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Multicriteria analysis of sustainable agri-food waste management for an agroecosystem in Finland

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Introduction: The reliance on fossil inputs of agricultural practices has led to maximizing yields and profitability, even at the expense of environmental sustainability. Implementing circular waste management solutions could help align the economic and environmental goals of farmers while reducing their reliance on fossil inputs. The co-application of anaerobic digestion and pyrolysis has been recognized as a potential solution to assist in the transition towards sustainable agriculture.

Objectives: This research assesses different waste management strategies of the major sidestreams generated in agroecosystems in Finland from a climate impact and financial perspective, particularly focusing on the integration of anaerobic digestion and pyrolysis as an emerging solution.

Methods: Six waste management options representing manure application, composting, incineration, anaerobic digestion, pyrolysis, and a co-application process of anaerobic digestion and pyrolysis, are simultaneously assessed with cash flow analysis and life cycle assessment.

Results: The results indicate that co-applying anaerobic digestion and pyrolysis strengthens the performance of a farm through reduced impact on climate, diversified revenue streams, and increased security of supply, even though the direct, short-term financial benefits remain marginal. The capability of co-application of anaerobic digestion and pyrolysis to reduce the climate impacts within the studied system supports the consensus that sustainable and self-sufficient agroecosystems could be supported by this solution in the future.

Conclusion: The adoption of more sustainable agricultural practices requires further expansion of technologies and additional value creation mechanisms, such as stronger employment of carbon markets, to even the economic competition and favor low-carbon operations for practitioners.

KEYWORDS

anaerobic digestion, pyrolysis, biochar, biogas, agriculture, life cycle assessment, cash flow analysis

1 Introduction

Fossil-based economies are driving serious ecological challenges, such as pollution and climate change, placing the global food and forest systems at risk. At the same time, food systems contribute to a third of global anthropogenic greenhouse gas (GHG) emissions globally (Crippa et al., 2021). In Finland, the agricultural sector alone generates about 13% of annual GHG emissions (Statistics Finland, 2022). Finland's national carbon neutrality target (Ministry of Economic Affairs and Employment, 2022) is currently falling short due to decreased forest carbon sinks and lack of new products that would sequestrate carbon, highlighting the need of sustainable solutions in the agricultural sector.

Despite efforts to implement sustainable operational models, such as regenerative farming practices, most of the agricultural operations still heavily depend on fossil inputs due to use of heavy machinery and insufficient circulation of materials. While coping with environmental concerns, agricultural entrepreneurs face vital socio-economic issues, such as rapid urbanization, ageing farming population, and declining profitability trend. In 2019, entrepreneurial income from Finnish farms decreased by around 20% compared to the previous year (Latvala et al., 2020).

To address these issues, new operational models that simultaneously prioritize environmental and financial goals while reducing reliance on fossil imports, are required. Establishing carbon sinks, closing material and energy loops, and producing long-lasting bioproducts show promise as potential ways to sequestrate carbon and reduce the reliance of fossil energy, thus improving the financial viability of rural entrepreneurs (Leppäkoski et al., 2021; Luhas et al., 2022). In the context of agricultural waste management, technologies that convert sidestreams into valuable by-products are gaining increasing interest (Demichelis et al., 2020). Treating manure and other biological waste with biorefinery processes, such as anaerobic digestion (AD) or pyrolysis (PY), has been recognized as more advanced alternative to traditional composting and incineration (Nayal et al., 2016) and favorable transition to meet circular bioeconomy requirements (Khoshnevisan et al., 2021; Leppäkoski et al., 2021; Luhas et al., 2022).

AD processes can be applied to treat organic matter (e.g., manure, bio waste, wastewater sludge), converting them into biogas and nutrient-rich digestate residue (Kaparaju and Rintala, 2011). Biogas can be used either to generate renewable energy in cogeneration of heat and electricity or by upgrading it to biomethane (Roubaud and Favrat, 2005), offering a domestic low-carbon alternative to imported fossil fuels. Utilization of AD has been increasing in Finland, reaching close to 1 TWh in 2019, representing 0.5% of Finnish renewable energy production (Huttunen et al., 2018; Virolainen-Hynnä, 2020). Agricultural feedstocks are still underemployed, with only 1% of animal manure used as biogas feedstock, while most of the commercial reactors utilize municipal and industrial wastewater sludge (Marttinen et al., 2018). Although AD is an advantageous and considerably researched technology, it suffers from technical issues, such as low methane production efficiency, high failure degree of equipment, problems with utilizing biogas digestate, and low financial performance especially on small and medium sized farms (Zhang et al., 2015; Chen and Liu, 2017).

Dry agricultural waste and lignocellulosic biomasses serve as suitable feedstocks for PY, the most widespread biochar production technology (Qian et al., 2015; Tisserant and Cherubini, 2019). Biochar is a long-lasting material which can maintain carbon in a stable form for over hundreds of years (Tisserant and Cherubini, 2019), making it an excellent carbon sink and nature-based solution for slowing down climate change (Leppäkoski et al., 2021; Tisserant et al., 2022). In the Boreal region measurements, biochar application indicated positive long-term impacts on crop yield, carbon dioxide (CO_2) efflux, non-CO_2 GHG emissions, and nitrogen (N) stability (Kalu et al., 2022). Bottlenecks concerning usage of PY are often related to generation of suitable feedstocks, high investment costs, regulatory issues, and unstable biochar market prices (Shackley et al., 2011; Kavitha et al., 2018; Leppäkoski et al., 2021). Recently, researchers have proposed applying AD and PY together to improve the product portfolio of both processes and relieve AD digestate treatment challenges (Fabbri and Torri, 2016; Ghysels et al., 2020; González-Arias et al., 2020; Caiardi et al., 2022).

When combining AD and PY processes, feedstocks can be routed within the system in multiple ways depending on their characteristic. Wet organic wastes are often more suitable for being digested, whereas dry lignocellulosic streams are ideal for PY. In some case, the remaining digestate of AD can be dewatered and treated in PY process, increasing the overall energy recovery and the value of the digestate (Song et al., 2021). Owing to its cellular format, biochar can improve soil quality and provide suitable conditions for microbes by retaining nutrients and water, making it an excellent component for chemical or organic fertilizers (Semida et al., 2019). In agronomic application, also biochar-enriched digestate has been demonstrated to increase plant growth in fields (Tayibi et al., 2019; Ronga et al., 2020). Biochar produced from digestate meets the IBI Biochar Standards recommendations for soil amendment (Tayibi et al., 2021) and serves as excellent material to be mixed with the liquid part of the digestate (Singh et al., 2022). Additionally, biochar acts as helpful catalyst in the AD process increasing the methane yields (Ma et al., 2019; Wu et al., 2019; Indren et al., 2020; Kaur et al., 2020; Lim et al., 2020; Sugiarto et al., 2021) and improving digester functioning by shortening the lag phase (Pan et al., 2019; Song et al., 2021). Therefore, circulating part of the produced biochar to back AD process could be beneficial also from the financial perspective.

