REVIEW: Opportunities and challenges for the pork industry from circular livestock waste management systems

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Abstract

Slurry management is becoming increasingly important as countries work to decarbonise towards Net Zero goals. After feed, slurry management and application is one of the main contributors to the greenhouse gas emissions and environmental pollution associated with pork production. Whilst traditionally considered a waste product, slurry is rich in nutrients, and could be harnessed to reduce environmental impacts and improve on-farm resilience. Along with reducing environmental impacts of pork production, farmers are increasingly looking to diversify their income streams and pig slurry offers tremendous potential to achieve this. This review identifies the opportunities and challenges to the pork sector from circular, sustainable waste management systems through insect bioconversion or on-farm biogas production, with a focus on the United Kingdom. Insect bioconversion of pig slurry, through the use of Black Soldier Fly larvae, presents opportunities not only to reduce the overall volume of slurry on a farm, but also to reduce heavy metal contamination, alter the microbiome and provide a myriad of additional products. These products include fertiliser in the form of insect frass, protein, oils, and chitin from the insect exoskeleton, which has applications in industries such as wastewater treatment, pharmaceuticals and healthcare. Through on-farm biogas generation, farmers, particularly those in rural areas, could reduce their reliance upon volatile energy prices and generate electricity and heat to power on-farm activities. With additional infrastructure, biogas could be upgraded to produce biofuel and CO_2 could be recovered, recycled, and sold into a variety of industries. Whilst there are still a number of outstanding questions that need to be answered and challenges that need to be addressed before wide-scale rollout of these technologies, there is huge potential to harness the power of pig slurry. When designing the farm of the future, solutions will likely need to be tailored to an individual farm due to a range of variables including the stage of production, the number of pigs, the pig diet and the availability of co-products. However, despite these potential challenges, there is still considerable opportunity for the pork sector to harness this 'waste' product to decarbonise pig production and improve farm resilience.

Key words: Insect Bioconversion, Biogas, Black Soldier Fly Larvae, Pig Slurry, Sustainable

Implications

There is growing pressure to decarbonise agriculture to meet Net Zero targets. After feed, most greenhouse gas emissions from pig production are primarily associated with slurry management and spreading. Bioconversion by insects or the generation of biogas from pig slurry provide viable options to reduce emissions and eutrophication, improve crop growth and generate additional income within the farm-gate. Whilst there are still unanswered questions around the safety of rearing Black Soldier Fly larvae on pig slurry and the feasibility of wide-scale, on-farm energy generation, the valorisation of waste holds tremendous potential to provide resilience and diversification to the pork sector.

Introduction

Agriculture faces the challenge of producing enough nutritious, safe and affordable food to feed the growing world population whilst at the same time reducing the environmental impact and exploitation of natural resources associated with its production. Global demand for pork has led to rapid growth in its production by approximately 4.5 times between 1961 and 2021, from 24.8 to 109.2 million metric tons, representing approximately 33% of global meat production (Ndue and Pál, 2022). Estimates suggest that demand for meat will continue towards 2050 and beyond, but this will vary by commodity and country (Henchion et al., 2021; Komarek et al., 2021). Whilst meeting the global demand for food, it is essential that farming systems are sustainable and reduce emissions as low as possible if countries are to meet the legally binding targets set out in the 2015 Paris Agreement (UNFCCC, 2018).

There is global pressure to decarbonise agriculture with livestock production estimated to be responsible for 8-14.5% of global greenhouse gas emissions (**GHGs**) depending upon the method of calculation used (Caro et al., 2014; Gerber et al., 2013; O’ Mara, 2011). Pig production contributes significantly less GHGs to the atmosphere than ruminant production (i.e. cattle, sheep, etc.) due to the inherent differences in the physiology of the animals. Whilst the majority of GHGs associated with pig production are attributable to feed at 31-76% (Andretta et al., 2021; Groen et al., 2016), this is followed by manure management (Lesschen et al., 2011). There is also concern around the impact of pig production on both water and air quality (Costantini et al., 2020; Li, et al., 2022). Concerns around pig production include eutrophication of nutrients into waterways, acidification of soils and reduced air quality due to NH_3, as well as emission of gasses such as CH_4, CO_2 and N_2O. These concerns are largely associated with the storage, handling and spreading of slurry. There is considerable opportunity to improve the utilisation of slurry on farm, to reduce environmental impact and to generate alternative income streams for farmers.

Overview of waste production

For centuries, animal slurries and manures have been used as an amendment to soil in place of, or alongside the use of inorganic fertiliser. The British Survey of Fertiliser Practice 2022, (DEFRA, 2022), estimated that approximately 67% of farms applied organic manures (e.g. manure, slurry or farmyard manure) to at least one field on their farm and it has been estimated that in the United Kingdom (**UK**), approximately 83 million tonnes of livestock manure is produced each year (Smith and Williams, 2016). The quality and quantity of animal waste produced will vary depending upon multiple factors including the type, age, diet and breed of the animal reared (Antezana et al., 2016; Van Horn, 1998).

Waste from livestock, such as pig slurry, is rich in nitrogen and phosphorous as well as other macro and micronutrients, which provide essential nutrients to soils and growing crops. However, despite otherwise sound environmental practices, the concentration of constituents such as N (in the form of nitrate, NO_3^-) and P can be in excess of the requirements for the soil and crops where slurry is spread, which may result in leeching or run-off into waterways, causing eutrophication of water sources. For example, in the UK, the failure of 31% of waters to achieve good water quality status has been associated with poor management of agricultural and rural land (Environment Agency, 2018). Animal wastes may also cause soil contamination due to the presence of heavy metals and pathogens, the concentration of which vary with animal species and management practices. Pig slurry, for example, has been shown to contain a 2-fold higher concentration of both zinc and copper when compared with cattle (Jakubus et al., 2013), although these numbers are likely to have declined since the removal of zinc oxide from nursery diets in the EU from 2022.

In intensive pig production with slatted floors, slurry is typically held in pits under the animals and then pumped, or gravity fed into a storage tank where it is held until required. During storage, microbes present in the slurry continue to ferment the organic material present. This, alongside the mixing of urine and faeces, results in the formation and release of CH_4, CO_2, N_2O and NH_3. The release of these gasses into the atmosphere results in pollution and odour and a high concentration of NH_3 in pig buildings, for example, could have negative health implications for both pigs (Witt et al., 2024; Zhang et al., 2021) and farm workers (discussed in Conti et al. (2021)). Whilst farms manage in-room emissions through ventilation (either natural or mechanical), this can be a challenge in colder months when also trying to maintain room temperatures. Improving management of slurry is therefore essential for reducing the environmental impact of pig production.

Along with reducing environmental impact of pig production to reach Net Zero goals, diversification of income streams is becoming increasingly important for farms. Changes to slurry management present an opportunity to reduce an individual farm's environmental footprint, reduce emissions and improve profitability and resilience. Whilst slurry is often considered a waste product from pig production, there is scope to capture and valorise the nutrient content that remains. This review will consider the opportunities and challenges for on-farm valorisation of slurry from pig production within a sustainable, circular farming system. Here we will discuss the bioconversion of slurry with insects as well as on-farm biogas production.

