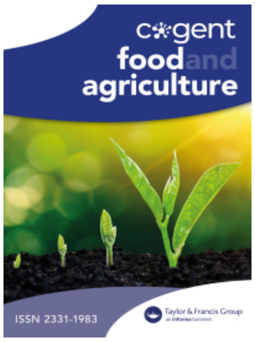

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Transforming arable and dairy farming systems by adopting anaerobic digestion and recirculating aquaculture systems to address the demand for sustainable profitability, environment and diets

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ABSTRACT

UK agricultural systems face pressures from environmental targets, policy reform, and market volatility, requiring innovative strategies for resilience and sustainability. This study examines integrating anaerobic digestors (AD, 500 kW) and recirculating aquaculture systems (RAS, 157 m^3/unit) in arable and dairy farms. Using a 2022 farm data-based linear programming model, we evaluate the economic viability of producing renewable energy and warm-water prawns alongside traditional outputs. Results show significant profit gains: AD alone boosts Net Margins by 24% in arable farms, while combined with RAS can increase margins by up to 56%. For dairy, AD effects are modest (5%), but RAS can improve margins by 70%, often replacing AD due to lower returns. These technologies recycle nutrients from digestate and waste, supporting circular economy goals. AD–RAS synergies maximise energy and heat recovery, with RAS enabling local seafood that reduces import dependence, carbon leakage, and ecological damage from overseas shrimp farming. Despite high capital costs, complexity, and energy price sensitivity, findings highlight AD and RAS's potential for sustainable diversification, align with UK net-zero and biodiversity goals, and improve resource efficiency, lower emissions, and conserve land. We conclude that integrated AD and RAS are viable paths to enhance farm resilience and deliver economic, environmental, and dietary benefits amid agricultural transition.

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1. Introduction

Agricultural systems face pressures from internal factors, such as limited natural resources and land and environmental degradation, as well as external factors, such as agri-food policies, exchange rates, and trade agreements. These challenges necessitate adapting farming systems and adopting innovative and alternative food production technologies (Crippa et al., 2021; Foley et al., 2011; Godfray et al., 2010). Therefore, implementing sustainable agriculture production practices and technologies is essential for transforming food production systems. Such farm management practices aim to reduce negative externalities, shift land use patterns and spare natural resources (land, water) for providing other land-based services (Popp et al., 2017; Weindl et al., 2017). This transformation of agricultural production systems is necessitating the optimisation of food production by adopting technologies that reduce input costs,

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improve technical efficiency and lead to the reduction of environmental pressures within the framework of sustainable intensification of farming practices (Gadanakis et al., 2015).

Designed in significant part to address this, the 2020 UK Agriculture Act commits to net zero carbon emissions while as a signatory to the Kunming-Montreal Global Biodiversity Framework (GBF) at COP15, the UK has recently committed to protecting 30% of its land area for nature by 2030 (UN, 2022). Furthermore, new food technologies and innovation systems can support the diversification of farm profitability, leading to its financial sustainability (Salvioni et al., 2020). In addition, farmers are required to develop strategies to adapt their production system within a shifting institutional context that concerns legislative changes, which could lead to significant economic pressures, i.e. removal of the Basic Payment Scheme (BPS) by 2028 (DEFRA & Rural Payments Agency, 2024). Hence, for farmers to meet the objectives of the goals for profit maximisation, environmental pressure mitigation and achievement of financial sustainability, a set of entrepreneurial skills and risk management skills is necessary (Gittins & McElwee, 2023). Under these pressures, farmers and agribusinesses must leverage their knowledge and experience while incorporating innovation, sustainability, and efficient management as central pillars of their food production and land management practices.

In this context, this study evaluates the integration of Anaerobic Digestion (AD) and Recirculating Aquaculture Systems (RAS) explicitly as diversification strategies for arable and dairy farms. These technologies are assessed not as replacements for existing agricultural activities but as complementary enterprises aimed at enhancing farm profitability, improving resource use efficiency, and contributing to environmental sustainability. The integration of terrestrial seafood production using RAS and renewable energy sources such as AD has the potential to provide a novel, diversified farming output.

This study assesses the economic viability of terrestrial "*King Prawn*" production (*Penaeus vannamei*–also known as "white-leg shrimp" or warm-water shrimp) combined with farm-based renewable energy provided by an AD unit in the UK as a first step to quantify and economically value this potential transformation. Economic viability is assessed within the framework of sustainable intensification of farming systems, with the principles of the circular economy serving as a core component of the analysis. An optimisation problem is formulated to determine the optimal allocation of resource endowments within the farming system. This approach simultaneously maximises economic output and reduces environmental pressures. Additionally, all by-products from the system's diversified enterprises are reintegrated into the production cycle, aligning with the principles of the circular economy to enhance efficiency and maximise overall output (Babu et al., 2020). Recent work highlights the role of RAS in enhancing domestic seafood production while mitigating international carbon leakage, reinforcing the potential of these technologies as part of sustainable diversification strategies (Morello et al., 2025).

This analysis is situated within the broader context of literature emphasising the role of circular economy principles and farm diversification in advancing sustainable food production systems. Duncan et al. (2023) highlighted that the principles of the circular economy are integral to the sustainable intensification of food production systems. Transforming food production requires adopting alternative agricultural practices and principles aimed at minimising resource use. This can be achieved by exploiting and closing resource loops, for example, effectively reusing the same resources or their residues. The development of business models based on the principles of circular economy, the use of alternative production technologies and the integration of alternative production technologies are combined to accomplish the sustainable intensification of production systems (Kirchherr et al., 2017, 2023). These new food production systems can lead to investments in new enterprises, often associated with solutions addressing the demand for sustainable diets (Mazac et al., 2022; Parodi et al., 2018). Remarkably, transforming food production systems is primarily driven by farm entrepreneurship and strategic agribusiness management (Gadanakis et al., 2024). In this regard, entrepreneurship in the agricultural sector is vital in fostering innovation, responding to changing market demands, and enhancing operational efficiency (Ang et al., 2013).

Literature reports studies focusing on on-farm enterprises being powered by AD outputs, i.e. power and heat, such as greenhouses (Bywater & Kusch-Brandt, 2022) and the use of heat for hot water in buildings and dairy washing in dairy farms (Marañón et al., 2011). Beyond farm activities, AD can also supply energy for campsites (space and water heating) and local food production operations (Bywater & Kusch-Brandt, 2022). Thus, convert an output which in other cases would have been considered a waste (excess heat from the AD) into a valuable input that fosters farm diversification and underpins a waste-based agricultural circular economy framework (Haque et al., 2023; Yue et al., 2022). Moreover, recent advancements in AD and RAS have significantly enhanced operational efficiency and reduced costs. In AD, these innovations have focused on improving methane production efficiency and overall stability of the digestion process (Kim et al., 2024; Wu et al., 2022). In the realm of RAS, technological innovations have focused on the integration of biological filtration systems, which effectively manage waste and improve water quality, thereby minimising the need for water exchange and reducing operational costs associated with water treatment (Laza et al., 2021; Lindholm-Lehto, 2023). Overall, these technological innovations in AD and RAS underscore a shift towards more efficient and cost-effective practices that align with sustainability goals.

Similar to other diversifications alongside AD, such as heated greenhouses (Bywater & Kusch-Brandt, 2022), indoor shrimp production units with AD will maximise the use of their (otherwise wasted) heat energy, enhancing the sustainability and circularity of both industries. Warm water shrimp is a healthy seafood with high protein, low calories, low fat, rich in vitamins, minerals and antioxidants, promoting brain and heart health (Farmery et al., 2018). Warm water shrimps are already a highly popular seafood in the UK, with imports of around 34,873 tons and a £291.2 M value in 2022 from mainly Central & South America and South Asia (Seafish, 2024). However, traditional overseas production is vulnerable to climate/disease crises, has high transport-related CO2 emissions, and often uses environmentally unsustainable practices such as mangrove forest destruction (Kauffman et al., 2018; Macusi et al., 2022). Mangroves can absorb and trap more CO2 than any other ecosystem on Earth, but some have reported that converting mangroves to shrimp ponds resulted in a 58–82% carbon stock loss (Kauffman et al., 2018). Mangroves also provide coastal protection against storms and coastal erosion (Macusi et al., 2022). Therefore, combining high-value shrimp aquaculture with farm-based renewable energy will provide a novel home-grown output with considerable economic, environmental and health potential.

Moreover, this kind of diversification raises the potential for substantial land sparing for biodiversity (Balmford, 2021; Green et al., 2005; Phalan et al., 2011) without the 'leakage' drawbacks associated with crude reductions of domestic food production, merely increasing imports and overseas environmental degradation (Fuchs et al., 2020; Lenzen et al., 2012; Searchinger et al., 2022). Some suggest that integrating RAS within UK agricultural systems can offset carbon leakage linked to afforestation policies, emphasising the importance of land-saving technologies in climate mitigation strategies (Morello et al., 2025).