A series-connected AD and PY, described by Song et al. (2021) and Singh et al. (2022), has been presented as a way to unlock the potential of agricultural sidestreams for significant financial and environmental benefits. With plenty of suitable agricultural and lignocellulosic residues available in the Finnish bioeconomy sector, co-application of AD and PY could relieve the environmental and socio-economic pressures of farmers. Integrating these technologies into agricultural waste management could also reduce the dependency of imported fossil-based inputs and improve the financial viability of agricultural operations with locally produced biogas, organic fertilizers, and biochar.

Although AD and PY technologies have been broadly researched separately (Sawatdeenarunat et al., 2015, 2016; Tisserant and Cherubini, 2019), their co-application has only recently begun to appear in scientific publications. Few studies have assessed their co-application with life-cycle assessment (LCA), namely in the treatment of manure (Mehta et al., 2022), sewage sludge (Mills et al., 2014; Havukainen et al., 2022), pulp and paper mill reject (Mohammadi et al., 2019), municipal solid waste (Wang et al., 2021), and food waste (Opatokun et al., 2017). It is still unknown to what extent the co-application of AD and PY could reduce the climate impacts of agricultural production. The technology combination has been assessed from the financial and environmental perspective together only in the treatment of sewage sludge (Mills et al., 2014), leaving its potential as a financially viable waste treatment option unexplored in the agricultural sector, which needs to be evidenced. Therefore, a key question remains whether this technology combination offers a viable low-carbon waste management strategy to support transition towards sustainable agriculture.

The purpose of this study is to document the financial feasibility and climate impacts of the co-application of AD and PY in the management of agricultural sidestreams, visualized in Figure 1, through cash flow analysis and LCA. Cash flow analysis and LCA are methods for evaluating the financial feasibility and environmental sustainability of a product, business, or operational model. LCA measures the environmental impacts of a project or a product by considering all the stages of the product's life-cycle: from the extraction of raw materials to the disposal or recycling of the final product (ISO 2006a). Cash flow analysis assesses the financial viability by considering financial factors, such as capital and operational expenses, revenue generation, amortization, and inflation, allowing individuals and business practitioners to make informed financial decisions (Tham and Vélez-Pareja, 2004). This study compares the co-application of AD and PY with the utilization of business-as-usual operations (composting and incineration) and single AD, within the same research setting. This is needed to ensure the relevance of the technology combination for practitioners and compare methods of agricultural waste management from the two important perspectives: environment and economy. In a broader context, this research aims to identify optimally sustainable and financially viable waste management options for the agricultural sector.

2 Materials and methods

2.1 Scenario description

The sidestream management strategies were examined in this study for a theoretical representation of a farm-scale agroecosystem in Finland. Straw is a significant sidestream originating from Finnish agriculture, where the majority of farms focus on cultivating oats, barley, and wheat (Statistics Finland, 2024). Manure is another major agricultural sidestream with Finnish livestock farming strongly centered around milk and beef production, representing 70% of farms outside of plant production (Statistics Finland, 2024). In this study, the agroecosystem was characterized by a dairy farm with a nearby oats field. To enable further comparison of managing different type of wastes in the system, the farm was assumed to also include a greenhouse. Thus, the sidestreams originating from this agroecosystem are manure, oats straw, and greenhouse green waste.

The co-application of AD and PY was compared with management options, including manure spreading, composting, and incineration with a total of six scenarios presented in Table 1. The feedstocks listed include straw, manure, green waste, solid fraction (SF) of digestate, and liquid fraction (LF) of digestate. These treatment scenarios present more common and emerging waste management strategies. Scenario 1 (*Baseline*) represents a common management strategy of these feedstocks, with straw incinerated, manure spread to farmlands for nutrient recovery, and green waste composted (Laurila and Saarinen, 2014; Natural Resources Institute Finland, 2023a; Motiva, 2024a). In Scenario 2 (*Compost*), all the feedstocks are composted except straw, which is incinerated. In Scenario 3 (AD_1), all the feedstocks are processed in a digester; then, the SF of the digestate is composted and the LF of digestate is spread to farmlands. In Scenario 4 (AD_2), straw is incinerated, other feedstocks are processed in a digester, and the SF of the digestate composted and LF are spread to the farmlands. In Scenario 5 (AD_1-PY), all the feedstocks are processed in a digester, after which the SF of the digestate is used in PY, and the LF of the digestate is spread to farmlands. In Scenario 6 (AD_2-PY), straw is used in PY, other feedstocks are processed in a digester, and the SF and LF of the digestate used in PY are spread to farmlands. Figure 2 presents

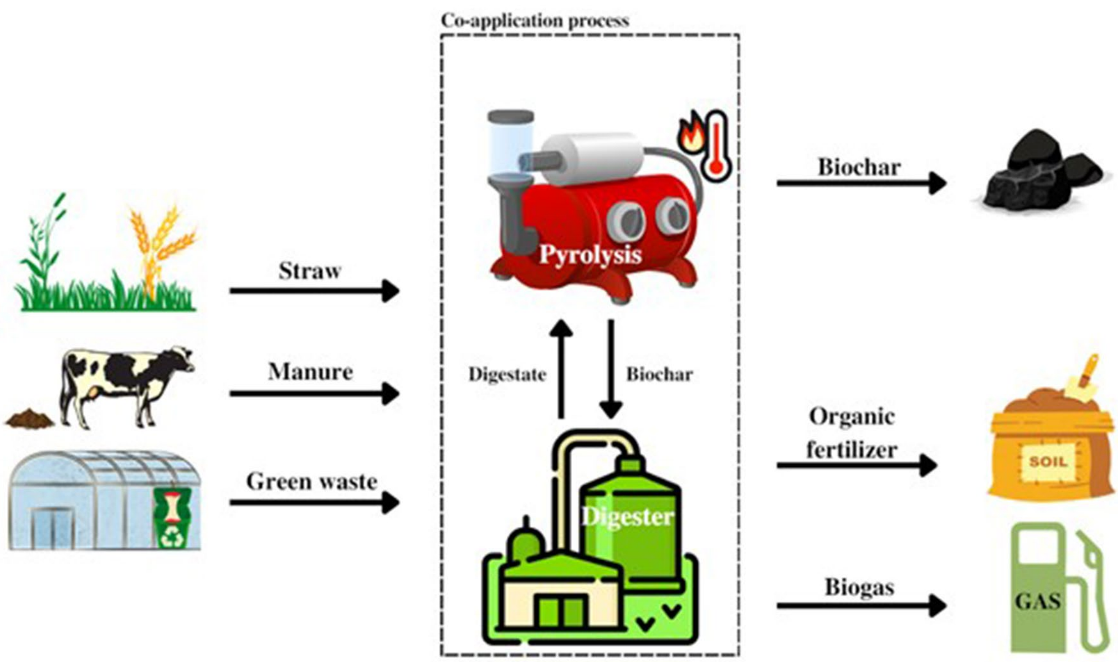

FIGURE 1
Management of agricultural sidestreams based on the co-application of AD and PY.

TABLE 1 Scenarios for the management of agricultural sidestreams.

