volume, which should represent real-world yields in a family-run AD set up such as a Deenbandhu fixed-dome digester.

The use of WH as a co-feedstock alongside CM for anaerobic digestion can offset the use of LPG for cooking. WH is considered to be a waste product, and is typically landfilled, therefore, its utilisation as a feedstock for AD represents a beneficial valorisation approach. It was demonstrated that offsetting 1–4 LPG cylinders per month could be facilitated with an attractive returns on investment opportunity. Three pre-treatment methods were investigated: mechanical and chemical, mechanical and no pre-treatment ones. Two key market strategies were analysed. One of them involved the AD user having CM readily available which is normally used as a bio-fertiliser. Their bio-fertiliser demand is, instead, met by the digestate slurry from AD. The CM, therefore, has no associated cost and the digestate is not sold. For this scenario, mechanical pre-treatment was the optimum pre-treatment, with a payback period range between 2.3 and 3.6 years.

The second market strategy proposes that the user does not have readily-available CM, and it is therefore purchased, and the digestate is used to offset the fertiliser costs, or it is sold as a premium organic fertiliser. Previous studies have shown that the market value of digestate is superior to that of CM due to its superior fertiliser properties. This improves the cost–benefit relationship of investing in the AD technology and facilitates potential payback periods between 1.9 and 3.3 years if the digestate is sold at INR 1 /kg digestate. This was the critical factor in the economic study, and it demonstrates that selling digestate or offsetting fertiliser purchases has a key impact on the economic feasibility of this study. The pre-treatment was mechanical, with a payback period ranging within 2.9–4.9 years at a digestate value of 0.5 Rs/kg, in comparison to no pre-treatment, with a payback period ranging within 3.7–7.1 years, and combined pre-treatment, with a payback period ranging within 4.7–11.8 years. In order to replace 1–4 LPG cylinders per month, an area of 11–55 m^2 would be required in order to cultivate the WH. However, it is recognised that a natural source in close proximity could reduce this.

The current integrated approach is a prediction of long-term behaviour, however, this has not been demonstrated along any scale. The WH cultivation was conducted during peak growth conditions, and the variable growth rates across the year must be considered.

Further research is needed on WH cultivation, utilising digestate as the sole nutrient source to develop a fully integrated system. A large-scale demonstration would be required to verify the complete behaviour of this system.

Author Contributions: Conceptualization, D.G.B., G.N., O.G. and A.B.R.; Methodology, D.G.B., G.N., O.G., V.D. (Vishwanath Dalvi) and S.R.; Validation, D.G.B., G.N., O.G. and A.B.R.; Formal analysis, D.G.B., G.N. and O.G.; Investigation, D.G.B., G.N. and O.G.; Resources, G.N. and A.B.R.; Data curation, D.G.B., G.N. and O.G.; Writing—original draft preparation, D.G.B., G.N. and O.G.; writing—review and editing, D.G.B., G.N., O.G., V.D. (Valerie Dupont), V.D. (Vishwanath Dalvi), S.R., M.A.C.-V. and A.B.R.; Visualization, D.G.B., G.N. and O.G.; Project administration, A.B.R.; Supervision, V.D. (Valerie Dupont) M.A.C.-V. and A.B.R.; Funding acquisition, M.A.C.-V., V.D. (Valerie Dupont) and A.B.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Engineering & Physical Sciences Research Council (EPSRC) (grant no. EP/L014912/1) and the Biotechnology and Biological Sciences Research Council (BBSRC) through the BEFWAM project (grant no. BB/S011439/1).

Data Availability Statement: The data presented in this study are contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

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