Using a linear programming (LP) approach, we model the profitability of "*King Prawn*" production combined with an AD unit relative to other farm activities in the context of arable and dairy agricultural systems. To assess the profitability of farm diversification, the LP is used to model changes in the whole-farm Net Margin (i.e. the gross margin less adjusted fixed costs allocated to the farm enterprises). Additionally, various crucial issues related to investment decisions, including current policy concerns such as environmental goals and energy prices, are explored. For example, the choice of AD production capacity and RAS scale, the synergies with other farm activities, impacts on land use due to AD feedstock choices, and the use of digestate and nutrients cycling, among others. The farm-type model's structural, technology and economic data refers to 2022 data. The data, technical coefficients and resource endowments have been derived from different sources, including the DEFRA Farm Business Survey (FBS), published farm management standards and peer-reviewed published literature, among others. Technical information and data on implementing and operational costs for the RAS and AD systems have been provided by industry stakeholders.

2. Materials and methods

We evaluate the farm-level economics of adopting anaerobic digestion (AD) and recirculating aquaculture systems (RAS) using a whole-farm linear programming (LP) model implemented in GAMS (https://www.gams.com/). The objective is to maximise the farm's Net Margin, accounting for variable, fixed and annualised capital costs, subject to land, labour and capital constraints as well as agronomic rotation rules. In compact form, the problem maximises total Net Margin over enterprise areas/activities, subject to the associated technical-coefficient matrix and resource availability constraints (Jones & Salter, 2013). This framework builds upon our earlier study for arable systems, but is extended, reparametrized, and applied to both arable and dairy farms, with an expanded scenario set and sensitivity tests. See Campos-Gonzalez et al. (2023), for the preliminary arable-only formulation.

The use of LP is appropriate here due to its capacity to handle complex optimisation problems involving multiple constraints and objectives, which is essential in agricultural systems (Alotaibi & Nadeem, 2021). LP is particularly suitable for maximising farm net margins by determining the optimal mix of inputs and resource use under specified constraints such as land, labour, and capital. By allowing for a detailed assessment of the financial and economic viability of integrating RAS and AD into typical farm systems, the farm optimisation model can reflect the intricate balance between these non-farming and the rest of the farm activities and their respective contributions to overall profitability. This approach facilitates the identification of the most economically viable configurations and ensures that all variable and fixed costs, including capital investments, are comprehensively considered. Consequently, LP serves the study's objectives effectively by providing a robust framework for optimising farm operations within realistic constraints, leading to more informed decision-making and better resource allocation.

The farm model can deploy different enterprises, including or not AD, AD+RAS, using selected inputs (e.g. seeds, fertilisers, feedstocks for AD, feed for prawns) and resources (labour and land) dated to 2022 (See Supplementary Material Table S1 for details). The model is based on a single-year business cycle reflecting only annual agricultural and non-agricultural activities. In this regard, we model land utilisation according to the net economic margins that the various enterprises can earn. Thus, each farm activity contributes to the total Net Margin of the farm as a whole but is subject to constraints, such as the availability of land and labour, the availability of inputs produced by the farm (e.g. the case of feedstocks) and rotational requirements (e.g. a minimum of 1/3 of the farm must be sown to break crops, i.e. a rotation requirement to establish a break crop every third year). As detailed by Jones and Salter (2013), the mathematical structure of the model is:

Maximise

$$Z = \sum_{ij} C_{ij} \times X_{ij}. \tag{1}$$

Subject to the following constraints:

$$Ax \le b; x \ge 0, \tag{2}$$

where: Z is a scalar product representing the objective function, i.e. the whole-farm Net margin; C_{ij} is the vector of Net Margin contributions for each farm enterprise, i, over j farm fields; X_{ij} is the vector of scalars for each enterprise (i.e. crop areas); A is the matrix of technical coefficients (α_{ik}) specifying the quantity of input k required per unit of output for enterprise i; b represents the resource endowment and input availability, and x refers to the unknown endogenous (model-determined) variables of the LP.

2.1. The arable and dairy farm models

The arable farm model represents a typical system based in East England with an average size of 300 hectares partitioned into 12 fields (25 ha each). We use 25-ha fields as in past studies, to increase the realism of the models. To express variation in yields across fields using a factor varying between 0.65 and 1.35 for each field (Jones & Salter, 2013; Redman, 2022; Vittis et al., 2017). The FBS data for 2020–2021 shows an average size of 298 ha for cereals-dominated farms in this area, representing approximately 57% of cereal farms in England. (Duchy College, 2022). The dairy enterprise is based on an entirely housed and self-contained Holstein herd of 530 milking cows (housed for six months of the year). Our real-world farm system is based on the University of Reading's Centre for Dairy Research (CEDAR), which operates commercially in the West of England, the region with the highest proportion of dairy farms (Duchy College, 2022). Following CEDAR practices and technical guidelines (Redman, 2022), dairy cows are culled, on average, after three lactations, and the herd replacement rate is 25% per annum. The herd Calving Index is 397, i.e. on average, there is a 397-day interval between calvings. Then, we assume around 364 replacements (182 heifers of 1–2 years, plus 182 calves of 0–1 years). Average farm stocking rates are constrained between 0.5 and 2 LSU/ha. In 2022, our 567 ha real-world dairy farm hosted 80 ha of combinable crops (cereals/oilseeds) and 150 ha of forage maize. The remaining 337 ha were grassland (245 ha for leys and 92 ha for permanent pasture, respectively). The rotational practice differs from the arable farm above in that grass leys form part of the rotation, i.e. grass ley acts as another break crop as with the arable farm, the rotational constraints mean that in any one year, a minimum of 1/3 of the arable/ley area must be sown to break crops, including grass leys–the area of permanent pasture is excluded from these restraints as it is fixed and not used in rotation with arable crops. Other restraints on areas of single crops follow the approach set out for the arable farm. Given the higher land availability, another difference to the arable farm above is modelling 15 notional fields (areas between 37.5 and 43.5 ha), which preserve the proportions of arable, ley and permanent pasture, as seen on our real-world farm.

Regarding feed requirements of dairy animals (in MJ of energy), milking cows are fed on farm-grown grass and silage (e.g. from maise), fodder crops, and imported concentrate feeds. We model these requirements by matching them to feed supply based on the nutritional value of feedstuffs, as shown in Table 1. We assume a feed requirement of 83,000 MJ per year for dairy cows (Sguizzato et al., 2020; Thomas, 2004). Regarding replacement herds, Table 2 calculates their nutritional requirements by applying livestock unit conversion ratios to calculate feed requirements of replacements as a fraction of average dairy cow requirements.

2.2. Farm enterprises and inputs

Table 3 shows the list of farm enterprises and inputs for both agricultural systems, including some intermediate products, such as forage crops. These forage crops can support AD production and, consequently, AD outputs (e.g. electricity and heat) for RAS production.

Regarding labour, we follow standard management practices (Redman, 2022). The model for the arable system is provided with 660 man-days for farming activities (one manager and two full-time staff working 220 days per year), while the dairy model is supplied with 1925 man-days of labour per year. The amount for the dairy system represents the equivalent of six full-time workers plus one farm manager (each working 2200 hours or 275 days per year). Contractors supply any additional labour required above the available man-days for both farm models. For AD + RAS, labour is included as a specific cost,

Table 1. Nutritive values of feedstuffs per t and per ha (MJ/ha based on yields detailed in Supplementary Material Table S3).

Feed	Dry matter (DM) content (g/kg)	ME (MJ/kg DM)	ME (MJ/t FM)	ME (MJ/ha)
Wheat (grain)	860	13.6	11,696	100,586
Wheat (whole crop)	350	10.5	3,675	141,855
Barley (grain)	860	13.2	11,352	72,653
Barley (whole crop)	350	10.5	3,675	135,975
Oats (grain)	860	12.5	10,750	69,875
Oats (whole crop)	350	10.5	3,675	135,975
Other cereals (triticale)	860	12.5	10,750	64,500
Other cereals (whole crop)	350	10.5	3,675	115,028
Potatoes (maincrop)	200	13.3	2,660	119,700
Maise (forage)	300	11.0	3,300	149,820
Other fodder crops (fodder beet)	180	12.0	2,160	129,600
Short-term ley (silage)	250	10.8	2,700	118,800
Permanent pasture	180	11.5	2,070	89,100
Rough grazing	180	11.5	2,070	29,700
Concentrate feeds (based on extracted soyabean meal)	880	13.4	11,792	

Sources: (Redman, 2022).
Notes: (i) FM = fresh material; DM = dry matter. ME = Metabolizable energy, MJ = Megajoule, (ii) Permanent pasture yields are notionally assumed to be 75% of leys and rough grazing yields 25%, (iii) Whole-crop data for wheat, barley and oat is for wheat whole-crop fermented, (iv) For concentrate feeds based on soybean is used field beans data.