Scenarios		Treatment routes and utilization of the sidestreams				
Scenario number	Scenario name	Straw	Manure	Green waste	Solid fraction of digestate	Liquid fraction of digestate
1	Baseline	Incineration	Spreading	Compost	–	–
2	Compost	Incineration	Compost	Compost	–	–
3	AD_1	Digester	Digester	Digester	Compost	Spreading
4	AD_2	Incineration	Digester	Digester	Compost	Spreading
5	AD_1-PY	Digester	Digester	Digester	Pyrolysis	Spreading
6	AD_2-PY	Pyrolysis	Digester	Digester	Pyrolysis	Spreading

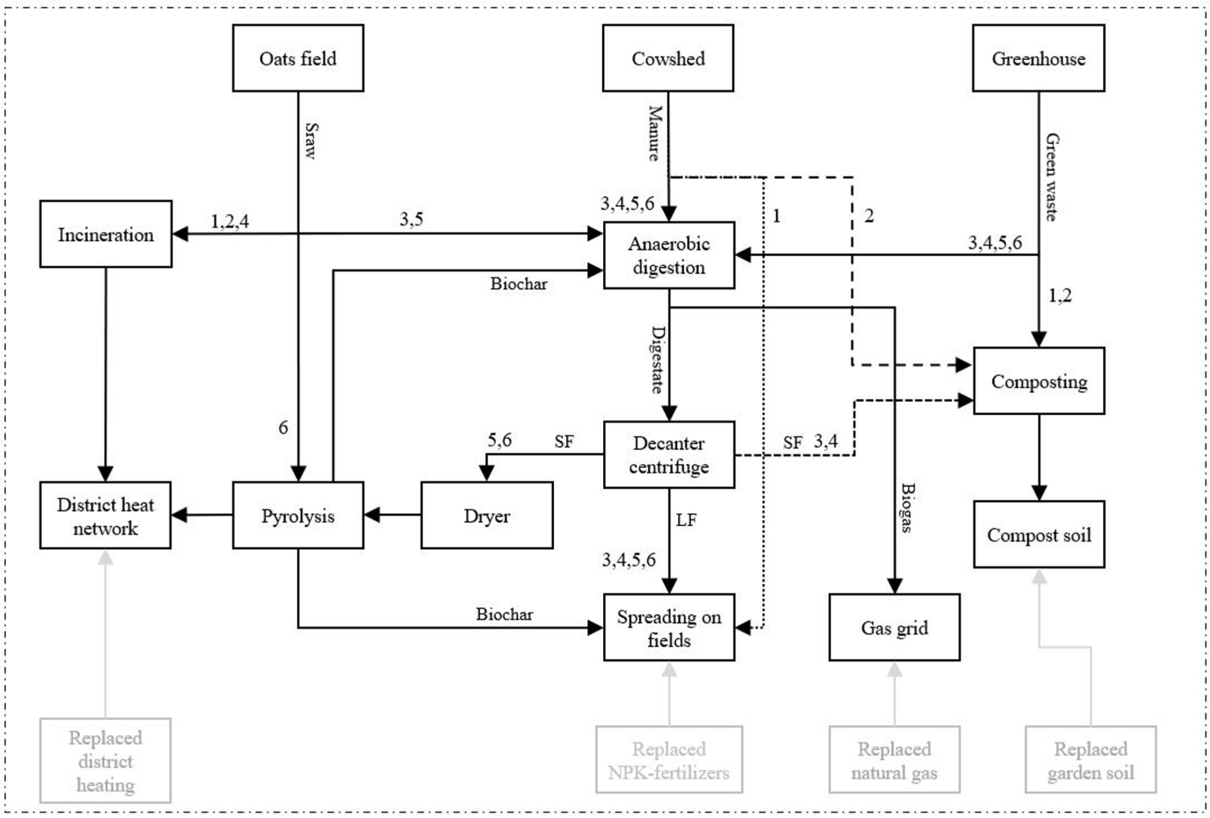

FIGURE 2
System boundary for the study. Numbering presents the specific flow for the waste management scenario.

the different scenarios and the system boundary for the treatment and utilization of the sidestreams of the agroecosystem. The system boundary entails the whole utilization chain from treatment to utilization, excluding the collection of sidestreams and the construction of equipment and machinery. Detailed flow charts of individual scenarios are presented in the Supplementary material.

2.2 Methodology

In this study, financial performance was assessed through profitability and environmental performance through climate impacts. Quantitative indicators selected for the assessment were net present value (NPV), internal rate of return (IRR), and global warming potential (GWP). Selected indicators have been previously used to assess the performance of similar operational models in the bioeconomy sector (el Kasmioui and Ceulemans, 2012; Mills et al., 2014; Li et al., 2017; Leppäkoski et al., 2021; Luhas et al., 2022). The results were further examined in the sensitivity analysis to assess the model's robustness, identify the important input variables, and understand how changes in the variables would affect the results. The sensitivity analysis considers several parameters of different scenarios, including the inclusion of carbon markets, electricity price, initial investment, methane price, biochar price, district heat price, methane yield, biochar yield, and quantity of replaced district heat.

2.2.1 Cash flow analysis

The financial analysis was carried out through a cash flow analysis, which commonly involves various financial metrics such as NPV and IRR to determine the profitability and feasibility of an investment or a project. This study evaluated the financial performance of selected operational models through NPV and IRR, considering capital and operational costs, revenues, amortisation, and inflation. The NPV is a measure of the profitability of an investment, calculated by subtracting the initial investment from the present value of the expected cash flows. A positive NPV indicates that an investment is profitable, whereas a negative NPV indicates that it is not. NPV is determined using Eq. (1):

$$\mathrm{NPV} = \frac{R_t}{(1+i)^t} \quad (1)$$

where R_t is net cash flow, t is the cash flow period, and i is the discount rate. To assess scenarios under different interest rates, 0, 5, 11, and 20% discount rates were assessed (Mikkilä et al., 2021).

The IRR is used to determine the rate of return on an investment. It is the rate at which the NPV of an investment is equal to 0. A higher IRR indicates a more profitable investment and is often used to compare different investment opportunities. In Finland, the required average IRR for investments for publicly listed companies is 16% (Liljeblom and Vaihekoski, 2004).

Effects of inflation were considered in the study with evolving market prices according to the estimation of the common price development in Finland in 2023 (Finanssiala, 2023). Fluctuating prices in the uncertain market situation were considered regarding fertilizers, primary energy, and energy carriers due to the instable geopolitical state during the study. The increasing prices of fertilizers, primary energy, and energy carriers were estimated to stabilize after a couple of years and conform to the estimations on the common price development and of suppliers (Finanssiala, 2023; Autoala, 2023; Helen Oy, 2023; Nasdaq, 2023; The World Bank, 2023). The itemized costs involved in the analysis of the selected operational models are detailed in the Supplementary material according to 2023 prices. For the capital costs, amortisation with a 2% interest for 5 years in a 20-year plant lifetime was considered (Demichelis et al., 2020).

2.2.2 Life cycle assessment

The climate impacts were assessed considering the energy and resource consumption, the emissions and waste generation associated with the management of agricultural sidestream biomasses of a farm-scale agroecosystem. Assessment was performed considering the following functional unit (FU): treatment and utilization of annually generated sidestream biomasses of the agroecosystem (Table 2). A cradle-to-cradle system boundary is defined in Figure 2.