Insect bioconversion

Bioconversion of pig slurry

Pig slurry is rich in organic matter and contains macronutrients such as nitrogen (5.8% of DM) and phosphorous (3.4% of DM) as well as micronutrients including iron (1871 mg/kg), copper (416 mg/kg) and zinc (1806 mg/kg), despite a relatively high water content (DM content averaging 5.7%) (Fernández-Labrada et al., 2023), though this will vary between farms and pig type (Yagüe et al., 2012). Whilst application to land as a fertiliser is well established, the nutritive value of pig slurry makes it a potential feedstock for insect bioconversion. During the bioconversion process, insect larvae consume the substrate to produce insect protein and oils, chitosan and frass (insect excretions and moulted exoskeletons). Diverting slurry through a bioconversion process prior to land application can generate additional high-value products on farm (see Section: Bioconversion Diversification Streams) whilst still producing a viable fertiliser albeit with a much lower water content (40-90% DM; Gärttling and Schulz (2022)). Additionally, due to the relatively short rearing period of insect larvae on animal wastes (approx. 20 days; (Rehman et al., 2019)), the rapid turnover of slurry would reduce the harmful emissions associated with prolonged storage.

Whilst a number of insect species have been explored for their potential in insect farming systems, this review will focus on the Black Soldier Fly (*Hermetia illucens*).

An introduction to Black Soldier Fly larvae

The Black Soldier Fly (**BSF**), *Hermetia illucens*, originates from the Americas (Sheppard,. et al., 1994), and is a non-pest, generalist feeder (Rindhe et al., 2019; Taufek et al., 2024). Females preferentially lay eggs in dry areas around decomposing organic matter (Booth and Sheppard, 1984), and the larvae undergo six instar stages before entering the prepupal stage (De Smet et al., 2018). Prepupae cease eating and migrate from the substrate to pupate (Georgescu et al., 2020). Adults do not need to feed and mate just once during their lifetime (Singh and Kumari, 2019). As such, the larval feeding stage (**BSFL**) is crucial for the insects' growth and energy storage. Crucial to larval growth is the main site of digestion, the midgut (Eke et al., 2023), which consists of three main sections, namely the anterior, middle and posterior midgut, that differ in morphology and pH (Bonelli et al., 2019). The midgut also displays morphological changes related to the type of substrate the larvae is feeding on, including changes to microvilli to aid absorption, as well as alterations in enzymatic activity (Bonelli et al., 2020). This is particularly significant given the generalist feeding ability of these larvae. Feeding efficiency of BSFL is dependent on a number of factors, including type (Liu et al., 2018) and moisture content of substrate (Cheng et al., 2017), rearing temperature (Sheppard et al., 2002) and fly strain (Zhou et al., 2013). The ability of larvae to survive and feed on different substrates, some of which will have high microbial loads, which could include pathogenic bacteria, is partially influenced by their immune system, including the production of antimicrobial peptides (Moretta et al., 2020) and through competition with their own microbiota (Shi et al., 2024).

Indeed, the microbiome of BSFL is critical to their successful bioconversion of substrates. Black Soldier Fly show high enzymatic activity in the gut, including lipase and proteases (Kim, W. et al., 2011), but are also able to digest tough fibres such as lignocellulose (Kariuki et al., 2023) and cellulose (Zhang, Jia et al., 2023) via the action of the microbiota; the composition of which is also largely affected by substrate type (Auger et al., 2023). As a result of these combined factors, BSFL can be reared on a large variety of substrates, including food waste (Cheng et al., 2017), livestock manure

(Zhou et al., 2013) and wastewater (Grossule et al., 2023), and this has given them an important status within the insect farming sector.

Black Soldier Fly larvae conversion of pig slurry

Black Soldier Fly larvae can be reared on a number of different livestock wastes including pig slurry (Miranda et al., 2020). Studies generally report that larval survivorship on pig slurry is high (for example, in the range of 70-97%) (Miranda et al., 2019; Miranda et al., 2020; Oonincx et al., 2015), and developmental times are often found to be shorter than those reared on dairy manure (Miranda et al., 2020; Oonincx et al., 2015), though this is not always the case (Miranda et al., 2019). Newton et al. (2005) found that mass of pig slurry can be reduced by BSFL by up to 56%, though in another study, dry matter reduction was lower at 37% (Oonincx et al., 2015). Other studies have also reported different waste reduction values (Miranda et al., 2019; Zhou et al., 2013). Thus, there are differences in dry matter bioconversion efficiencies between studies, for example an efficiency of 12.5% was found by Parodi et al. (2021), whilst 4.5% was observed by Oonincx et al., (2015).

Many properties of the slurry, such as nitrogen levels (Oonincx et al., 2015), moisture content (Cheng et al., 2017), and even the stage of production that the slurry was collected from (Hao et al., 2023b), can affect the bioconversion efficiencies of the larvae (Miranda et al., 2019; Oonincx et al., 2015). Fly strain has also been found to have an effect (Zhou et al., 2013), and the microbiota is also critical (Zhang, Jia et al., 2023). As a result, values reported in the literature can be variable. However, a number of studies have found bioconversion of pig slurry by BSFL can be successfully attained, and this has resulted in an increasing interest in this area in recent years, with a range of factors involved in this process, being investigated (**Table 1**).

Bioconversion diversification streams

Fertiliser

The process of insect bioconversion of pig slurry results in a number of products, which offer a variety of diversification streams on an individual farm (Figure 1). These products include a low-moisture content fertiliser, high value proteins, oils, and other insect products such as chitin, which has the potential for a myriad of downstream applications across a variety of different industries.

Fertilisers are used to provide crops with essential nutrients such as nitrogen and phosphorus, in order to stabilise and increase yields. The frass that is produced from insect bioconversion of livestock waste has potential as a fertiliser (Lomonaco et al., 2024). For example, bio-stimulating substances present in the frass, such as humic acid, amino acids and chitin, could be beneficial for crop growth (Abd Manan et al., 2024). Whilst, the availability of nitrogen and soluble phosphorus, combined with a reduction in heavy metals, also increases its potential for fertiliser use (Amorim et al., 2024). Ammonia content of BSF frass can be lower than other manures (Abd Manan et al., 2024).

In addition, aromatic structures that increase the stability of organic matter (He et al., 2011), can be increased in animal manure by the addition of BSFL (Wang, et al., 2021). In one study, the uptake of nitrogen was increased in plants treated with frass compared to those treated with commercial fertiliser (Beesigamukama et al., 2020). Frass could also provide beneficial microbes that could positively impact on plant growth, for example, BSFL residues can shift soil microbial communities more so than the addition of conventional composts, subsequently affecting plant yields (Fuhrmann et al., 2022). In general, the high dry and organic matter content of frass, the alkaline pH values and micronutrients are often within the range of commercial fertilisers (Gärttling and Schulz, 2022). Therefore, the use of frass could reduce reliance on other fertilisers as part of a circular agricultural system. As frass is usually a much drier substance than pig slurry, there may be reduced emissions associated with transport on farm due to the weight reduction in water content. The market size of frass has been valued at $96.12 million in 2023, and is predicted to grow to 135.88 million by 2030, with North America and Europe holding the greatest shares (VMR, 2023). Challenges include changing reliance on chemical fertilizers, scaling-up, and differences in regulations between countries (VMR, 2023).

Chitin and chitosan

The frass produced by BSFL bioconversion of waste is rich in the biopolymer, chitin, which is a significant component of insect exoskeletons and is shed during moulting (Soetemans et al., 2020). Much of the current developments around chitin production centre around its collection from crustacean waste (Amiri et al., 2022). With the global market of chitin and its derivatives valued at $5.01 billion, and projected to reach $13.12 billion by 2031 (VMR, 2024), insect farming could be another option for its production. Black Soldier Fly larvae contain around 8% chitin, with prepupae containing 11%, and frass typically having higher quantities due to the presence of shed exoskeletons (Soetemans et al., 2020). Chitin/chitosan extraction is established for aquaculture and can be used to estimate projected costs for insect farming, for example, production of 1kg of chitosan from shrimps, for a plant in Ecuador costs $8.39 (Riofrio et al., 2021), £10.5-12 in Colombia (Gómez-Ríos et al., 2017) and $14 in Spain (Moreno de la Cruz, 2019).