Table 2. Nutritional requirements of dairy herd replacements.

Class of animal	Livestock unit	Nutritional requirement (MJ/animal/year)
Calf 0–1 year	0.34	28,220
Heifer 1–2 years	0.65	53,950

Source: Livestock units from Redman (2022). Nutritional requirement based on average feed requirement for dairy cows (Sguizzato et al., 2020; Thomas, 2004).

Table 3. List of enterprises and inputs included in the farm models.

Agricultural system	Enterprises/activities
Arable and Dairy	Cereals – winter wheat, winter barley, winter oats, other (triticale)
	Other crops – peas/beans (for stockfeed), Rapeseed, Field-scale vegetables (Swedes)
	Forage crops – maise, fodder beet
	Anaerobic digestor (AD)
	Recirculating aquaculture system (RAS)
Only Arable	Sugar beet, potatoes
Only Dairy	Dairy, grass silage
	Inputs
Arable and Dairy	Agricultural labour – regular, casual/seasonal, contractors
	Seed, sprays, fertilisers, and other crop costs
	Agricultural machinery costs – fuels/oils, repairs, depreciation
	General farming costs – land and property, miscellaneous
	AD costs – equipment, feedstocks preparation, digestate processing
	RAS costs – equipment, water, prawn juveniles, electricity and heat
Only Dairy	Concentrate feeds, rearing or purchase of herd, veterinary and medicines, and other related costs

Source: Adapted from Jones and Salter (2013).

given the need for specialised labour and AD + RAS size/capacity. In this regard, operating RAS production unit in the UK powered by AD (RASTECH, personal communication, July 2024), a system of six RAS units demands three workers in total (two operational and one managerial). In contrast, the second variant demands five workers in total (three operational and two managerial). All these workers must be 100% FTE. Their skill grade corresponds to the initial grade of an agricultural worker, in the case of the operational worker, and to the supervisory grade of a farm worker, in the case of the managerial worker, as specified in the UK agricultural labour skill grading system.

For both systems, detailed data on crops, input prices, and margins are provided in the Supplementary Material Table S1. Specialised reports have also published higher margins for cereals and combined crops using 2022 prices (Topliff, 2025). Details on crop outputs and nutrient requirements used in both models are also provided in the Supplementary Material Table S2, including average yields for crop enterprises (considering the whole crop, seed/tubers/beets, and residues) and crops' demand for primary nutrients, i.e. Nitrogen (N), Phosphate (P), and Potassium K). The nutrient requirements used here reflect common commercial practice (see Redman, 2022 for details), and they must be met each year by fertiliser applications. Fertilisers can be supplied from purchased inputs or AD digestate, where the latter is available (see section 2.3.3 for details).

2.3. The AD unit

2.3.1. Capacity

Following published guidance on farm-scale AD (Bywater & Kusch-Brandt, 2022; Jones & Salter, 2013; Parsons Brinckerhoff, 2015), we allow adoption up to a nominal 500 kW(e) unit operating ~95% of the year with typical combined heat and power conversion (CHP) efficiency. Capital expenditure is annualised over ten years at 4%, and operating costs include plant operation and maintenance. Electricity sales revenue combines a 2022 baseload price with the applicable feed-in element; we subsequently test price sensitivity in scenario analysis. Additional details about these settings can be found in Campos-Gonzalez et al. (2023). Additionally, all digestate generated can be used on the farm's land as a fertiliser substitute, provided that applications do not surpass the nutrient requirements.

2.3.2. AD costs and revenues

Since AD is a new activity on the farm, capital costs must be accounted for this new investment. According to available sources on a per kW basis, as shown in Table 4, the establishment cost of a 500 kW AD is assumed to be £2.9 million. Similar estimates are available in Redman (2022). Assuming all capital costs were borrowed and assuming loan repayment over ten years, average repayment charges at 4% interest on borrowing of £2.9 M would be approx. £357,544. A 4% interest rate follows Bank of England estimates for 2022 and farm management assumptions (Redman, 2022). Some assumed that the farm would provide 100% of the funding without applying for bank loans (Bywater & Kusch-Brandt, 2022). Regarding operational costs, estimates from Table 5 show values for 500 kW AD around £143,237.

Table 4. The capital cost of AD installation, on a per kW basis, at a range of AD unit sizes.

AD unit size (kW)	Capital cost (£M)	Capital cost per kW (£)
<250kW	1.44	5,953
250–500kW	1.45–2.9	5,804
>500	2.23	4,465

Source: Parsons Brinckerhoff (2015). Past studies applied these parameters (e.g. Bywater and Kusch-Brandt (2022).
Note: Capital cost per kW (£) corresponds to Parsons Brinckerhoff Central Case (i.e. median).

Table 5. Operating cost estimates for 500 kW AD based on published data.

Item	Value	Unit	Running costs for 500kW AD (£/year)	Sources
AD operation and maintenance	2.5%	Percentage of capital value	72,500 (Based on £2.9M)	Bywater and Kusch-Brandt (2022); Redman (2022)
CHP operation and maintenance	£0.017	£/mW produced	70,737 (Based on 4,161 mW produced)	Bywater and Kusch-Brandt (2022)
Total (£/year)			£143,237	

Related to revenues from AD output, these are generated by selling electricity to the national grid. The quantity of sold electricity depends on the scenario modelling (see section 2.5). According to Ofgem data, electricity prices based on Day Ahead Baseload Contracts for 2022 averaged £0.21145/kWh (OFGEM, 2023a). Regarding the average Feed-in tariff, we estimate £0.045/kWh based on Ofgem's available data (OFGEM, 2023b). Thus, total receipts for electricity generation are £0.256/kWh.

Regarding electricity price estimations, we also recognise that adopting AD technology in farming operations is significantly influenced by the economic viability of electricity production from biogas. As energy prices fluctuate, particularly electricity prices, they are crucial in determining the feasibility of implementing AD systems on farms. Studies have shown that the economic feasibility of anaerobic digestion is closely tied to the revenue generated from electricity sales, which can be affected by market conditions and energy prices (Cowley et al., 2019; Diaz Huerta et al., 2023; Wang et al., 2011). In this regard, we evaluate the robustness of the results to changes in electricity prices using a sensitivity analysis approach. Specifically, we analysed the effect of a 20% decrease in electricity prices (£0.204/kWh, which approximates the average price in the last 5-year period, 2017–2021) and 20% increase (£0.307/kWh, which approximates the average peak on prices between June and September 2022) on farm Net Margins and AD size for arable and dairy farms under all the scenarios.

2.3.3. AD feedstocks and nutrients from digestate

Potential feedstocks are restricted to materials produced on the farm (e.g. whole-crop cereals, forage maize, residues, and slurries/manures from dairy). Methane yields and digestate nutrient contents shown in Table 6 are drawn from established sources (see e.g. Bywater & Kusch-Brandt, 2022) and mapped into the LP via energy output and nutrient-balance constraints. Primary digestate nutrients (N, P and K) are

Table 6. Methane yields (m^3/t fresh material, FM) and nutrient content from the AD digestate for crops.

	Methane yield (m^3/t FM)		Nutrient content (kg/t whole crop/slurry)		
Crop	Residues	Whole crop/slurry	Nitrogen (N)	Phosphate (P)	Potassium (K)
Winter wheat	141	115	3.5	0.35	3.85
Winter barley	119	115	3.5	0.35	3.85
Winter oats	203	76	5.4	0.9	7.8
Other cereals (triticale)	141	122	3.9	0.78	3.9
Oilseed rape	253	50	3.42	0.54	3.78
Field peas	237	47	3.5	0.5	3.7
Field beans	237	47	3.5	0.5	3.7
Sugar beet	32	76	1.76	0.44	2.2
Potatoes (maincrop)	–	27	3.5	0.55	4.95
Maise (forage)	201	98	3.9	0.6	3.6
Fodder beet (forage)	49	70	1.8	0.4	4.2
Field-scale veg (swedes)	31	70	3.1	0.33	1.98
Grass silage (ley/perm. pasture)		57	3.7	0.8	3.7
Cattle – Slurry		13.8	5.13	0.9	4.32

Source: the ADAT tool (University of Southampton, 2017).

credited against crop requirements up to agronomic optima, reducing purchases where feasible (Campos-Gonzalez et al., 2023). Additionally, the modelling approach only allows for the application of nutrients (including those sourced from digestate) according to optimal nutrient requirements for crops (see Supplementary Material Table S3).