LCA was performed in accordance with the ISO 14040/44 framework (ISO 2006b) by using the Gabi LCA software. Study applied impact assessment method CML2001–Aug. 2016 with climate change as the midpoint impact category represented by GWP to evaluate the treatment technologies and their upgradation products. GWP accounts for all sources of GHG emissions, including biological sources and land-use changes but does not include any normalization or weighting. In this study, the GWP was assessed over a 100-year period.

TABLE 2 Composition of annually generated agricultural sidestreams of the agroecosystem.

Index	Straw	Manure	Green waste
Mass (t a^{-1})	280	2,250	50
Feedstock properties			
TS (%)	90	15	27
TS (t a^{-1})	252	329	14
VS (t a^{-1})	237	246	12
VS/TS	0.94	0.75	0.86
Methane yield (ml g^{-1} *VS*)	280	260	320
Chemical composition (dry basis)			
C (g kg^{-1})	429	39	126
N (g kg^{-1})	4.5	5	5
Soluble N (g kg^{-1})	0	2.9	0.6
P (g kg^{-1})	1	1	0.6
K (g kg^{-1})	13	4.5	2.2
Reference	Lei et al. (2010), El-Adly et al. (2015), Kern et al. (2012), Lee et al. (2013), Natural Resources Institute Finland (2022)	Kaparaju and Rintala (2011), Natural Resources Institute Finland (2022), Nayal et al. (2016), Zhang et al. (2013)	Gunaseelan (2004), Zhang et al. (2013), Natural Resources Institute Finland (2022)

2.3 Description of data

2.3.1 Sidestreams

The scope of this study considers a farm-scale agroecosystem that would be a representation of a dairy farm in Finland with an average inventory of the agricultural biomasses and inputs. The agroecosystem was assumed to consist of a dairy farm of 150 cows (European Commission, 2021), including a 140-hectare (ha) oats field (MTK, 2023) and a 3,000-m^2 greenhouse. The annual quantities and compositions of the generated sidestream biomasses of manure, straw, and green waste are presented in Table 2.

Dairy farms often have adult and young animals that generate manure with a mean average of 28.6 m^3 y^{-1} (Kaparaju and Rintala, 2011). Manure can be used as a fertilizer on farmlands to enrich soil with essential nutrients and organic matter, reducing fertilizer costs and increase soil fertility and leading to financial and environmental benefits (Tanskanen, 2017). While untreated manure has the potential to be an effective fertilizer, its use can lead to health and environmental risks. Spreading untreated manure to fields can be risky as antibiotic resistance genes have been found to be disseminated on Finnish animal farms (Ruuskanen et al., 2016; Muurinen et al., 2017). This practice can also lead to environmental issues, such as eutrophication and runoff into nearby waterways, disrupting local ecosystems and harming water quality (Luostarinen et al., 2020). Thus, use of untreated manure restricted by laws and regulations, such as a six month "closed period" for cold seasons, in some cases enforcing treatment of manure before spreading on farmlands (Liu et al., 2018; Enbuske et al., 2020). Manure can be pre-treated using composting or AD to also improve its nutrient content by providing a more balanced mix of nutrients for crops (Luostarinen et al., 2020). In Finland, composting has been the most common method for solid manure treatment, applied by nearly 4 % of all farms in 2016. In contrast, separation, aeration, or fermentation methods were relatively uncommon treatment options for manure (Natural Resources Institute Finland, 2023a).

Straw is generated as a by-product from crop harvesting. In Finland, the average crop yield of oats is around 4,000 kg ha^{-1} with approximately same quantity of straw (Leppäkoski et al., 2022; MTK, 2023; Natural Resources Institute Finland, 2023b). Laurila and Saarinen (2014) have estimated that half of the straw could be collected without decreasing the soil organic carbon (SOC). In Finland, straw has multiple uses but is most commonly applied as a component in animal feed and beddings, or burned for energy (Laurila and Saarinen, 2014; Weiser et al., 2014; Motiva, 2024a). Consensus has also been that leaving part of the straw on fields improves soil quality and SOC (Lafond et al., 2009; Lindorfer et al., 2014; Monforti et al., 2015; Singh et al., 2015). However, studies on the impacts from leaving straw on to the fields has shown conflicting results, particularly concerning its effects on the crop yield (Gabrielle and Gagnaire, 2008; Leppäkoski et al., 2022) due to its poor N/*p* value. The decomposition and burning of straw will release most of the carbon captured to the straw, which is why it would be better to be utilized in long-lasting products (Leppäkoski et al., 2022). While straw can be co-digested with biological waste to improve the methane yield of AD (Natural Resources Institute Finland, 2022), past studies also consider it as a desirable material to be pyrolyzed (Yanik et al., 2007; Huang et al., 2008; Kern et al., 2012; Lee et al., 2013). Pyrolyzing straw would stabilize its carbon into a more permanent form, after which it could be used as a soil conditioner (Lee et al., 2013; El-Adly et al., 2015).

In Finnish greenhouses, the production of tomatoes generates, on average, 16 kg m^{-2} of green waste (Marttila et al., 2021; Natural Resources Institute Finland, 2021) consisting of discarded products and plant waste. This study assumed this waste with the chemical properties of miscellaneous organic green waste (Natural Resources Institute Finland, 2022). Green waste from greenhouses is commonly in low quantities and composted for soil improvement purposes. However, composting large quantities of biowaste can cause significant CO_2 emissions and N losses. With its high methane yield properties, green waste would be advantageous material for AD (Zhang et al., 2013).

2.3.2 Composting

Manure and green waste can be composted to reduce their volume, odors, and pathogens, as well as to produce a nutrient-rich soil amendment for agriculture to improve soil fertility and structure. In the management scenarios, composting is used to treat manure, green waste, and the SF of the digestate originating from biogas production to produce compost material for the replacement of garden soil. The main bulk material inputs of composting are peat, sand, and biotite, applied for required minerals (Havukainen et al., 2022). Operation of composting consumes also a small amount of electrical energy and light fuel oil. Composting requires investments in composting facilities, operational inputs, and personnel (described in detail in the Supplementary material). The water, ash, carbon, and volatile solids (*VS*) of the feedstocks were transferred to composting products, which were utilized to replace garden soil in this study. Table 3 presents the amounts of the operational inputs, the transfer coefficients to compost, and the emissions from composting and from the use of compost products.

2.3.3 Anaerobic digestion

Manure and green waste can be treated in AD, where microorganisms break down organic matter in the absence of oxygen to produce biogas and digestate. Biogas can be further upgraded to biomethane. Digestate can be applied to farmlands after treatment in the hygienisation unit. The data for the AD process was gathered from Natural Resources Institute Finland's biogas database tool (Natural Resources Institute Finland, 2022). By adjusting the digester sizes in the waste management scenarios to achieve a desired methane potential level, wet digestion with a 21 – day retention time and 4.76 kg m^{-3} d^{-1} feed rate of *VS* was applied for all management scenarios (Pohl et al., 2013; Natural Resources Institute Finland, 2022).

Prior to digestion, the feedstocks were diluted to 12% TS. From the produced biogas, 25% was assumed to be lost as a slip or in the burning of biogas to cover the heat demand of AD. The rest of the biogas was upgraded to methane and sold to the national gas grid (Natural Resources Institute Finland, 2022). The digester sizes, storage tank capacities, methane yield potentials, and the realized methane yields were defined according to the feedstock and process parameters presented in Table 4. Further process specifics and the financial data regarding the process are detailed in the Supplementary material.