There are multiple potential downstream uses for chitin, and its derivatives, that offer diversification of income for the pig industry. Chitin can be integrated into biodegradable packaging material (Le et al., 2023), but can also be deacetylated into the copolymer chitosan. Chitosan has been shown to have antimicrobial properties (Guarnieri et al., 2022), to bind contaminants such as mercury, making it a possibility for wastewater purification (Bhatnagar and Sillanpää, 2009), and to be a target for biomedical products, owing to its chemical properties (Triunfo et al., 2022). Indeed, chitosan has applications in the pharmaceutical, cosmetics and textile industries (Morin-Crini et al., 2019; Rehman et al., 2023). There are even potential benefits for reducing crop pathogens and promoting plant growth (Morin-Crini et al., 2019; Sharp, 2013), with chitosan shown to influence defence gene expression, pathogen resistance enzymes and reactive oxygen species production in plants (Torres-Rodriguez et al., 2021). The wealth of opportunities for chitin/chitosan usage suggests that it could be a commercially viable by-product from agricultural systems using insects for waste reduction.

Protein

Demand for animal feed is increasing with the global growing human population, and there is a rising need to establish economically viable, sustainable systems to cope with this demand (Barragan-Fonseca et al., 2017). Insect protein could reduce the reliance on soya imports (Wilkinson and Young, 2020) which are often associated with land use change and GHGs associated with their importation. Insect protein can be used as an alternative in animal feed, and as of 2017, insects fed on plant-based substrates have been permitted for use as feed for aquaculture, poultry and pig feed in the European Union (**EU**; EU 2017/893 and EU 2021/1372) (EU, 2021). The UK, however, retains greater restrictions on using insect protein in livestock feed of animals reared for human consumption (Tiwasing and Pate, 2024).

Black Soldier Fly Larvae contain high amounts of amino acids (Crosbie et al., 2020) and fatty acids, especially lauric acid (Danieli et al., 2019; Ewald et al., 2020), as well as vitamins such as thiamin (B_1) and vitamin C (Zulkifli et al., 2022), and minerals such as phosphorus and calcium (Chia et al., 2020; Makkar et al., 2014), strengthening its potential as an animal feed source. Replacement of fish meal in pig diets with BSFL has been shown to increase body weight, with faster weight gain in finisher pigs (Chia et al., 2021), and addition of BSF oil to the diet can increase daily gain of nursery pigs (van Heugten et al., 2022), and support growth without negative effects on gut morphology (Crosbie et al., 2021).

However, the substrate that BSFL are reared on has a large effect on their nutritional composition (Barragan-Fonseca et al., 2017; Ewald et al., 2020). As such, depending on the consistency and availability of the substrate, larvae may vary in their specific nutrient composition and digestibility, and studies suggest that it may be more useful to add BSFL as partial replacement for other sources of protein in the pig diet (as reviewed by Barragan-Fonseca et al. (2017) (see also Table 2 for examples of nutritional content of larvae reared on pig slurry). It is important to note, that there is additional work needed to determine whether larvae meet international standards around the heavy metal, pathogen, parasite and antimicrobial resistance levels found in BSFL reared on pig slurry. For example, the reported heavy metal content of larvae reared on slurry varies between studies, and there is a lack of consistency in the specific metals that are analysed (Table 3). Additionally, determination of the fate of pharmaceutical and chemical residues that may be present in the pig slurry is required before this protein stream can be unlocked.

Oils

Oils extracted from BSFL are high in fatty acids, such as lauric, oleic, linoleic and palmitic acids, omega-3 and omega-6, and show high antioxidant activity (Muangrat and Pannasai, 2024). Studies have shown that these oils can be used in aquaculture feeds (Li et al., 2016) and for poultry (Kim et al., 2020). For example, replacing soybean oil with BSFL oil in turkey diets was found to increase amylase activity, and reduce *Bacteroides-Prevotella* growth in the cecum (Kierończyk et al., 2022). BSFL oil also has potential applications in human skincare where it has been shown to inhibit growth in human keratinocyte cells, an important factor in psoriasis (Muangrat and Pannasai, 2024). In mice, BSFL oil has been shown to produce an anti-inflammatory response (Richter et al., 2023). There is an additional application for BSFL oil in the health care sector, where it has been shown to accelerate wound healing (Rahayu et al., 2024).

Furthermore, larvae oil can be used to produce biodiesel (Mohan et al., 2023). The addition of BSFL oil to diesel has been shown to lower smoke emissions and fuel consumption (Rehman et al., 2018). The generation of biodiesel from larvae can produce fuel that meets the standards of a number of countries, and can use less energy than other biodiesel-producing systems (as reviewed in Mohan et al. (2023)). Biodiesel from BSFL fat has been shown to have similar properties to biodiesel from rapeseed oil, as well as higher saturated fatty acid methyl esters which may confer oxidative stability (Li et al., 2011), and has potentially reduced climate change effects compared to rapeseed and soybean oil, however, pre-treatment steps and chemical usage contribute to its overall impact (Liew et al., 2023).

Current challenges for implementation

Whilst BSFL demonstrate huge potential as a method to valorise pig slurry, there are a number of potential challenges and current unknowns that need to be resolved before large-scale implementation can begin. A list of these potential challenges is shown in Table 4 along with opportunities for future research. One of the main areas of concern for rearing BSFL on pig slurry is on the safety of the products produced and this raises questions about their downstream applications. For example, there is some evidence to suggest that BSFL are able to bio-accumulate heavy metals present in pig slurry (Diener et al. 2015). Heavy metals may be naturally occurring in livestock feed ingredients or may be added as supplements to enhance the health and growth performance of the animals (Nicholson et al., 2006). Pig slurry has been found to contain high levels of zinc and copper (Provolo et al., 2018), and contributes to heavy metal input to agricultural soils (Nicholson et al., 2006). Long-term use can result in copper accumulation that could be toxic to crops (Drescher et al., 2022). Utilising BSFL to valorise animal wastes could result in heavy metal bioaccumulation in the larvae or they may excrete these metals into the substrate (Jiang et al., 2022). Studies have found that the amount of bioaccumulation differs between metals, for example Diener et al. (2015) found an accumulation of cadmium, but not zinc or lead, and larval feeding substrate has also been shown to affect this (Biancarosa et al., 2018; Elechi et al., 2021). Further, Jiang et al. (2022) showed that cadmium, copper, chromium and zinc were removed from pig slurry that had been bio-converted by insects. Hoffmans et al., (2024) detected heavy metals, such as manganese, arsenic and lead in the frass of larvae reared on pig waste, and noted although frass can be used in the EU as a fertilizer if heated to 70° C for 1 hour (amendment Regulation (EU) 2021/1925) in order to control pathogens, the regulation does not set limits for metal concentrations in the frass.

An additional concern is around the presence of pathogens. Slurry contains a rich microbiota excreted from the pig which may include pathogenic species, or species which have the potential to be pathogenic, found as commensal members of the pig microbiome. For example, genera such as *Escherichia coli, Campylobacter, Salmonella and Staphylococcus* are all commonly observed in pig gut samples (Adekolurejo et al., 2023; Sutton et al., 2021). Although there are limited studies to date, there is evidence to show that pig slurry that has been bio-converted by insect larvae shows decreased levels of bacteria such as *Salmonella* and *Staphylococcus aureus* (Elhag et al., 2022; Lalander et al., 2015; Zhang et al., 2022). It is currently unclear, however, what microorganisms are present and viable in the larvae themselves as well as the frass produced and what impact (if any) this may have on, for example, insect growth or soil communities.