2.4. The RAS unit

2.4.1. Capacity and costs

We represent modular warm-water prawn (*Penaeus vannamei*) units at ~157 m^3 capacity each. Each unit entails capital outlays (annualised as above), fixed operation and maintenance, labour, juveniles, feed, water/treatment and monitoring (see Timmons et al., 2018 for details about RAS technologies). Revenues and costs estimates for the LP modelling of RAS technology have been derived from an already operating RAS production unit in the UK (RASTECH, personal communication, July 2024). The data relates to a modular RAS production unit implemented at the farm level with an annual king prawn yield of ~5,000 kg yr^{-1}. This yield is based on a prawn stocking density of 8 kg/m^3 at the time of harvest, four production cycles per year in a modular RAS tank with a maximum capacity of 157 m^3 and an annual water usage of around 500 m3 (assuming a 30% water change per year). Also, this unit requires over 30 MWh yr^{-1} for electricity, supplying water pumps, treatment equipment and water heating requirements provided by the AD unit.

Similar to AD, capital costs must be included since RAS is a new venture on the farm. The setup cost of a 157 m^3 modular unit is estimated between £90,000 and £100,000, covering housing, delivery, construction, and equipment. All capital costs were assumed borrowed, with ten-year loan repayments averaging about £11,600 annually at 4% interest. Operational costs are estimated at about £120,000 yearly, including variable costs like water, effluent treatment, and salts (~£17,000), juvenile prawn supply (~£15,700), and prawn feed (~£8,400); fixed costs include water testing, treatment, and monitoring (~£14,700), equipment maintenance (~£3,000), and labour (~£60,000).

2.4.2. Revenues and use of prawn waste as fertiliser

Revenue streams include prawn meat (assumed £23 kg^{-1}) and additional income from exoskeleton valorisation via chitin recovery (RASTECH, personal communication, July 2024. Campos-Gonzalez et al., 2023). The commercial sale of waste prawn exoskeletons/shells, considering an average yield of ~7650 kg yr^{-1}, assumes a value ~£12/kg for the industrial extraction of chitin (~25% by weight). Chitin is used extensively in producing biopolymers and in the pharmaceutical industry (Islam et al., 2023). These estimates result in an annual revenue of ~£204,700 yr^{-1} for each 157 m^3 RAS unit. Additionally, prawn waste (excreta) can be concentrated, dried, and used as fertiliser due to its nutrient content for use on the farm, following the same approach as AD digestate. In this regard, the model considers content for N, P and K of 5,

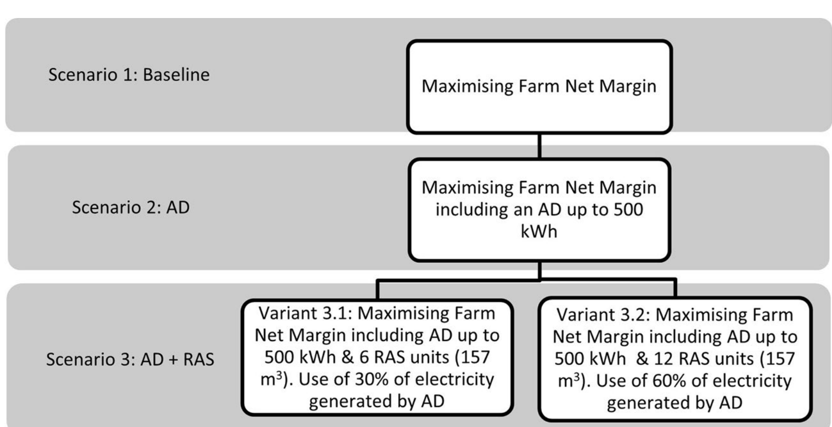

Figure 1. The simulated scenarios for dairy and arable farms.

4 and 1.3 kg/ton of prawn waste, respectively, following reported estimates for farm-derived prawn waste (Dufault & Korkmaz, 2000; Suwoyo et al., 2019).

2.5. The scenarios

We solve the LP under: (i) a baseline with no AD/RAS; (ii) AD-only; and (iii) combined AD + RAS, with 6- and 12-unit RAS variants sized against AD energy output. We then examine robustness to electricity price changes around the 2022 baseline. This scenario structure extends the arable-only analysis in Campos-Gonzalez et al. (2023) to cover dairy systems, larger RAS adoption, and explicit energy-price sensitivity. The optimisation is based on a set of scenarios reflecting prices and levels of technology prevailing in 2022, as presented in Figure 1.

The AD-only solves the LP model and optimises the farming systems by integrating an AD plant with a capacity of up to 500 kWh. The AD + RAS scenario considers that a 500 kWh AD produces enough outputs to freely supply energy and heat to six to twelve "King prawn" production units. Two variants are explored under the AD + RAS scenario: AD + RAS (6) deploys six units of RAS, with the AD unit providing 30% of its output to these units and the rest being sold to the grid as electricity, and AD + RAS (12) deploying twelve RAS units powered by 60% of the AD unit; the rest are sold as electricity. We construct these variants based on energy (electricity and heat) requirements for a 157 m^3 capacity RAS unit, as well as complementary equipment and buildings.

3. Results and discussion

This section presents and discusses the outcome of the LP optimisation process regarding the maximisation of the Farm Net Margin for the simulated scenarios. That is the output of the introduction of AD and AD + RAS compared to the baseline scenario. The analysis highlights the impact of these two non-agricultural enterprises on the total Farm Net Margin and their influence on cropping patterns, livestock numbers, and nutrient purchases, among other factors.

3.1. The baseline scenario of farm system optimisation (Scenario 1)

The baseline scenario represents the operation of the arable and dairy farms with no AD or AD + RAS as diversification opportunities. Consequently, this scenario enables the validation of the model and the evaluation of changes in economic and financial outputs (e.g. the Farm Net Margin) of the whole farming system due to the introduction of the two non-agricultural enterprises, i.e. AD and RAS. In this regard, our results produce expected outcomes from a cropping pattern perspective. For the arable farm, as shown in Figure 2 (left-side), we observe a typical rotation (Jones & Salter, 2013; Upcott et al., 2023) with about one-third of the farm under cereals based in the East of England (100.2 and 9.6 ha of wheat and barley, respectively) and two-thirds of crops such as sugar beet, rapeseed and field vegetables. Considering the average wheat prices in 2022 and their 37% increase compared to the average prices over the past five years (Agriculture and Horticulture Development Board (AHDB), 2023), the cropping

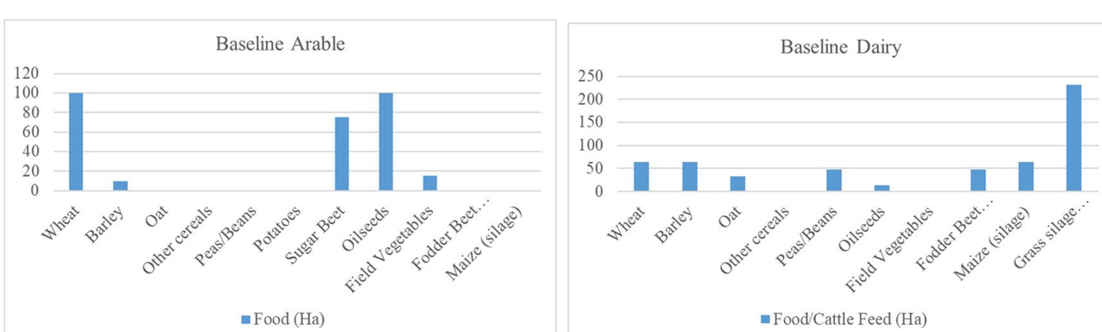

Figure 2. Baseline results for cropping pattern of arable farm (left-side) and dairy farm (right-side).

pattern presented here as the optimum solution for the LP model is justified. The structure of the dairy farm is representative of a dairy farm based in the southeast of England. The dairy system has 493 dairy cows in milk production and 345 cows as replacement herds (similar to our real-world dairy herd of 530 dairy cows in milk production, as detailed in the section 2.1), and cultivated 335 ha of cereals and other crops and 232 ha for grass silage (from ley and permanent pastures).