Digestate quantity was higher in the AD_1 scenario, where straw was digested, in comparison to AD_2 scenario due to the increased amount of feedstocks and water. Decanter centrifuge, a widespread and popular technology for the separation of manure-based digestate, was used to separate the digestate into LF and SF (Al Seadi et al., 2013; Drosg et al., 2015). Separating the digestate into LF and SF improves

TABLE 3 Inventory data related to composting (Havukainen et al., 2022).

Composting	
Electricity demand (kWh t^{-1})	1.56
Light fuel oil demand (L t^{-1})	1.58
Peat demand (kg t^{-1})	0.24
Biotite demand (kg t^{-1})	0.007
Compost soil sand demand (kg t^{-1})	0.84
Transfer coefficients to compost	
Water (%)	75
Ash (%)	100
C (%)	47
VS (%)	55
Emissions from composting	
N loss (% of tot N)	2.7
N_2O emissions (% of N loss)	42
C loss (% of tot C)	53
CH_4 emissions (% of C loss)	2.1
Compost use	
N_2O emissions (% of tot N)	5.2

the management of nutrients, as the high N and organic material concentrated LF can be spread on farmlands, while the P-concentrated SF can be treated by composting or pyrolysis (Czekała et al., 2017; Peltonen and Hagelberg, 2019). The LF and SF compositions are presented in Table 5. Before spreading on the fields, the LF of the digestate was sanitized in a hygienisation unit.

2.3.4 Pyrolysis

Straw and dry digestate can be thermally treated in the PY process, leading to formation of biochar. In the treatment scenarios, PY was applied as energy self-sufficient process by utilizing other PY products as heat energy. Prior to PY, the moisture content of the SF of the digestate was reduced to 10% using a thermal dryer, which was expected to utilize the excess heat from the PY. After satisfying the heat demand for drying with the excess heat, 50% of the remaining surplus energy was estimated to replace district heating. Same approach was applied for surplus heat generated in both PY and incineration of straw. The average emission factors for district heating and electricity in Finland are 145 and 70 kgCO_2 MWh^{-1}, respectively (Motiva, 2024b).

Biochar, after mixing with the LF of the digestate, was used as a soil conditioner to store carbon into the ground. It has been assumed that after 10 years, more than 80% of carbon in the biochar can remain stable in soils (Heinonsalo, 2020). However, over longer periods biochar stability decreases. Based on a review of 34 studies (Tisserant and Cherubini, 2019), 68% of the carbon can remain in the soil after 100 years, which is applied in this study. In this study, the carbon content of biochar was averaged from three previous studies (Mašek et al., 2013; Ronsse et al., 2013; Rasa et al., 2018), resulting in a value of 72%.

Jang et al. (2018) have assessed the effects of biochar on methane production in dry dairy manure-fed AD, suggesting that relatively large quantities of biochar can improve methane yields up to 35%. In the present study, a 10% increase in the AD methane yield was assumed with 1 g L^{-1} addition of biochar. Pyrolyzer sizes and biochar yields were defined according to the feedstock and process parameters presented in Table 6. The financial data and more detailed specifics of the thermal dryer and PY process are further described in the Supplementary material.

2.3.5 Field application

In the scenarios, mineral fertilizers were replaced with manure, digestate, and biochar. Applying nutrients to farmlands is limited based on their N and P doses. For oats, the optimum dose of N is close to 10 t km^{-2} annually (Chalmers et al., 1998; Gonzales Ponce and Santin, 2001; Mohr et al., 2007). With the high P concentration limiting the use of applicable fertilizer, manure fertilization can leave N doses short (Peltonen and Hagelberg, 2019). The usage of P in farming is monitored and limited by the Finnish Food Authority (2023). The P application rate has been set to a maximum of 1.4 t km^{-2} y^{-1} for cereals by the Finnish Agri-Environmental Program (Amery and Schoumans, 2014; Finnish Food Authority, 2023).

Spreading fertilizer replacements on farmlands requires investments in manure collection, storage, and spreading equipment and machinery. In this study, storage facilities are fit to store annually produced manure or digestate quantity (Enbuske et al., 2020). Investments in the machinery required for spreading fertilizer replacements were excluded from this study, as it was a similar process in all the studied scenarios. By applying the replacements to farmlands, the use of NPK-fertilizers, namely urea, diammonium phosphate (DAP), and potassium chloride, was reduced. IPCC (2006) guidelines report N_2O emissions from all fertilizers at 1%. However, in a review of 48 studies on N_2O emission factors following the application of N-fertilizers, Walling and Vaneeckhaute (2020) found values ranging from as low as 0.03% to as high as 14%. Bruun et al. (2006) have modelled the N-N_2O formation from total N to be around 1.8% in land use of compost and digestated municipal solid waste. This

TABLE 4 Inventory data related to anaerobic digestion (Natural Resources Institute Finland, 2022).

Anaerobic digestion	AD_1	AD_2
Cattle manure (t a^{-1})	2,250	2,250
Green waste (t a^{-1})	50	50
Straw (t a^{-1})	280	–
Dilution water (m^3 a^{-1})	2,371	551
Total feedstock (t a^{-1})	4,951	2,851
TS (t a^{-1})	594	342
TS (% of total)	12	12
Retention time (d)	21	21
Digester size (m^3)	328	189
Feed rate *VS* (kg m^{-3} d^{-1})	4.76	4.76
Storage tank capacity (m^3)	4,482	2,609
CH_4 yield potential (m^3 CH_4 a^{-1})	134,015	67,688
Realized CH_4 yield (% of potential)	68.88	71.22
Electricity input (kWh a^{-1})	112,545	71,300
Hygienisation unit (m^3)	12.9	7.5

TABLE 5 Liquid and dry digestate fraction compositions calculated based on Al Seadi et al. (2013), Drosg et al. (2015), Natural Resources Institute Finland (2022).

Index	AD_1	AD_2
Liquid fraction		
Quantity (t a^{-1})	3,874	2,253
TS (%)	4.17	4.67
C (kg t^{-1})	69	83
N, total (kg t^{-1})	2.28	3.53
Soluble N (kg t^{-1})	1.75	2.82
P (kg t^{-1})	0.17	0.25
K (kg t^{-1})	3.04	3.86
Dry fraction		
Quantity (t a^{-1})	850	495
TS (%)	24.20	27.06
C (kg t^{-1})	735	882
N total (kg t^{-1})	4.66	7.22
Soluble N (kg t^{-1})	1.75	2.82
P (kg t^{-1})	2.26	3.46
K (kg t^{-1})	2.45	3.10

TABLE 6 Inventory data related to pyrolysis (Kern et al., 2012; Li and Feng, 2018; Leppäkoski et al., 2021; Havukainen et al., 2022).