Finally, an important consideration are the costs involved in construction and running of insect farms. A joint World Wildlife Fund and Tesco report estimated that for a medium-sized insect farm, it would require about £10m in construction costs, with approximate operational costs in the first year of £2.5 million, with the report also suggesting the potential for 237,000 tonnes of insect protein to be produced by 2050 in the UK (World Wildlife Fund and Tesco, 2021). The cost of production of larvae was estimated at £540 per tonne by 2030, with insect oil sales valued at £586-655 per tonne and frass at £5 per tonne (World Wildlife Fund and Tesco, 2021). In recent years, there have been some insect farming businesses that have stopped production or are struggling to be profitable (Shah, 2024), and more research on cost-effectiveness and scaling is required (Madau et al., 2020). Sales of larvae may start from around $400 per tonne, but prices depend on location and market, which need to be balanced by operational costs such as those for energy generation, water and feedstocks (for non-circular systems) (Niyonsaba et al., 2021).

Bioenergy production

On-farm energy generation of biogas from pig slurry

An alternative route to valorise pig slurry comes through the generation of energy on farm, in the form of biogas. Biogas is a renewable energy resource that has an important role to play in the green energy transition (Rafiee et al., 2021). Biogas is generated from the breakdown of biological material, (“feedstocks”), such as animal manures under anaerobic conditions to produce CH_4, CO_2 and other trace gasses. Biogas can be used to generate commodities such as electricity, heat and fuel. By using waste from animal production as a feedstock for biogas production alongside, or in place of crops, this can reduce competition for land through demand for growth of cash crops (Gaworski et al., 2017) and allow crop residues to remain on, or be ploughed into the soil.

The generation of biogas from pig slurry can reduce the amount of methane that enters the atmosphere and reduce a farm’ s reliance upon fossil fuels. Other benefits include a reduction in odour, reduced contamination of groundwater through runoff, improved air quality (Nagy et al., 2012) and the generation of digestate, which can be harnessed as a bio-fertiliser (Monard et al., 2020).

The use of animal waste for the generation of biogas is a cost-effective method to reduce GHGs and re-capture nutrients required for plant growth. Studies have shown that biogas generation from pig slurry produced biogas ranging in methane content from 32.4 to 68% (Luján-Facundo et al., 2019; Silva et al., 2018) although depending upon the type of anaerobic digestion (**AD**) technology used, this can be improved (Häner et al., 2022). A theoretical analysis of pig slurry determined a maximum methane yield of approximately 83% (Santos et al., 2022). Pig slurry has been identified as having a high buffering capacity, which may reduce the risk of failures of anaerobic plants by preventing accumulation of volatile fatty acids and the associated decline in pH (Cuetos et al., 2011). It is important to note that acidification of pig slurry, to reduce NH_3 release, prior to use in anaerobic digestion has been shown in some cases to lower biogas potential (Sommer et al., 2015).

Opportunities from producing biogas from pig slurry

Whilst conventional, large scale anaerobic digestion plants are both cost and resource prohibitive for individual farmers (Wilkinson, 2011), small scale, modularised AD technologies or wheel and spoke developments, may provide a range of benefits to individual farmers and the pork sector more broadly (Figure 2). There are a number of potential diversification opportunities available to pig farmers through harnessing waste as a source of energy and these include generating electricity, income, heat, fuel, fertiliser, saleable CO_2 and reducing emissions associated with slurry storage.

By harnessing the fermentative digestion of nutrients present in pig slurry, the generation of biogas can be used to power a combined heat and power (**CHP**) engine, to generate both electricity and heat or alternatively, can be used to power a combustion engine, fuel cell or gas turbine to produce electricity alone (Kang et al., 2014; León and Martín, 2016; Patania et al., 2012; Wu et al., 2016). On-farm generation can provide farmers with a more stable, reliable energy supply, which is of particular interest to farmers in more rural areas, and those with limited access to the grid (O'Connor et al., 2021). Through CHP, heat can also be generated and used to warm water, for example, which could be used in farm buildings, or used to heat pig rooms, reducing energy consumption from fossil fuels. However, differences in the potential may occur between effluents from different life stages (Gopalan et al., 2013).

Alternatively, the biogas produced can be upgraded through pre-treatment and separation steps (e.g. removal of water vapour and CO_2) to produce biomethane (renewable natural gas) which can be fed directly into the grid as a source of income (Hengeveld et al., 2014; Rotunno et al., 2017). Biomethane can also be compressed to generate fuel, which can be used to power on-farm vehicles. During the separation process, CO_2 can be recovered and recycled and undergo additional purification steps.

Ultimately, if the processing technology is available, CO_2 from biogas production can be purified to a food-grade quality, producing additional revenue for farmers. Additional uses for CO_2 include production of dry ice and stunning in abattoirs and CO_2 is required in multiple industries such as food and drink manufacturing, the manufacturing of pharmaceuticals, chemical product synthesis, fire extinguishers and enhanced oil recovery (Supekar and Skerlos, 2014; Valluri et al., 2022). Methods to capture CO_2 from biogas have been discussed elsewhere (Kanso et al., 2024).

As mentioned previously, by diverting slurry directly into anaerobic digestion, GHGs associated with slurry storage can be reduced. An Irish case study showed that mono-digestion of pig slurry reduced GHGs by 48% (190 tonne CO_2 equivalent) compared with spreading directly to land (Zhang, et al., 2021). Modelling of biogas generation from available pig slurry in Cyrpus estimated that approximately 20% of the country' s energy requirements could be met through renewable biogas generation from AD of pig slurry alone (Theofanous et al., 2014). This highlights the potential for utilisation of pig waste.

At the end of the AD process, digestate remains, which similarly to frass, can be applied to land as a biofertiliser due to its high nutrient concentrations (Czekała, 2022). Digestate has been shown to have a lower pathogenic load than raw slurry (Pourcher et al., 2023). However pathogens of concern to human health do still persist (Nag et al., 2020), and digestate has been shown to have a more appealing nutrient profile, with higher concentrations of molecules with higher biological stability such as lignin

(Tambone et al., 2009). Digestate from pig slurry showed similar biomass yields in wheat plants when compared with a mineral fertiliser, outperforming cattle manure derived digestate when applied to sandy loam soils (Doyeni et al., 2021). Digestate from pig slurry was also suggested to be a useful basal fertiliser in rice paddies when used alongside urea and some additional top-dressed compound-fertilisers, with no detrimental effects on plant growth as well as improved cooking and eating qualities of the rice (Zhang et al., 2017). Digestate produced on farms could be sold providing an additional income stream to farmers.

Challenges for producing biogas from pig slurry

As with insect bioconversion, there are a number of challenges that may prohibit or limit the uptake of biogas production on pig farms. Many of these focus around the suitability of pig slurry as a feedstock. Firstly, animal slurries are highly variable from farm to farm (Prado et al., 2022) and therefore variation in energy production is likely to be observed. This may be due to the breed stocked, the diet fed to the animals or the stage of production that a given farm rears. Slurry composition may also vary with season (Kowalski et al., 2013) and it is important to consider when slurry is obtained for biogas production. In order to generate the most biogas, slurry storage time should be kept as short as possible to minimise the loss of gasses, or alternatively, slurry should be treated in such a way to minimise fermentative digestion e.g. cooling (Blázquez et al., 2021; Blázquez et al., 2022) which requires additional infrastructure. Alternatively, slurry additives can be used which limit gas production during storage

(Im et al., 2021; Thorn et al., 2022). Room management may also affect slurry composition; chemicals and detergents used to wash rooms between batches of animals may suppress the biogas potential of the slurry due to the presence of compounds that inhibit microbial growth. Therefore, it is important to consider when slurry is drawn out of pits for biogas generation relative to cleaning.