3.2. Maximising the farm net margin with AD adoption (Scenario 2)

3.2.1. Changes in whole-farm net margin and optimal AD size

Scenario 2 assumes the introduction of an AD plant in both large-scale arable and dairy commercial farms. Under this scenario, the LP model specified in Equations (1) and (2) is maximised and, thus, demonstrates how AD as a new non-agricultural enterprise can be commercially viable at 2022 prices. Figure 3 shows the changes in the net margin for all scenarios (along with AD sizes using only farm-based feedstocks) compared to the Baseline. Related to the whole-farm net margin, once AD is adopted, there is a 24% and 5% increase on the baseline for the arable and dairy farms, respectively. The rise in Farm Net Margin is attributed to income generated from farm outputs, including crops, milk, and electricity sales. AD is taken up at 304.6 kWh on the arable farm, while on the dairy farm, the AD is adopted at a scale of around 140 kWh. The use of low methane yield feedstocks such as slurries and manures, as

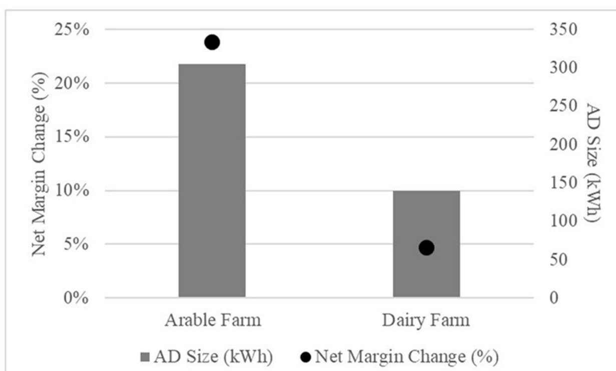

Figure 3. Whole-farm Net Margin change (%, dots – primary axis) and AD size (kWh, bars – secondary axis) for Scenario 2 compared to Baseline.

reported in Table 6 and management guidelines (Redman, 2022), explains the lower AD capacity for the dairy case since there is no provision for crops to be used as AD feedstocks, as discussed below (see section 3.2.2). In Scenario 2, the optimal dairy herd size is 739 (435 dairy cows and 304 replacements), representing a reduction of around 9% in the baseline. Before discussing changes for the AD and RAS scenarios, we analyse the impacts on cropping patterns and fertiliser savers due solely to AD introduction.

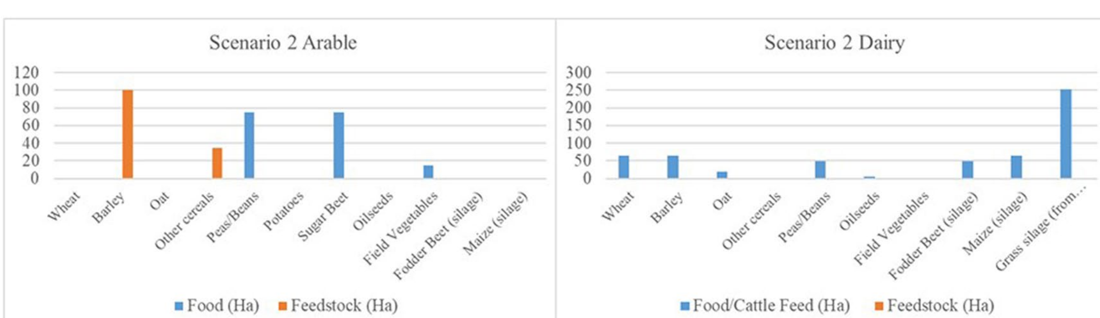

Figure 4. Cropping pattern under only AD (Scenario 2) for arable farm (left-side plot) and dairy farm (right-side plot).

3.2.2. Changes in land use under Scenario 2

Figure 4 (left-side plot) illustrates that in Scenario 2, the primary feedstock for the AD plant on the arable farm originates from 135 ha of harvested whole-crop cereals (barley and triticale). Additionally, the farm produces three other crops for commercial sale as food and livestock feed: peas and beans (75 ha), sugar beet (75 ha) and field vegetables (15) ha. Compared to the Baseline scenario output, this scenario prioritises feedstock production for the AD over food crops. It is interesting to note two key emerging points. Firstly, cereals are utilised as feedstocks despite the availability of alternative crops that yield more methane (see Table 6) since barley and triticale offer lower enterprise net margins. Secondly, unlike typical AD plant introductions on farms, this scenario excludes maize (silage), a common feedstock choice (Ackrill & Abdo, 2020). Although whole crop yields of barley, triticale and maize are similar (see Supplementary Material Table S3), maise offers a lower methane yield and, consequently, a lower net margin for AD. Regarding the dairy farm, for most crops, there is no change in area between the AD (Figure 4, right-side plot) and baseline scenarios (see Figure 2, right-hand plot). For example, the areas for wheat, barley, peas/beans, and maize (silage), among others, remain consistent. However, some crops change, such as oats and oilseeds, whose area reduces in the AD scenario (32.9 to 19.7 hectares and 13.8 to 5.3 hectares, respectively). In contrast, grass silage (from ley and permanent pasture) witnesses an increase, expanding from 232.0 hectares in the Baseline to 253.7 hectares once AD is added. These land-use changes do not result from introducing crops cultivated explicitly for the AD, as most feedstock is derived from livestock slurry rather than crop cultivation. Reducing land use for oats and oilseed areas allows for expanding the area utilised to produce grass ley, which is intended for silage production. This optimisation was likely made to increase the demand for N and P on the farm, in this manner facilitating the disposal of a digestate rich in N and P due to the primary use of slurry as feedstock (Jones & Salter, 2013).

3.2.3. Production input savings in scenario 2 for fertilisers

In Table 7, the results from Scenario 2 are compared with the baseline (Scenario 1) regarding savings in fertiliser purchases. The introduction of AD leads to savings in all nutrients: N, K and P. This reduction is primarily due to the cycling of digestate from cereal crops back onto the land (Ackrill & Abdo, 2020; Jones & Salter, 2013). Specifically, arable farms benefit under the 'AD' (Scenario 2) since N and K purchases decrease significantly by 69% and 62%, respectively. This reduction is attributed to the rich nutrient content present in whole-crop cereal (as shown in Table 6). In contrast, the dairy farm's nutrient dynamics under the 'AD' scenario differed. While there were no purchases of N and K in either the Baseline of 'AD' scenarios, P purchases surged by 56.6% and, therefore, increased from 3,380 kg in the Baseline to 7,795 kg under 'AD'. Dairy farms increased their P intake because slurries and manures have a high content of N and K but a low content of P (see Table 6). Consequently, while the demand for N and K can be satisfied, off-farm provision of P becomes necessary. This stark contrast highlights how the 'AD' scenario impacts nutrient purchasing behaviours differently between arable and dairy farms. Arable farms benefit from reduced N and K requirements, while dairy farms adapt to the unique nutrient composition of their waste materials.

Table 7. Whole-farm purchase of nutrients under the baseline and scenario 2 (AD).

	Arable farm			Dairy farm		
Nutrient	Baseline (kg)	AD (kg)	Change (%)	Baseline (kg)	AD (kg)	Change (%)
Nitrogen (N)	46,314	14,214	−69.3%	0	0	N.A.
Phosphorus (P)	16,534	14,795	−10.5%	3,380	7,795	56.6%
Potassium (K)	24,750	9,263	−62.6%	0	0	N.A.

Source: Own on base to LP output.

In this regard, the use of animal slurry and manure contributes to the recycling of organic waste and reduces the need for synthetic fertilisers (Bittman et al., 2005). Additionally, it can improve soil attributes and stimulate enzymatic activities, leading to improved soil health (Ferreira et al., 2021). However, there are also drawbacks to consider. One disadvantage is the inconsistent crop response to the broadcast application of slurry manure, which is attributed mainly to the volatilisation of ammonia (Bittman et al., 2005). Odour emissions from manure can also be offensive and a nuisance, and its application alone may pose a risk of lower crop yields compared to mineral fertilisers, as the release of nutrients from organic fertilisation is slower (Bittman et al., 2005; Hjorth et al., 2009). Also, the land application of slurries can impact nutrient and contaminant transfers to the aquatic environment (Glæsner et al., 2011). Then, proper slurry treatment and management practices are necessary to maximise the benefits and minimise the drawbacks.

The reductions in nutrient purchases, especially in the arable farm context, have economic and environmental implications. From an economic-financial standpoint, reduced nutrient purchases directly translate to savings for farmers, potentially enhancing the profitability and sustainability of their operations (Bhatta et al., 2021; Tsai, 2019). Environmentally, excessive use of nutrients, primarily N and P, has been linked to a range of ecological issues, including eutrophication of water bodies, loss of biodiversity, and greenhouse gas emissions (Dhandapani et al., 2021; Hautier et al., 2009). By reducing nutrient purchases, farms can play a pivotal role in mitigating these environmental challenges. Furthermore, the reduction in nutrient use can lead to positive externalities such as improved soil health, reduced groundwater contamination, and enhanced ecosystem services (Pieterse et al., 2005; Whitmore et al., 2012), which benefits not just the farmers but society at large.