Pyrolysis	AD_1-PY	AD_2-PY
Digestate SF (t a^{-1})	228.8	148.8
Straw (t a^{-1})	–	280
Total (t a^{-1})	228.8	428.8
TS (% of total)	90	90
LHV (MJ kg^{-1})	15.1	13.5
Fuel thermal input (kW)	120	200
Pyrolysis heat efficiency (%)	76.7	76.7
Electricity demand (kWh a^{-1})	23,040	43,200
Light fuel oil use (kg a^{-1})	545	754
Heat for dryer (MWh)	696	512
Excess heat (MWh)	40	715
Transfer coefficient to biochar		
C (%)	33	33
N (%)	28	28
P (%)	61	61
K (%)	100	100
Biochar P usability (%)	33	33
Biochar N usability (%)	28	28

emission factor is applied in this study for all N in field spreading. Bruun et al. (2006) also estimated that carbon losses of compost and digestate can reach over 90% of total carbon 100 years after application on fields. Considering the modest carbon stability of compost, manure, and digestate, and the great uncertainty in soil carbon persistence (Heinonsalo, 2020), their carbon sequestration potential is excluded from this study.

3 Results

The scenarios for the utilization of manure, straw, and green waste were examined from a financial and climate impact perspective, and the results are presented in Table 7; Figures 3, 4. The results are described in detail in the following subsections.

3.1 Net present value and internal rate of return

The progression of cash flow, NPV, and IRR for the treatment and utilization of agricultural sidestream biomasses are presented in Figure 3; Table 7. Baseline scenario outperformed other scenarios in financial performance based on its eight-year payback period. The baseline scenario NPV value varied between 521,734 € and – 74,862 €, with interest rates from 0 to 20%, and presented an IRR of 12.90%. As burning the straw for energy and spreading manure to farmlands without treatment can be accomplished with significantly lower investment and operational costs than AD or PY, incomes from replaced district heat and nutrients are enough to make the scenario financially attractive. Small quantities of compostable matter also obviate the demand for large investments in composting treatment. The weak financial performance of the compost scenario was presented by an IRR of 0.53% and the variation of NPV ranging from 42,514 € to −464,417 € (interest rate between 0 and 20%), demonstrating how the low return of investment of composting counterbalances the financial benefits of spreading untreated manure to farmlands.

The AD_1 and AD_2 scenarios presented no financial advantage, indicated by the relatively high payback periods, 12 and 13 years, respectively, due to high investment costs compared to income. These scenarios have the modest feasibility after composting, suggested by IRRs of 6.80% for AD_1 and 5.21% for AD_2. The NPVs ranged from 625,543 € to −333,847 € for AD_1, and from 451,659 € to −361,035 € for AD_2 within 0 and 20% interest rates. The feasibility of the AD process can be improved with high carbon concentrated lignocellulosic feedstock, as presented in AD_2, but this operational option falls financially short compared to AD_1 due to savings achieved by burning straw to replace district heating.

The co-application of AD with PY increases the feasibility of the treatment because of the high market price of biochar, improved biomethane yield, and obviation of composting treatment. These were actualized by payback periods of 9 and 9.5 years and IRRs of 11.03 and 10.17% in scenarios AD_1-PY and AD_2-PY, respectively. These scenarios presented NPVs between 1,085,721 € and – 230,808 € for AD_1-PY, and between 877,373 € and – 223,961 € for AD_2-PY within 0 and 20% interest rates, respectively, presenting improvement in the profitability compared to using AD alone.

3.2 Global warming potential

Most of the climate impacts within the examined waste management scenarios occurred with the application of nutrient-rich manure, digestate, or compost on farmlands as presented in Figure 4. Emissions are released in composting, straw burning, AD, and PY processes, and avoided by replacing district heat and natural gas with bioenergy, soil material with compost soil, and mineral fertilizers with organic fertilization. Along avoided emissions, carbon sequestration was established by storing biochar carbon to ground.

The co-application of AD and PY, presented by AD_1-PY and AD_2-PY, indicating the closely to carbon neutral operational models; they had the lowest GWPs of 21,636 $kgCO_2$eq. FU^{-1} and – 4,122 $kgCO_2$eq. FU^{-1}, respectively. The low GWP of these scenarios is due to carbon sequestration with PY biochar, improved biomethane yields, and reduced quantities of feedstock composted and spread to farmlands. By burning straw in PY instead of digesting, as in AD_2 – PY, the amount of carbon sequestered to farmlands in the form of biochar was increased.

The higher GWP of AD_1, 95,610 $kgCO_2$eq. FU^{-1}, and lower GWP of AD_2, 36,900 $kgCO_2$eq. FU^{-1}, are indicating that in this study, replacing district heat by burning straw leads to lower emissions rather than digesting it. Burning straw instead of digesting reduces the amount of compostable digestate and increases the amount of heat energy that can replace district heating. Digesting straw does improve the methane yield of AD; however, required composting of the increased amount of digestate neutralizes any benefits it brings.

TABLE 7 IRR and NPVs on 0, 5, 10, and 20% discount rates of treatment scenarios.

Scenario	NPV € (0%)	NPV € (5%)	NPV € (10%)	NPV € (20%)	IRR (%)	Payback period (years)
Baseline	521,734	208,877	53,648	−74,862	12.90	8
Compost	42,514	−243,667	−375,372	−464,417	0.53	19
AD_1	625,543	110,365	−139,124	−333,847	6.80	12
AD_2	451,659	12,473	−198,957	−361,035	5.21	13
AD_1-PY	1,085,721	388,722	46,460	−230,808	11.03	9
AD_2-PY	877,373	293,085	6,722	−223,961	10.17	9.5

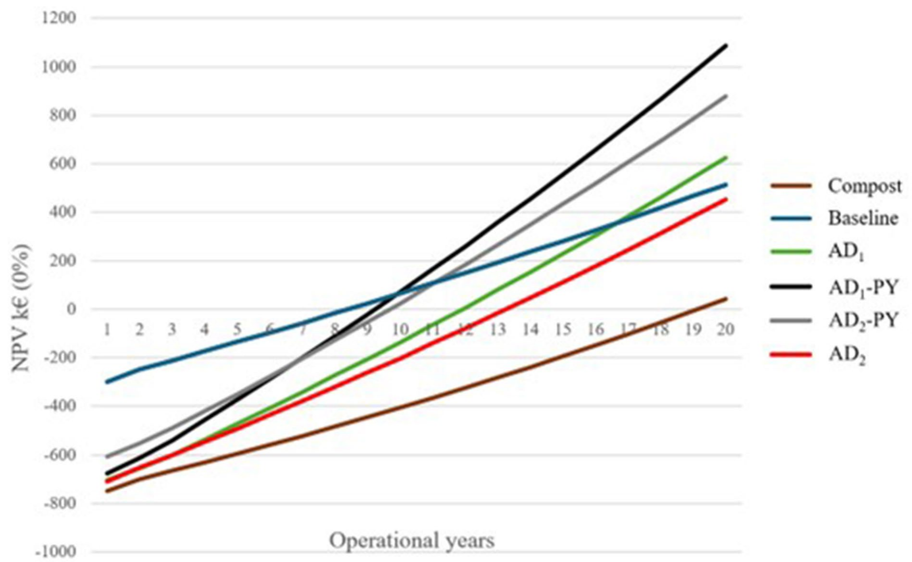

FIGURE 3
Accumulated cash flows without discounting for the assessed scenarios on 20-year-lifetime.