Slurry also has a low DM content of approximately 3-5% (KeChrist et al., 2017), and as such, has a relatively low amount of volatile solids available for biogas generation (Marchetti et al., 2022). Because of this, some authors suggest that biogas production from pig slurry requires the addition of co-products to allow it to be viable (Guo et al., 2020; Tian et al., 2023). Pig slurry also has high levels of nitrogen due to the amount of crude protein fed to the animals to maximise growth performance and lean tissue deposition. This leads to a higher amount of ammonia in the slurry relative to carbon, leading to a suppression of methanogenesis and therefore lower biogas yields (Cuetos et al., 2011; Gaworski et al., 2017).

There are also challenges around the cost of implementation – can a farm afford to install this technology on their unit and what is the return on investment? The answer to this will likely be dependent upon the size of the farm and the access to substrate for AD. Smaller farms (<500 sows) may require additional inputs (e.g. farmyard manure, agri-food waste, crop residues) to maximise generation of biogas, depending upon energy generation required. Increasing the amount of biogas produced on farms within a country, or a particular region, may also be limited by the current energy infrastructure and technologies available. For example, selling energy back to the grid may not always be possible depending upon the capacity at any given time, therefore limiting potential income streams if battery storage is not available. It has been suggested that pig slurry should instead be used to generate an inoculum for anaerobic digestion plants as opposed to acting as a substrate for digestion itself due to the beneficial microbial community that pig slurry contains (Marchetti et al., 2022). In this situation, it may be more economically viable for farmers to sell their slurry to a business that specialises in generating the microbial inoculum. This may be an opportunity for some farms, but it is unlikely to require the sheer volume of slurry being produced within a country at any given time.

Considerations for a farm of the future

When designing future farms, it is evident that we must ensure that the farm sits within a renewable, sustainable, potentially circular system. In order to do this, we must take into account energy usage, generation and disposal of waste materials. The solutions and opportunities for waste management on farms are likely to vary depending on a number of factors. For example, the route taken may differ depending upon the stage of production found on an individual farm. BSFL have been shown to grow quicker on slurry derived from pigs of a younger age (Hao et al., 2023b; Shao et al., 2024), coinciding with higher amounts of crude protein in the diets at this stage. Therefore, breeding units or those with finishing pigs may be better suited to send slurry directly to AD due to the higher fibre diets fed to these animals or additional proteinaceous co-products may be needed in addition to pig slurry to enhance insect bioconversion. Units with younger, growing pigs however would benefit from capturing the excess nitrogen that passes through the animal and converting this into insect biomass, reducing their environmental impact through lowering N loading onto land. Whilst units producing animals on a straw-based system may have different process flows to those on slatted floors.

As technologies develop, it may be possible to link both insect bioconversion units and AD plants within the farm-gate. Under these circumstances, the challenges around energy generation for the insect bioreactor could be met by the AD process, for example by providing the necessary heat to grow the insect larvae, whilst the digestate from the AD plant may provide a substrate for insect bioconversion due to their generalist feeding ability. More research is required to understand how these systems may link.

There is also substantial opportunity to consider how we can feed the pig to manipulate the waste produced. Is it possible to alter the properties of slurry, via the diet, to enhance biogas potential or the growth of BSFL without compromising the health, welfare or efficiency of the animal? If we could achieve this through the incorporation of agri-food by-products such as those produced from the dairy industry or food processing, we could further enhance the circularity of pork production whilst adding further value to animal slurries. Through unlocking the potential of pig slurry, farmers may be able to convert this ‘waste’ product into a viable end product, be that through insect bioconversion or as energy to support on-farm activities whilst ensuring net zero targets can be achieved.

Conclusions

It is important to note that whilst bioconversion and biogas generation from pig slurry offer potential opportunities for the pork sector, they are in varying degrees of market readiness depending on individual countries legislations and current capabilities. However, there is tremendous scope to capture the nutrients in slurry to produce a range of diversification streams through insect bioconversion, or on-farm energy generation. Whilst more research is needed to ensure that these circular waste management streams are cost-effective, sustainable and safe (in the case of the BSFL), the opportunity to the pork sector to harness this ‘waste’ product offers huge potential as steps to decarbonise pig production and improve farm resilience.

Ethics Approval

Not applicable

Data and model availability statement

Information can be made available from the authors upon request.

Declaration of Generative AI and AI-assisted technologies in the writing process

The authors did not use any artificial intelligence assisted technologies in the writing process

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Declaration of interest

None

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Tables:

Table 1: Main findings and primary parameters investigated of literature incorporating Black Soldier Fly Bioconversion of Pig Slurry as part of the study

Reference	Primary Parameters Investigated	Main Findings
Ao et al. (2021)	Microbiome	➢ *Enterococcus, Providencia* and *Morganella* dominant genera in the larval gut. ➢ Proteobacteria decreased in manure-fed larvae.
Awasthi et al. (2020)	Pathogen Load	➢ Reduced abundance of pathogenic bacteria in larval-treated manure.
Beskin et al. (2018)	Waste Type on Emissions	➢ Volatile organic compounds were reduced by larvae addition to manure. ➢ More volatile organic compounds emitted from poultry manure than swine or dairy. ➢ Phenol, indole and 4-methylphenol were reduced to undetectable levels by larvae in swine manure.
Beyers et al. (2023)	Waste Type and Agro-waste disposal	➢ Effects on energy consumption and environment for insect production varies between food source and type of energy used during production.
Boafo et al. (2023)	Oviposition Preference	➢ Heaviest pre-pupal weight for larvae fed on pig manure and lowest on chicken manure. ➢ Preferred oviposition substrate was millet porridge mash, which had a lower pre-pupal weight than pig manure.
Chen et al. (2019)	Emissions	➢ Total greenhouse gas emissions reduced compared to traditional composting at 75% moisture. ➢ Methane emissions increased with moisture content of manure.
Choi (2024)	Larval Stages on	➢ Greater conversion ability of 2^{nd} and 3^{rd} instar larvae on pig manure.

	Bioconversion	➢ 3rd instar larvae also largely reduced NDF and ADF.
Deng et al. (2024)	Plantation Waste addition to Manure	➢ Type of planation waste added to pig manure affected accumulation of heavy metals by larvae. ➢ Bamboo chips addition had positive effect on heavy metal accumulation. ➢ Bacteria such as Proteobacteria are involved in the transformation of heavy metals in the residue.
El-Dakar et al. (2021)	Waste Type	➢ Growth increased in larvae reared on bird manure compared to goat and pig manure. ➢ Higher fatty acids in pre-pupae fed on bird manure. ➢ No significant difference in ratio of essential amino acids for pre-pupae from different substrates.
Elhag et al. (2022)	Pathogens	➢ *Staphylococcus aureus* and *Salmonella* spp. significantly decreased in pig manure with larvae. ➢ Isolated microbes from the larval gut shown to inhibit *Staphylococcus aureus* and *Escherichia.coli in vitro*.
Ewusie et al. (2019)	Oviposition Preference	➢ Oviposition preference for pig waste trap. ➢ Substrate of oviposition affected larval length growth in first 10 days.
Ganda et al. (2019)	Waste Type	➢ Greater larval yields from crop and agri-food substrates than from manures.
Hao et al. (2023b)	Type of Pig Manure	➢ Lower larval weights for those reared on finishing pig manure, compared to younger stages. ➢ Significant correlation between hemicellulose content and larval weight.
Hao et al. (2023a)	Disinfectants	➢ Effects of disinfectants on microbiome composition. ➢ Larval growth was increased by potassium peroxymonosulfate. ➢ Waste reduction ratio decreased by glutaraldehyde.