3.3. Scenario 3: maximisation of farm net margin with AD+RAS

As introduced above, Scenario 3 considers introducing the two non-agricultural enterprises into arable and dairy farming systems. The LP optimisation model, therefore, is based on two distinct variants of Scenario 3 (see Figure 1). The results of the optimisation process are then compared to the baseline scenario. In these variants, we model the assumptions made in Scenario 2 about the AD plant. Still, RAS units (6 RAS units, Variant 3.1 and 12 RAS units, Variant 3.2) are added as new enterprises for both farming systems. In both variants, the AD size is modelled up to 500 kWh, representing a more significant size than the 304.6 kWh capacity in Scenario 2. As we discussed in the section 5.3.1 Below, we observe a higher land use to produce feedstocks to respond to the higher AD capacity as RAS, as new enterprises demand output from AD operations (e.g. electricity and heat).

Regarding the arable farm system, the inclusion of the AD plant alongside 6 and 12 RAS units for prawn production leads to an increase in the whole-farm Net Margin by 30% and 56%, respectively, in comparison with the baseline scenario (see Figure 5). This increase in whole-farm Net Margin is attributed to several factors: the sale of prawn meat, which amounts approximately 30 and 60 tonnes p.a. for 6 and 12 RAS units, respectively; the sale of exoskeleton chitin derived from shrimp waste; and the revenue generated from the sale of surplus electricity to the grid (AD unit supplying 30% and 60% of its output for electricity and heat consumption for 6 and 12 RAS units, respectively). Additional contributions include the sale of crops and the cost savings from reduced fertiliser purchases, as discussed below (see section 5.3.2).

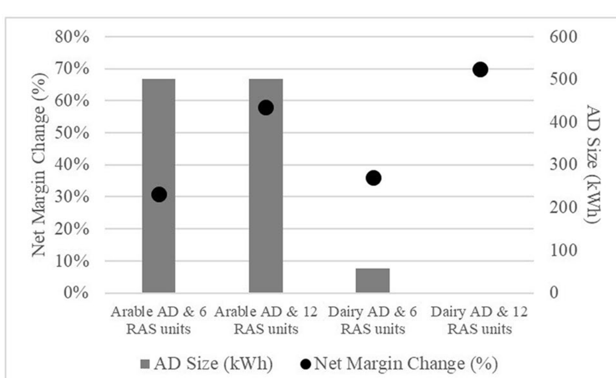

Figure 5. Whole-farm Net Margin change (%, dots – primary axis) and AD size (kWh, bars – secondary axis) for Scenario 3's variants (AD + 6 or 12 RAS units) compared to Baseline.

Significant changes were observed in the dairy farm's AD size and whole-farm net margin across the two variant scenarios. Firstly, in Scenario 2, the size of the AD plant is 140.25 kWh (see section 3.2). However, in Scenario 3 – Variant 1, when AD is combined with 6 RAS units, the optimisation procedure of the LP model results in a reduction of the capacity of the AD plant (see Figure 5). Specifically, the AD production capacity decreases substantially to 56.85 kWh. Remarkably, in Scenario 3 – Variant 2, when AD is combined with 12 RAS units, the whole-farm Net Margin will be maximised when the farm system is optimised, and the AD plant is eliminated. Regarding the whole farm's Net Margin, adding the AD results in a margin change of 4.7%. However, when AD is combined with 6 RAS units, there is a significant increase in the net margin, rising to 36.0%. With the inclusion of 12 RAS units and the removal of AD, the farm Net Margin surges even further to 70.4%. These results indicate that AD and RAS compete as enterprises when adopted by dairy farms, potentially leading to the reduction or replacement of AD.

The results for the dairy farm case can be justified in a context where RAS offers significantly higher revenues compared to AD. Thus, the LP optimisation prioritises the RAS over AD due to its higher contribution to the Farm Net Margin. Therefore, since farmers, in economic terms, are driven by profit maximisation, among other factors (Mzyece, 2021; Niemi, 2020; Tang et al., 2015), they will select investing in RAS over an AD plant. This could lead to the diversion of resources (e.g. financial, land use if there are land constraints) from AD to RAS. Also, operating agricultural and non-agricultural activities such as AD and RAS might make farm management more complex (Edwards et al., 2015; Egger et al., 2021). These non-agricultural enterprises require distinct skill sets, increased financial investment, and adherence to regulatory frameworks beyond farm activities. Also, farm managers must balance their time and resources between agricultural production and the demands of non-farm enterprises. Since RAS is more profitable, farmers might simplify by only focusing on RAS and removing AD.

Regarding RAS's profitability, as introduced, there might be a growing market demand for "*king prawn*" products following the establishment of RAS in the UK. Imported prawns and shrimp are the shellfish predominantly consumed in the UK (Boase et al., 2019), with imports of around 78 thousand tonnes in 2022, worth £665 million (Marine Management Organisation, 2023). If the market is willing to pay a premium for this UK-produced product, as suggested by past food-related studies reporting that UK consumers demonstrate a preference for locally sourced food due to higher quality, safety concerns compared with imports, the importance of supporting local farmers, among others, (Balcombe et al., 2021; Connors et al., 2022), it might be more rewarding for farmers to focus on RAS and decrease or substitute other less profitable farm activities.

3.3.1. Changes in land use under Scenario 3

As discussed above, the higher AD size in this scenario leads to changes in crop production to maximise efforts for sale (e.g. food, livestock feed) and feedstocks for AD. As a new enterprise, RAS does not demand crops (e.g. as a feed for prawns); instead, this enterprise demands electricity and heat from AD operations. Since upgrading from 6 to 12 RAS units does not significantly alter the cropping pattern, the impact on arable and dairy farms' land use pattern is only discussed for adding 6 RAS units and AD, i.e. Scenario 3 Variant 1.

In the case of the arable farm, when AD and 6 RAS units are jointly introduced in the model, as shown in Figure 6 (left-hand side plot), the feedstock for the AD unit is supplied by 100, 8 and 75 ha of wheat, barley and sugar beet, respectively. These crop areas represent an increase of approximately 50 ha of feedstocks for AD, compared to Scenario 2, where the AD size is estimated at 304.6 kWh. Thus, the cropping patterns prioritise electricity sales and electricity and heat provision for RAS. In this configuration for Scenario 3, 30% and 60% of AD output is allocated to meet the energy requirements of the 6 and 12 RAS units, respectively. Regarding the land use for non-AD crops, four crops are produced to supply the food chain and livestock feed: oats, peas and beans, potatoes and field-scale vegetables. Among them, peas and beans are the most prominent crops. They serve as break crops in the cereal's rotation. Additionally, as with most organic materials, their crop residues can be used as AD's feedstock (Redman, 2022).

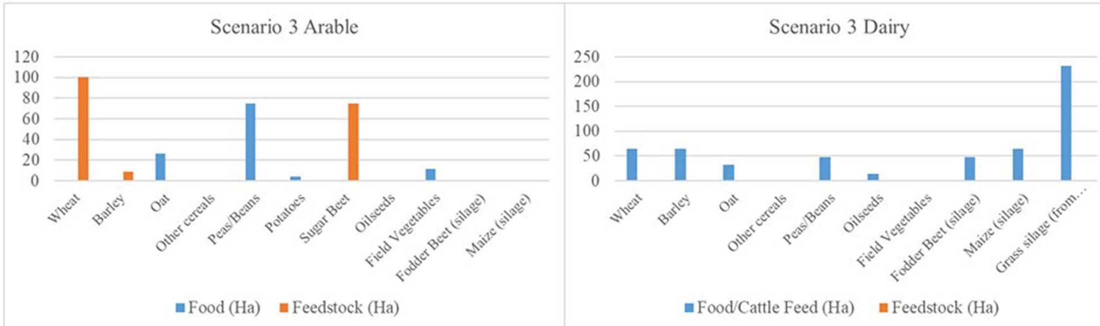

Figure 6. Cropping pattern under Scenario 3: AD + RAS (6 and 12 units) for the arable farm (left-side plot) and dairy farm (right-side plot).

3.3.2. Production input savings in scenario 3's variants for fertilisers

Table 8 shows nutrient purchases under Scenario 3 – Variants 1 and 2: AD plant combined with 6 or 12 RAS units for both the arable and the dairy farming systems. Significant changes are observed in purchases of fertilisers, including a 100% reduction in potassium (K). As mentioned above, these reductions can lead to substantial savings for farmers, enhancing the viability of their operations. To illustrate the suggested saving in fertiliser purchases, our results show a reduction of 24,750 kg of K. Following specialised guidelines such as Redman (2022), for wheat, 90 kg/ha of K is recommended. Therefore, with the reduction of K, we are saving fertiliser for 275 ha. With an estimated cost of £90/ha, the reduction of K suggests savings of over £24,000.

Table 8. Whole-farm purchase of nutrients under the baseline and scenario 3 – variants 1 and 2 (AD + RAS).