Based on their climate impacts, the baseline and composting scenarios were found to be poor treatment methods, suggested by the GWPs of 76,307 kgCO_2eq. FU^{-1} and 104,513 kgCO_2eq. FU^{-1}, respectively. These findings emphasize the importance of establishing carbon sinks through biochar application as soil conditioner and replacing high emission-intensive fossil fuels with renewable alternatives.

3.3 Parameter sensitivity

The results from financial and climate impact assessment are further analyzed in terms of most significant parameters. Table 8 presents an absolute change of the results, expressed in terms of NPV (0%) in k€ and GWP in tCO_2eq FU^{-1} with +25% changes of the parameter value applied. For example, when the electricity price increases by 25%, the NPV (0%) of the AD_1 scenario decreased by 35.7 k€, whereas in the compost scenario, the effect on the NPV (0%) is minimal. Setting a carbon market price differs from other parameter changes. Here, the price for GHG emissions is set to 100 € tCO_2eq.$^{-1}$ (Luhas et al., 2022), which increases the NPV (0%) for the AD_2-PY scenario but decreases it for other scenarios.

The sensitivity analysis revealed that the parameters presenting the most significant sensitivity for the NPV (0%) results were initial investment, methane price, and biochar price. Electricity price fluctuations do not present remarkable changes in the results of the waste management scenarios. The results of the financial analyses showed a remarkable sensitivity to fluctuations in biochar and methane prices, whereas district heat prices present low sensitivity. GWP results are highly sensitive to changes in the methane yield and amount of district heat replaced. Methane yield fluctuation causes the most significant change in the AD_1 and AD_1-PY scenarios, whereas the baseline, compost, and AD_2 scenarios were most sensitive to changes in the amount of replaced district heating. The AD_2-PY scenario presents no remarkable sensitivity for any certain parameter in terms of GWP.

4 Discussion

The current study presents that the co-application of AD and PY effectively reduces the climate impacts of agricultural operations as a treatment option of sidestreams of straw, manure, and green waste compared to alternative operational practices. However, the financial

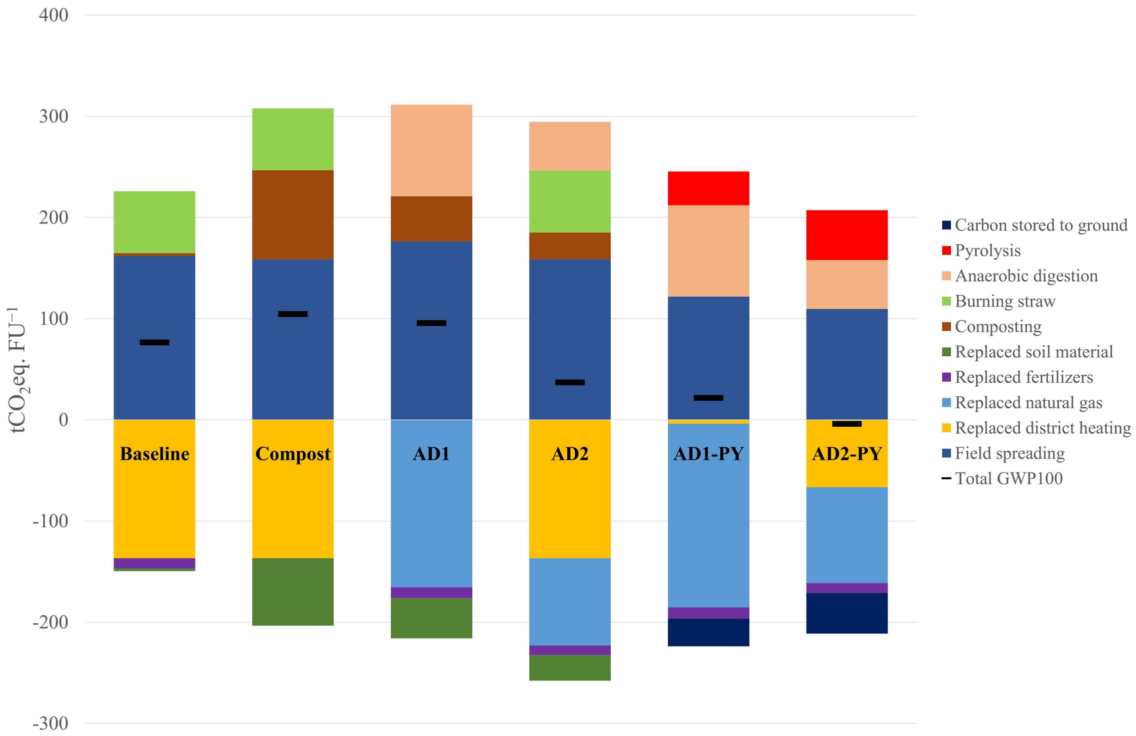

FIGURE 4
Climate impact of the scenarios and their specific life-cycle stages.

TABLE 8 Sensitivity analysis of uncertain parameters of the treatment scenarios.

Parameter	Change	Indicator	Baseline	Compost	AD_1	AD_2	AD_1-PY	AD_2-PY
Setting carbon market price	100 € / tCO_2eq^{-1}	NPV k€ (0%)	**−145.0**	**−198.6**	**−181.7**	−70.1	−24.9	+7.8
Electricity price	+25%	NPV k€ (0%)	0.0	0.7	−35.7	−22.7	−46.6	−38.3
Initial investment	+25%	NPV k€ (0%)	−70.4	**−230.5**	**−238.2**	**−231.0**	**−228.7**	**−218.3**
Methane price	+25%	NPV k€ (0%)	0.0	0.0	**+421.7**	**+220.2**	**+463.8**	**+242.2**
Biochar price	+25%	NPV k€ (0%)	0.0	0.0	0.0	0.0	**+196.5**	**+291.0**
District heat price	+25%	NPV k€ (0%)	**+179.4**	**+179.4**	0.0	**+179.4**	+1.6	+29.2
Methane yield	+25%	GWP ($tCO_2eq.$)	0.0	0.0	**+41.3**	+21.6	**+45.4**	+23.7
Biochar yield	+25%	GWP ($tCO_2eq.$)	0.0	0.0	0.0	0.0	+6.8	+10.0
Replaced district heat	+25%	GWP ($tCO_2eq.$)	**+34.2**	**+34.2**	0.0	**+34.2**	+0.9	+16.6

The bolded values mark the most significant sensitivity: >100 k€ change for the NPV (0%), and > 30 $tCO_2eq.$ FU^{-1} change for the GWP.

performance of the co-application indicated a longer payback period than the baseline option of spreading untreated manure on fields. To our knowledge, this is the first report of a simultaneous financial and environmental assessment of the co-application of AD and PY against competing technologies in the agricultural context. Through cash flow analysis and LCA, we show that the co-application could offer a low-emission waste management solution for agriculture.