Hoek-van den Hil et al. (2023)	Waste Type and Pathogens	➢ Cadmium bioaccumulated in larvae. ➢ Oxytetracycline detected in frass samples from pig manure treatments. ➢ *Salmonella* spp. detected in pig manure and one larval sample.
Hoffmans et al. (2024)	Heavy metals and Veterinary Drugs	➢ Cadmium bioaccumulated in larvae. ➢ Low levels of veterinary drug detection in substrates and larvae.
Huang et al. (2020)	Pathogens	➢ Reduced *Staphylococcus aureus* and *Salmonella* spp. in pig manure with larvae. ➢ Toll pathway genes involved in regulating of gut microbiome.
Jiang et al., (2022)	Heavy Metals	➢ Bioaccumulation of heavy metals depended on larval inoculation density. ➢ Inoculation density of 0.40% had greatest absorption effect of heavy metals for pupal yields.
Naser El Deen et al., (2023)	Waste Type	➢ Low growth rate of larvae reared on pig slurry mixed with silage grass. ➢ Larvae also had undetectable fatty acids when reared on this mix. ➢ Waste reduction index low for larvae reared on the mix and for pig slurry alone compared to other substrates such as chicken feed.
Lalander et al., (2015)	*Salmonella* reduction	➢ Larvae reduced *Salmonella* spp. concentrations. ➢ Viable virus concentrations decreased in substrate.
Li, Q. et al., (2011)	Biodiesel	➢ Highest yield of crude fats extracted from larvae fed on chicken manure, followed by pig then cattle manure.
Li, T. et al., (2023)	Mixed Wastes	➢ Adding wet distiller grains increased bioconversion rate of pig and cow manure. ➢ Waste reduction rate was increased by 67% in pig manure when grains were added.

Li, T. et al., (2024)	Heavy Metals	➢ Little accumulation of heavy metals in larvae. ➢ Predicted gut enzymes with ability to transport heavy metals such as Zn could reduce bioaccumulation in larvae.
Lin et al., (2023)	Heavy Metals	➢ Cadmium content of larvae high on pig manure. ➢ High protein content in larvae fed pig manure.
Liu, Z. et al., (2018)	Waste Type on Reduction and Larval Development	➢ Longer developmental time and lower weight gain on pig manure than on wheat middling. ➢ Survival similar on wheat middlings and pig manure, but lower on semi-digested grass. ➢ Larvae reduced pig manure DM by 13.81%.
Liu, Tao et al., (2019)	Waste Reduction and Nutrients	➢ Larvae decreased nitrogen by 13.18% on pig manure. ➢ Volatile fatty acids were reduced in manure.
Liu, T. et al., (2020)	Humification and Trace Elements	➢ Larvae enhance humification of manure. ➢ Larvae increased the quantity of bioavailable trace elements in the residue.
Liu, Tao et al., (2021)	Cornstalk Addition	➢ Adding cornstalk to manures reduced methane and ammonia emissions, but increased CO_2. ➢ Adding cornstalk influenced microbial communities in substrates.
Liu, Tao et al., (2022)	Metals and Bacteria	➢ Addition of cornstalk to manure substrates increased toxic metal immobilization rate. ➢ Adding cornstalk affected bacterial diversity.
Matos et al., (2021)	Methane Emissions	➢ Larva reduced 32% of pig manure dry matter. ➢ Methane was reduced by up to 86% in animal manure with larvae compared to traditional manure storage.

Mei et al., (2022)	Antibiotic Degradation	➢ Temperature significantly affected degradation of tylosin and enrofloxacin antibiotics by larvae fed on swine manure. ➢ Antibiotic resistance genes increased in expression in the gut of manure-fed larvae.
Miranda et al., (2020)	Waste Type on Larval Development	➢ Longer developmental time and lower survivorship on dairy manure compared to poultry and swine manure. ➢ No significant difference in weight of prepupae on different manures.
Miranda et al., (2021)	Waste Reduction and Type for Different Study Sizes	➢ Higher reduction in N found in dairy manure than in poultry and swine manure. ➢ Scale of study affected P and K reductions.
Newton et al., (2005)	Waste Reduction	➢ Manure reduced by 56%. ➢ N and P reduced in substrate by 55 and 44% respectively.
Nguyen et al., (2013)	Waste type on Larval Development	➢ Larvae reared on pig manure took longer to develop than those on other substrates such as kitchen waste. ➢ Larvae reared on manure had lower final weights.
Nguyen et al., (2015)	Waste Type on Larval Development	➢ 44% greater waste reduction for manure compared to poultry feed. ➢ Slower reduction of waste for larvae on pig manure compared to poultry feed. ➢ No difference in larval weight.
Oonincx et al., (2015)	Waste Type and nutrients	➢ Higher survival on pig manure than chicken manure. ➢ Longer development time on dairy manure. ➢ DM reduced ~37% and N:P ratio reduced in all manure types tested.

Pang et al., (2020)	Carbon and Nitrogen and Gas Emissions	➢ C:N ratios in pig manure/corncobs mix affect greenhouse gas emissions from larval bioconversion. ➢ Greenhouse gas emissions reduced compared to traditional composting.
Parodi et al., (2020)	Larval Substrate Preference	➢ Larvae showed preference to pig manure over plant by-product diet. ➢ Preference for manure increased with age.
Parodi et al., (2021)	Waste reduction, nutrients and emissions	➢ Larvae reduced pig manure DM by 12%. ➢ Larvae reduced N and P in substrate. ➢ CO_2 emissions increased from manure with larvae compared to manure without larvae. ➢ No difference in CH_4 emissions.
Parodi et al., (2022)	Ammonia-Nitrogen Uptake	➢ 13% of NH_3-N in pig manure assimilated into larvae.
Peng et al., (2022)	Frass Properties	➢ Effects of pig manure thickness on bioconversion efficiency.
Ramírez-Méndez et al., (2022)	Waste Type	➢ Greatest weight gain in larvae fed on restaurant waste. ➢ Lowest on dairy manure. ➢ Bioconversion efficiency faster on pig manure than on dairy manure.
Shao et al., (2024)	Stage of Pig and Bacteria	➢ Manure from different stages of pig affected larval conversion, with that of growing pigs showing highest overall values. ➢ Stage also affected larval gut microbiome composition. ➢ Cellulose-degrading bacteria isolated from larval guts.
Shen et al., (2024)	Fatty Acids	➢ Larval density did not affect fatty acid composition.

		➢ Scaling the system up decreased larval survival and reduced fatty acids.
Veldkamp et al., (2021)	Waste Type	➢ Lower larval growth rate on pig manure than chicken feed. ➢ Larvae growth rate was not different from chicken feed if pig manure was mixed with chicken feed. ➢ Mixed manure and chicken feed also had increased bioconversion efficiency compared to separate chicken feed and pig manure.
Wang, S. et al., (2019)	Waste Type	➢ Shorter development time on food waste and pig manure than on cow manure. ➢ Reproductive rate also higher for food waste and pig manure- reared flies than for cow manure. ➢ Fatty acid and amino acid content altered between pre-pupae reared on different feedstuffs.
Wang, Q. et al., (2021)	Properties of Residue	➢ Increased aromatic components of manure after larval bioconversion. ➢ Decrease in proteinaceous components.
Wang, X. et al., (2021)	Heavy Metals	➢ High bioaccumulation of Cd in larvae. ➢ Heavy metals also transferred to faeces.
Wang, X. et al., (2022)	Cadmium Accumulation	➢ Addition of Cd to pig manure did not influence larval growth. ➢ Larvae fed on pig manure bioaccumulated Cd. ➢ Only small amounts of Cd from manure-fed larval frass entered maize plants when treated with it as a fertilizer.
Wang, L. et al., (2024)	Microbiome	➢ Moisture content affected conversion efficiency of pig manure. ➢ Microbiome composition altered on different moisture levels of pig manure.
Wu, N. et al.,	Microbiome and	➢ Larvae reared on pig manure accumulated Cu and Zn.