	Arable farm					Dairy farm				
Nutrients	Baseline (kg)	AD + RAS-6 units (kg)	Change (%)	AD + RAS-12 units (kg)	Change (%)	Baseline (kg)	AD + RAS-6 units (kg)	Change (%)	AD + RAS-12 units (kg)	Change (%)
Nitrogen (N)	46,314	8,294	−82%	7,862	−83%	0	0	N.A.	0	N.A.
Phosphorus (P)	16,534	12,119	−27%	11,728	−29%	3,380	3,380	0	3,380	0
Potassium (K)	24,750	0	−100%	0	−100%	0	0	N.A.	0	N.A.

Source: Own on base to LP output.

In the case of the dairy farming system, Table 8 results demonstrate no purchases in either the baseline or the two variants of Scenario 3 for N and K. P remained consistent at 3,380 kg across the Baseline and the two variants of Scenario 3. Hence, introducing the RAS enterprise, especially for the arable farm, further accentuates the reduction in nutrient purchases. Environmentally, the pronounced decrease, especially in nitrogen and the complete elimination of potassium, can significantly mitigate ecological issues such as eutrophication, loss of biodiversity, and greenhouse gas (GHG) emissions (Dhandapani et al., 2021; Hautier et al., 2009).

Combining AD + RAS has several environmental benefits, as discussed above. Nutrient recycling through AD includes reduced GHG emissions and improved water quality since replacing synthetic fertilisers leads to reducing nitrous oxide emissions, which are a potent GHG (Bittman et al., 2005). Additionally, AD reduces methane emissions by capturing biogas from organic waste, unlike traditional manure storage practices (Hjorth et al., 2009). These environmental benefits underscore the potential of AD and RAS to contribute to broader sustainability goals while enhancing farm profitability. Moreover, the AD and RAS systems deeply embed the circular economy principles (Yue et al., 2022). The AD process converts agricultural waste into biogas and digestate, the latter used as a nutrient-rich fertiliser, closing the loop on waste. The heat and energy generated by AD units power RAS, creating a synergistic relationship that maximises resource efficiency and minimises waste. This integration exemplifies the circular economy by turning potential waste into valuable inputs, fostering a sustainable and resilient agricultural system.

Beyond the economic results, the RAS adoption offers significant environmental advantages compared to conventional shrimp farming. Unlike open-pond systems, which often lead to mangrove deforestation, high nutrient discharge, and habitat degradation (Kauffman et al., 2018; Macusi et al., 2022), RAS operates as a closed, controlled system. This design drastically reduces water usage and prevents nutrient-rich effluents from entering surrounding ecosystems, thereby mitigating eutrophication risks (Lindholm-Lehto, 2023). Additionally, localised RAS production in the UK eliminates the need for long-distance seafood imports, lowering the carbon footprint associated with transportation. While our analysis focuses on nutrient recycling and local environmental outcomes, complementary studies show that RAS also plays a significant role in reducing global GHG emissions by avoiding carbon-intensive imports and mitigating leakage effects (Morello et al., 2025). These features highlight RAS as a technology that aligns with both environmental sustainability and the goals of circular economy frameworks, while avoiding the ecological drawbacks typically linked to traditional shrimp aquaculture.

3.4. Sensitivity analysis: impact of electricity price changes on farm net margins and AD size

We evaluate how sensitive our results are to changes in the assumed electricity price for 2022, i.e. £0.256/kWh. We analyse the impact of a 20% decrease and increase in electricity prices, £0.204/kWh and £0.307/kWh, respectively, on the farm Net Margins and AD size under scenarios involving AD and AD+RAS (see section 3.4.2 for details). Table 9 shows the results for the arable farm. A 20% decrease in electricity prices results in a modest increase in Net Margins. For instance, in the AD scenario, the percentage increase in net margin decreases from 24% (2022 prices) to 5% when a price reduction of 20% is considered. Under this reduced price, there is no deployment of AD, and the net margin is based on sales of crops such as wheat, beans, sugar beet, oilseeds, and field vegetables. In other words, AD is not commercially viable when, in addition to lower electricity prices, we observe high crop prices (e.g. cereals) as observed in 2022. Conversely, a 20% increase in electricity prices to £0.307/kWh enhances the Net Margin gains significantly, with increases of up to 74% under the AD + 12 RAS scenario, compared to 58% under 2022 prices. When RAS is adopted, the AD plant size remains optimal at 500 kWh across all electricity price scenarios, indicating that electricity price variations impact profitability rather than the scale of adoption.

Table 9. Impact of electricity price changes on farm net margin and AD size for arable farms.

	Scenario 2: AD			Scenario 3.1: AD + 6 RAS units			Scenario 3.2: AD + 12 RAS units		
Arable	£0.204	£0.256	£0.307	£0.204	£0.256	£0.307	£0.204	£0.256	£0.307
Farm net margin % change	5%	24%	54%	4%	31%	58%	43%	58%	74%
AD size (kWh)	0, No AD	500	418	500	500	500	500	500	500

For dairy farms, results from Table 10 shows that electricity price changes have less pronounced effects on Net Margins than on arable farms. Under the AD scenario, Net Margin changes range from 0% (prices equal to £0.204/kWh) to 10% (prices equal to £0.307/kWh). The Net Margin change remains relatively stable in the AD + 6 or 12 RAS units' scenarios, suggesting that RAS adoption provides resilience to electricity price fluctuations. Regarding the optimal size of the AD plant, it fluctuates in response to electricity price changes, decreasing to 56.85 kWh under lower prices and being omitted altogether when combined with 12 RAS units. As discussed above, these results show how the LP optimisation prioritises the RAS over AD due to its higher contribution to the Farm Net Margin. From a practical perspective, farmers facing financial and other constraints might favour RAS and remove AD due to higher profitability. In this regard, supportive energy policies to facilitate the adoption of sustainable farming diversification are needed, such as subsidies targeting operational costs or monetary support when electricity prices are lower (Smith et al., 2021). It is also important to highlight our assumptions underlying this analysis, such as constant feedstock costs and market conditions for prawn production. Future research should include simultaneous variations in other key factors (e.g. crop yield and prices).

Table 10. Impact of electricity price changes on farm net margin and AD size for dairy farms.

	Scenario 2: AD			Scenario 3.1: AD + 6 RAS units			Scenario 3.2: AD + 12 RAS units		
Dairy	£0.204	£0.256	£0.307	£0.204	£0.256	£0.307	£0.204	£0.256	£0.307
Farm net margin % change	0%	5%	10%	34%	36%	38%	70%	70%	71%
AD size (kWh)	57	140	140	57	57	140	0, No AD	0, No AD	57

3.5. Exploring the market's potential for UK-based prawn production, extended societal benefits, alternative diversification systems and practical challenges of AD + RAS

This section explores some additional dimensions of AD+RAS diversification, such as the potential for UK-based prawn production from a consumer acceptance and market potential perspective, potential societal impacts, and evaluation of alternative diversification systems. These dimensions contribute to a more holistic evaluation of integrating AD+RAS.

Regarding the potential market for UK-based prawns, the annual average of imported warm water prawns during 2010–2023 was 31,422 tonnes (Seafish, 2024). We can evaluate the market potential by assuming the imported volume as a proxy for the maximum quantity demanded of the fresh prawns produced by UK-based farms. To illustrate, let it be assumed that, in the initial stage of the diffusion of the system across the UK, production achieves a level of 10% of imports. This approximately 3,000 tonnes could be supplied by 60 farms adopting 12 units of RAS each, which is a promising start for a project based on sustainability, as some suggested that consumers are willing to pay a premium for seafood (Campos González and Gadanakis, 2025) that is perceived as fresh and of high quality, often linked to sustainability practices in fishing and aquaculture (Cantillo et al., 2021; Smetana et al., 2022).

Related to the potential social impacts of introducing RAS facilities being powered by AD, a desirable effect is the possibility that the facilities, being more profitable than other agricultural activities whose land requirement is more extensive, such as livestock grazing, would stimulate farmers to reduce the area allocated to such competing activities. This land use change is socially beneficial as it permits natural vegetation to return to the land parcels that are no longer used and grow, sequestering carbon and providing habitat for fauna, thus enhancing biodiversity, as argued in the introduction. Nevertheless, there are two contradictory and interrelated potential social impacts. On the one hand, farmers who adopt AD+RAS can become more profitable, given the increases in net margins discussed above, which helps them achieve greater well-being. On the other side, that would make profitability distribution more unequal. This undesirable consequence has been observed for other enterprises being adopted at the farm level in the UK, such as hire work, renting of farm buildings and forestry, since it has been suggested that adoption likelihood is strongly related to farm size and farmer education, among other aspects featuring high-profitability farms and farmers (Hopkins et al., 2017; McNally, 2001). Also, the demand for specialised labour and skills to maintain and operate AD and RAS systems (see footnote 8) contributes to improved agricultural productivity and efficiency. For example, the presence of skilled labour facilitates the adoption of modern farm technologies and practices, which are essential for sustainable farming and environmental stewardship (Jara-Rojas et al., 2020; Pérez-Silva & Campos-González, 2021).