(2021)	metals.	➢ Larval faeces contained lower abundances of potential pathogens than the pig manure.
Wu, N. et al., (2024)	Frass Quality	➢ Pig manure lost more N during bioconversion than chicken manure. ➢ Higher humification in frass compared to compost.
Xiao et al., (2020)	Waste Type	➢ Adding rice bran improved conversion efficiency of pig and chicken manure. ➢ Adding cow manure reduced conversion efficiency.
Zhan et al., (2020)	Microbiome	➢ Greater complexity of the microbiome for dairy and swine manure-fed larvae compared to those fed on poultry manure. ➢ Larvae fed dairy manure show differences in gene expression profiles compared to larvae fed on other manures.
Zhang, Y. et al., (2022)	Pathogens	➢ Larvae reduced *Staphylococcus aureus* and *Salmonella* spp. in pig manure. ➢ Gut microbes required for inhibition of *Staphylococcus*. *aureus* and *Salmonella* spp.
Zhang, B. et al., (2024)	Transcriptome and Metabolome	➢ More downregulated differentially expressed genes in larvae reared on pig manure compared to swill. ➢ Upregulation of genes associated with stress response and antioxidants in pig manure-fed larvae.
Zhao et al., (2023)	Antibiotic Resistance	➢ Larvae reduced abundance of antimicrobial resistance genes by 93.2%. ➢ Larval conversion also reduced the number of main antibiotic-resistant bacteria.
Zhou et al., (2013)	Fly strain	➢ Fly strain affected development time and weight of larvae. ➢ Reduction of DM from swine manure ranged from 28.8 to 53.4% depending on strain. ➢ DM reduction also differed with manure type.

Table 2: Nutritional composition of Black Soldier Fly Larvae reared on pig slurry (all nutrient values are expressed on a DM basis, except for DM or where otherwise stated)

DM	Reference
27.6 (SD ± 0.4) (%)	Parodi et al. (2021)
20.2 (SD: ±0.46) (%)	Oonincx et al. (2015)
20.3 ± 0.8 (%)	Hoek-van den Hil et al. (2023)
~22 (%)	Naser El Deen et al. (2023)
21 (%)	Veldkamp et al. (2021)
Energy	
2042 ± 33 kJ/100g	Parodi et al. (2021)
Protein	
34.7% (se: ± 0.5)	Boafo et al. (2023)
43.2%	Newton et al. (2005)
42.59% (se: ± 0.71) to 46.60 (se: ± 0.54)	Wang et al. (2024)
32.27% ± 0.23 to 33.16 ± 0.29	Zhou et al. (2013)
Fats	
31.8% (se: ±0.8)	Boafo et al. (2023)
6.05% (SD: ± 0.46) to 8.92% (SD: ± 0.56)	Wang et al. (2024)

Omega Fatty Acids	
Omega 3: Linoleic acid=1.96% (SD: ± 0.23)	El-Dakar et al., 2021
Omega3: Linolenic acid=0.04% (SD: ± 0.06)	El-Dakar et al., 2021
Omega3=0.15(%DM)	Naser El Deen et al., 2023
Omega6=1.77 (%DM)	Naser El Deen et al., 2023
Phosphorus	
1.2% (SD: ± 0.1) (per 100g of DM)	Parodi et al., 2021
1.99% (SD: ±0.190)	Oonincx et al., 2015
0.88 (%DM)	Newton et al., 2005
1.37% (SD: ± 0.08) to 2.08 (SD: ± 0.10)	Wang et al., 2024
Nitrogen	
6.90 (%DM) (SD: ±0.215)	Oonincx et al., 2015
6.9% (SD: ± 0.2)	Parodi et al., 2021
Potassium	
1.6% (SD: ± 0.1)	Parodi et al., 2021
1.16 (%DM)	Newton et al., 2005
Amino Acids	
Alanine	

6.87 ± 0.15 (Mean (g/100g) ± SD)[a]	El-Dakar et al., 2021
2.82±0.07 to 2.93±0.12 (Mean % amino acids ± SD)	Jiang et al., 2022
Arginine	
5.14 ± 0.03[a]	El-Dakar et al., 2021
1.63±0.05 to 1.75±0.16	Jiang et al., 2022
1.77 (% amino acids)	Newton et al., 2005
Aspartic acid	
9.41 ± 0.13[a]	El-Dakar et al., 2021
3.28±0.08 to 3.48±0.16	Jiang et al., 2022
Cystine	
0.21±0.03 to 0.22±0.02	Jiang et al., 2022
Glutamic acid	
10.57 ± 0.08[a]	El-Dakar et al., 2021
4.12±0.09 to 4.60±0.20	Jiang et al., 2022
Glycine	
5.41 ± 0.02[a]	El-Dakar et al., 2021
2.27±0.06 to 2.42±0.06	Jiang et al., 2022

Histidine	
3.22 ± 0.08[a]	El-Dakar et al., 2021
0.78±0.04 to 0.90±0.07	Jiang et al., 2022
0.96	Newton et al., 2005
Isoleucine	
4.13 ± 0.03[a]	El-Dakar et al., 2021
1.05±0.06 to 1.11±0.12	Jiang et al., 2022
1.51	Newton et al., 2005
Leucine	
7.08 ± 0.04[a]	El-Dakar et al., 2021
2.47±0.06 to 2.48±0.11	Jiang et al., 2022
2.61	Newton et al., 2005
Lysine	
6.17 ± 0.08[a]	El-Dakar et al., 2021
1.86±0.11 to 1.94±0.07	Jiang et al., 2022
2.21	Newton et al., 2005
Methionine	
4.46 ± 0.04[a]	El-Dakar et al., 2021

4.01±0.21 to 4.10±0.27	Jiang et al., 2022
0.83	Newton et al., 2005
Phenylalanine	
4.90 ± 0.10^{a}	El-Dakar et al., 2021
1.48±0.03 to 1.58±0.08	Jiang et al., 2022
1.49	Newton et al., 2005
Proline	
11.15 ± 0.12^{a}	El-Dakar et al., 2021
2.01±0.03 to 2.07±0.08	Jiang et al., 2022
Serine	
4.19 ± 0.02^{a}	El-Dakar et al., 2021
1.80±0.04 to 1.89±0.05	Jiang et al., 2022
Threonine	
4.12 ± 0.02a	El-Dakar et al., 2021
1.47±0.04 to 1.52±0.05	Jiang et al., 2022
1.41	Newton et al., 2005
Tryptophan	
0.59	Newton et al., 2005

Tyrosine	
7.55 ± 0.03[a]	El-Dakar et al., 2021
2.19±0.06 to 2.46±0.17	Jiang et al., 2022
Valine	
5.61 ± 0.03[a]	El-Dakar et al., 2021
1.50±0.07 to 1.56±0.13	Jiang et al., 2022
2.23	Newton et al., 2005

a Amino acid contents from El-Dakar et al., 2021 were determined by standard method GB 5009.124-2016 and is expressed per protein content.