Related to competitive and alternative diversification strategies compared to AD+RAS regarding profitability, sustainability and risk, forestry seems a good example, as it requires a similar set of resources, i.e. land, labour and water. Moreover, it has been incentivised by key policies in the UK, such as the Net-Zero strategy (Climate Change Committee, 2020). Based on published estimates, conifer forestry has a net present value of approximately £6,000/ha after accounting for cost-covering grants and carbon sequestration payments, including timber revenue (Redman, 2022, pp. 110–119). This forestry value falls in the profitability range of six to 12 RAS units powered by AD when we compute a revenue per ha considering our arable farm compounds of 300 ha. Furthermore, both systems could be sustainable and comparable since AD+RAS, by increasing the profitability and productivity of land usage, would reduce the land area occupied by agriculture, opening space for forestry and thus increasing carbon sequestration and enhancing biodiversity. Regarding associated risks, one of them is the price of prawns. From the perspective of the whole economy, RAS-based domestic prawn production is not subject to volatility from international currencies and overseas freight, an advantage compared with imported prawns. However, the import trends have not shown an increasing demand for prawns in recent years (Marine Management Organisation, 2023; Seafish, 2024). In synthesis, a RAS+AD system is comparable to forestry, one of the main diversification alternatives incentivised by the UK, in terms of profitability and sustainability. Still, it may be, from farmers' perspective, riskier than forestry and agriculture, given the stagnation in demand for prawns. Further studies should address the land use change discussed, focusing on impacts on food and feed production and the demand aspects of UK consumers.

3.6. Barriers to scaling up AD and RAS & policy issues

Transitioning to RAS presents practical challenges for farmers. As mentioned above, the operation of RAS requires specialised knowledge in aquaculture, including water quality management, waste handling, and prawn husbandry. These activities often necessitate additional equipment and training, which can be a barrier to adoption. Conversely, AD is more familiar to many farmers, particularly those already managing organic waste streams like manure. Economically, while RAS offers higher revenue potential due to premium products like prawns, the higher capital and operational costs pose significant trade-offs compared to AD (see sections 3.3.2 and 3.4.1 for AD and RAS, respectively). For example, RAS typically requires modular infrastructure and ongoing energy input. In contrast, AD leverages existing waste streams like slurries and manures for energy production, particularly in dairy farms, offsetting some costs. Ultimately, farmers' decisions will depend on factors such as access to training, market opportunities for RAS products, and the relative importance of energy self-sufficiency versus revenue diversification (Hopkins et al., 2017; Iakovidis et al., 2024; McNally, 2001).

Another consideration is the barriers to scaling up AD and RAS systems at the farm level that extend beyond access to capital, regulatory, and policy support. As was highlighted, high upfront costs, limited access to affordable finance, and uncertain long-term economic returns deter investment in both technologies. Technical barriers include the complexity of AD and RAS systems, feedstock supply issues for AD (Röder, 2016; Tranter et al., 2011), and energy-intensive operations and water management challenges for RAS (Badiola et al., 2012). Social barriers include resistance to change (Rose & Chilvers, 2018), lack of technical expertise, and uncertainty around market demand for outputs like biogas and sustainably farmed fish. Infrastructure gaps, such as inadequate waste management systems for AD and supply chains for RAS, coupled with competition for resources, further limit scalability (O'Connor et al., 2021; Zhang et al., 2024). Addressing these challenges requires targeted financial incentives, enhanced technical support, streamlined regulations, and infrastructure development to unlock the potential of these sustainable technologies.

From a policy perspective, the feasibility and successful adoption of AD and RAS systems in the UK are heavily influenced by agricultural and energy schemes that support farmers in addressing challenges such as high initial capital costs and limited access to finance. Current renewable energy support, such as the Green Gas Support Scheme (GGSS), is designed to provide financial incentives for establishing new AD biomethane plants to increase the proportion of green gas in the gas grid. The Department for Energy Security and Net Zero is responsible for designing support policies and promoting and tailoring these to the needs of the UK (Department for Energy Security and Net Zero, 2023). Related to a policy targeting smaller-scale or on-farm AD systems in food production, it needs essential adjustments to ensure that eligibility criteria and requirements include the diverse range of farming systems across the country. Towards this direction, policies aiming to deliver a reduction in the carbon emissions of the agricultural sector is the "Development of more sustainable protein sources for human diets" (Department for Energy and Net Zero, 2023) that is supporting the development of production units for sustainable proteins. Thus, creating innovations and diversified systems that integrate AD and RAS may offer environmental benefits through low emissions intensity associated with production. These savings could be derived via a shift in the agricultural sector in response to market drivers, and hence respond to the demand for prawns in the UK market. In addition, although at the moment, there is no specific policy that could be used to support the adoption of RAS systems, support could be provided under initiatives that target monitoring of emissions from wastewater treatment, as these are presented in the Carbon Budget Delivery Plan (Department for Energy Security and Net Zero, 2023).

It is important that future policies aiming at supporting the development and adoption of AD plants at the farm level will require simplifying financial incentives for smaller projects, enabling carbon credit monetisation, and investing in biogas infrastructure to enhance economic viability. Policy insights from Morello et al. (2025) further suggest that financial incentives, including lower loan interest rates, could improve the adoption of RAS, aligning with our findings on economic viability and risk mitigation. The capital intensity of RAS investment requires support in the form of capital grants, R&D for efficiency improvements, and regulatory streamlining. In addition, an integrated policy framework and knowledge-sharing network to promote synergies and adoption at the farm level could reduce barriers and promote the diversification of sustainable energy production and alternative proteins. Addressing these gaps can enable UK policies to foster a more supportive environment for AD and RAS, encouraging their wider adoption of sustainable agriculture and aquaculture practices.

3.7. Limitations and future research

A first limitation focuses on LP issues and estimating potential long-run impacts of market or climate-related factors. We acknowledge that LP techniques provide valuable insights into the economic viability of AD and RAS integration, but it has certain limitations. The model assumes static prices for inputs and outputs, which may not capture the volatility of energy markets or fluctuations in commodity prices. Although we have added a sensitivity analysis to analyse the impact of electricity price changes on profitability, the model does not consider the potential impacts of future climate variability on crop yields or energy demand. These factors could influence the financial performance of the modelled systems. They should be addressed in future research by incorporating stochastic modelling or similar techniques that could provide a more comprehensive understanding of risks and uncertainties.

In addition, future modelling of the integration of AD and RAS systems within agricultural production systems will also need to address long-term considerations related to factors influencing yield, productivity and efficiency of both systems. Climate change may change the way crop yields and develop, as well as energy demand (Gornall et al., 2010), influencing AD and RAS economic viability. Moreover, the Natural Environment Valuation Online tool – NEVO (Day et al., 2020) could be tailored in an effort to evaluate the environmental impacts, including water use, greenhouse gas emissions, and other ecological indicators. Technological advancements could improve resource use efficiency, lower operational costs, and address barriers like high capital intensity and energy demands (Rushchitskaya et al., 2024). Future research could, therefore, adopt a dynamic modelling approach to assess uncertainties and integrate spatial analyses to identify optimal farm locations for these systems.

4. Conclusion

Our results evaluating the integration of AD and RAS within UK farming systems suggest financial, economic and environmental potential. This study employed LP optimisation to model the profitability of AD and RAS technologies, showing that combining a 500 kW AD unit with 6 or 12 RAS units for king-prawn production can enhance the whole-farm Net Margin by 30% to 56% compared to traditional farming practices on medium and large arable farms in the UK based on 2022 production and output costs. The feedstock for the AD comes primarily from harvested whole-crop cereals. Furthermore, the introduction of AD and RAS results in savings in all nutrients due to the cycling of digestate from crops back onto the land. For large dairy farms, including 12 RAS units and AD removal, the farm Net Margin surges even further to 70.4%. This diversification strategy improves farm profitability and reduces reliance on external inputs, promoting a more sustainable and resilient agricultural system.

Authors' contributions

CRediT: **Jorge Campos González**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Writing – original draft, Writing – review & editing; **Yiorgos Gadanakis**:

Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review & editing; **Trystan Sanders**: Investigation, Writing – review & editing; **Thiago Fonseca Morello**: Investigation, Writing – review & editing; **Mattia Mancini**: Conceptualization, Investigation, Writing – review & editing; **Ian Bateman**: Funding acquisition, Investigation, Writing – review & editing.

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Data availability statement

The data that support the findings of this study are available from the corresponding author, Jorge Campos Gonzalez, email: jorge.camposgonzalez@reading.ac.uk, upon reasonable request.

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