Table 3: Heavy metal content of Black Soldier Fly larvae reared on pig slurry

	Arsenic	Cadmium	Lead	Manganese	Zinc	Selenium	Mercury	Chromium	Copper	Iron	Nickel	Reference
Mean ± SD (mg/kg; substrate dependent)	0.31 ± 0.04	0.61 ± 0.02 to 0.85 ± 0.11	1.06 ± 0.18	640.8 ± 22.4 to 974.5 ± 160.9	510.4 ± 56.5	0.33 ± 0.06 to 0.80 ± 0.09						Hoffmans et al., 2024
Mean ± SD (mg/kg)	<0.10	0.22±0.06	0.27±0.06				<0.004					Hoek-van den Hil et al., 2023
Mean ± SD (mg/kg; density dependent)	none	3.56±1.18 to 23.46±3.62	0.44±0.06 to 0.55±0.1		0.46±0.05 to 0.74±0.02			0.35±0.03 to 0.57±0.05	0.44±0.03 to 0.66±0.04			Jiang et al., 2022
mg/kg	0.30	0.24	0		538.34		0.001	25.99	521.16	1452.2	6.28	Lin et al., 2023
mg/kg (read from graph)	27-30	2.4-3.2	3.0-3.6	700-900	380-460			2-6	100-120	800-1200	1-3	Li et al., 2024
ppm				348	271					776		Newton et al., 2005
mg/kg	1.01	0.29						11.56				Wang et al., 2021

% accumulation	38.8%			Wang et al., 2022
mg/kg		356.2	475.9	Wu et al., 2021

Table 4: Potential challenges that may or currently curtail the growth of the Black Soldier fly bioconversion of pig slurry including potential avenues for future research and current unknown and under-researched areas of knowledge

Potential challenge	What don't we know and opportunities for future research
Presence of heavy metals in insects and/or frass	• What is the heavy metal content of different insect frasses? • How does heavy metal accumulation vary across slurry sourced from different farms, animal breeds, diet types etc.? • What factors affect bioaccumulation of heavy metals into larval tissue e.g. density? • How does heavy metal accumulation affect down-stream processing opportunities? • How can we mitigate against larval uptake of heavy metals (where appropriate)? • How can we appropriately utilise insect bioaccumulation of heavy metals to 'clean-up' animal wastes? • Can heavy metals be extracted and utilised from insects post-harvesting? Is there a market for this? • What is the welfare impact on the larvae? • What are the risks to downstream users or consumers of insect products?
Presence of pathogenic bacteria or those of concern to the food industry	• What factors affect the pathogenic load of insect larvae after consuming pig slurry? • How does this vary with different slurry types? • What affect does the presence of pathogenic bacteria have on the immune system of the larvae – what are the repercussions of this on insect growth? • Do insects harbour more pathogenic bacteria when reared on animal wastes? • What does the presence of potentially pathogenic or undesirable microbes look like before and after insect bioconversion?

	• Are the pathogenic/undesirable microbes viable after processing of insect frass? • If necessary, what processing steps would be required to sterilise the insects and/or frass before downstream applications?
Viral, fungal, parasite and prion contamination	• Majority of the work looking at the microbiome in insect larvae reared on pig slurry has concentrated on the bacterial populations but what happens to fungal and viral communities? • What is the biological relevance of the fungal/viral load? • Whilst there are no known naturally occurring prion diseases in pigs, and pigs show high resilience to infection with prions (Espinosa et al., 2020), is there risk of prion transmission or proliferation within an insect bioconversion cycle? • What effect does insect bioconversion have on the proliferation of parasites such as *Ascaris spp.*? • What additional processing would be needed to prevent land contamination with parasites? How does this compare to application of raw pig slurry?
Antimicrobial resistance risks and proliferation	• What effect do veterinary medicines used on farms that are biologically active in slurry have on antimicrobial resistance genes in insects and their frass? • What effect does the presence of detergents from room washing have on insect growth, microbial populations and antimicrobial resistance? • How does the level of mobile genetic elements vary across a bioconversion cycle? • Do Black Soldier Fly larvae act as a reservoir for antimicrobial resistance genes? • What is the risk of co-selection for antimicrobial resistance genes in the presence of heavy metals found in the slurry? • How do antimicrobial resistance geness move from slurry to insect to frass to soil to plant? • How can we mitigate against these risks? • How does the production system, farm, pig diet and stage of

	production affect these risks?
Accumulation of polychlorinates biphenyls (PCBs), dioxins and pharmaceuticals	• How do pharmaceuticals used on farm affect larval growth and development? • Does insect bioconversion of pig slurry result in a higher concentration of pharmaceuticals in the larvae or insect frass? • Larvae can show bioaccumulation of PCBs on food waste (Van der Fels-Klerx et al., 2020) but is there an accumulation of PCBs from pig slurry and what other factors affects this?
Suitability of frass as a fertiliser	• How variable is the NPK ratio of frass when insects are provided with pig slurry as a substrate? • How does the diet of the pig influence this? • What effect does frass application as a fertiliser have on different soil microbial communities? • How does presence of phytotoxins influence plant growth? • How can further processing e.g. composting or heat treatment affect their concentration? • How does addition of frass as a fertiliser affect crop development? • Chitosan can affect defence plant gene expression of plants (Torres-Rodriguez et al., 2021), but what other effects does the application of frass to crops have on plant gene expression? • What is the eutrophication potential of frass compared to pig slurry? • What is the cost benefit of frass vs pig manure when taking into account additional steps e.g. heat treatments? • What are the greenhouse gasemissions associated with frass compared to pig slurry and inorganic fertiliser? • How does using a mixture of traditional fertilisers and frass impact these factors?
Protein production	• Will protein from insects reared on currently non-permissible feedstocks such as pig slurry be allowed to enter the food and

	feed chain? • What safety measures need to be documented to allow this protein to be utilised? • How can insect protein be utilised outside of consumption? • How much insect protein could feasibly be produced from pig slurry? • How much demand would there be for this from farmers and the public in general?
Rearing Black Soldier Fly larvae	• Black Soldier Fly larvae are a tropical species, requiring a high temperature and humidity in order for them to survive – how much energy does this require? • How does the energy requirement change throughout the year? • Is this sustainable through the colder months? • How can renewable energy be used to power an insect bioconversion unit? • What is the impact of the gasses produced from insect rearing compared to storage and spreading of raw pig slurry? • What personal protective equipment and health and safety requirements would a farmer need in place in order to rear insects on farm? • How should waste water generated e.g. from cleaning between batches be disposed of? Can it be safely used for irrigation?
Lack of infrastructure and knowledge	• Whilst there is research looking at rearing Black Soldier Fly larvae on pig slurry, more work is needed to standardise protocols and answer the current unknowns. • How can we support farmers to invest in insect bioconversion facilities? Does it require incentivisation? • What infrastructure is needed to process insect larvae and/or insect frass for downstream applications? • How do we support the development of the insect market?

Unknown legislation, welfare of insects as a mini-livestock species	• UK legislation tightly regulates insect production and curtails use of insects reared on pig slurry • What legislation is there to protect insect as mini-livestock? • How might legislation change in the future? • If insects are determined to feel pain, how will insects be harvested humanely on a large scale? • How will differences in legislation in different countries affect trade in the industry?
Suitability of the feedstock for insect rearing	• Is pig slurry a viable option for large scale insect production? • How can we handle the moisture content of slurry? • How can we reduce the variability in the slurry produced to ensure consistent growth and development of the larvae? • Does pig slurry require a co-product added to maximise economic return on insect production?

Figure Legends:

Figure 1: A schematic of the different opportunities available to the pork industry through on-farm Black Soldier Fly bioconversion of pig slurry. Examples of subsequent downstream markets for products are provided.

Figure 2: A schematic of the different opportunities available to the pork industry through the use of pig slurry to generate biogas and the subsequent downstream uses.