In terms of sidestream management, the results suggest that the digestion of straw generates slightly higher profitability compared to being burned for energy. However, by replacing fossil energy with burning straw, the climate impacts can be decreased tremendously. Additionally, it was observed that utilizing biochar in AD decreases the system-level emissions by improving methane yields but slightly decreases the overall financial performance due to lost profits from high biochar price. The results confirm that complementing AD with PY reduces the climate impacts of agricultural activities in a reasonably profitable way while improving the product portfolio in comparison to business-as-usual practices and use of single AD. Therefore, for farms already utilizing AD for treatment of agricultural sidestreams, investing in PY technology seems highly beneficial. It is worth noting that the sensitivity analysis presented greatest uncertainty for the profitability of co-application scenarios in terms of high investment costs and fluctuation in the methane price, which were less critical for the baseline scenario.

Figure 5 visualizes the scales of financial and climate impacts of different waste management strategies assessed in this study. The

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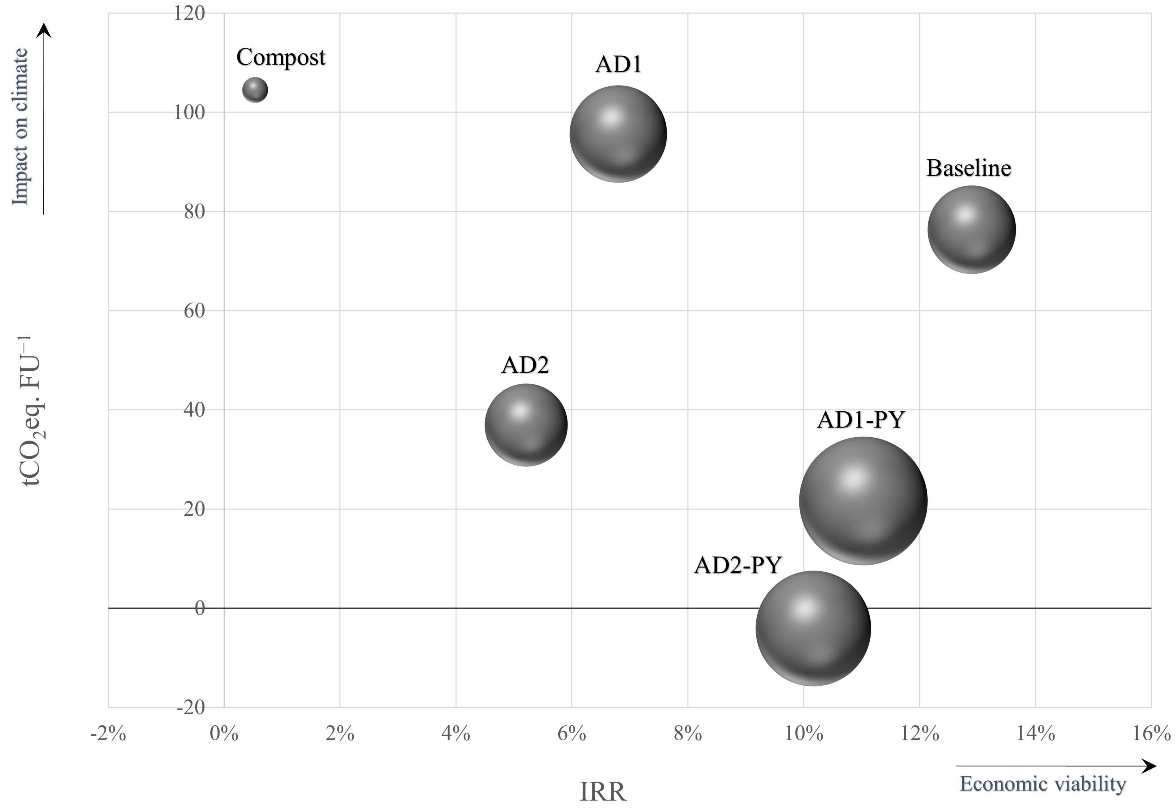

FIGURE 5
Waste management scenarios were compared according to based on economic viability and impact on climate.

further on the right on the scale and the larger the bubble, the better the profitability of treatment option in terms of NPV and IRR. The lower on the y-axis, the desirable the climate impacts. Even though the baseline scenario stands out in the comparison in terms of IRR, the co-application of AD and PY is displayed as a favourable treatment option when prioritizing both financial and environmental goals. In comparison to baseline, the non-discounted NPV of the co-application scenarios was higher, indicating a positive signal for the financial attractiveness of the investment at low discount rates. The results of the financial analysis are in line with Mills et al. (2014), who assessed the co-application of AD and PY in treatment of wastewater sludge. They reported a slightly lower profitability (IRR 7.64%) for AD-PY than this study, which can be explained by their exclusion of biochar utilization. This indicates that the co-application of AD and PY could present a promising option for farmers looking to reduce or even neutralize their climate impacts without compromising excessively on profitability. However, this solution would require financial support or further development for entrepreneurs to adopt the technology.

The absolute values regarding climate impacts are challenging to compare against previous studies, especially due to the different type of FUs and system boundaries applied. Most of the related LCA studies define the FU based on kg or tonne of treated waste (Mills et al., 2014; Wang et al., 2021; Caiardi et al., 2022; Havukainen et al., 2022). In this study, the FU was set for the annual management of the sidestreams in the agroecosystem, enabling assessment of financial and climate impacts within the same FU. The FU of annual management of the sidestreams was selected due to the systemic approach that also differentiates from earlier studies. For example, Caiardi et al. (2022) did not include the N_2O emissions from the field application of nutrients, and Wang et al. (2021) did not treat the LF of the digestate, resulting in lower GWP compared to in this study. Regardless of the absolute values, the interpreted results obtained here are consistent with those reported in earlier literature that assessed the GWP of AD and PY in treatment of different types of organic wastes. Similarly to the present study, coupling AD and PY processes was found to be a significantly favorable waste treatment option compared to single AD usage (Mills et al., 2014; Wang et al., 2021) or performing at least at a similar level (Opatokun et al., 2017; Caiardi et al., 2022).

The data used in the study were based on peer-reviewed publications and publicly available reports. The performance of the co-application of AD and PY can be scaled for larger systems, and the study results are reasonably applicable in other geographic locations, after considering the study limitations. However, the reliability of the results was affected by geopolitical instability, which had caused fluctuating prices of energy and fertilizers, making them difficult to predict for the future (Autoala, 2023; Helen Oy, 2023; Nasdaq, 2023; The World Bank, 2023). With changing energy prices, the profitability of the AD and PY pathways could be affected significantly. Similarly, changes in biochar price and inclusion of carbon markets could influence the results notably, as presented in Table 8. Therefore, the solution also presents potential as a financially viable strategy in a future where GHG emissions are more strongly tied to economic activities, for instance through carbon markets.

The methane production potential of straw differentiates greatly with some studies presenting typical potentials between 224- and 278-ml g^{-1} *VS* (Contreras et al., 2012; Ferreira et al., 2013; Sapci, 2013; Ferreira et al., 2014). The methane potential can vary significantly between the feedstock, reaching potentials as low as 162- and high as 336-ml g^{-1} *VS* (Dai et al., 2020). Dilution of straw has been shown to slightly improve the methane production from straw due to reduced solids concentration (Ferreira et al., 2014). As straw was not digested separately in the present study, the methane potential of 280 mL g^{-1} *VS* defined by Lei et al. (2010) for straw with anaerobic sludge was applied here. Studies also recommend heat pretreatment of straw to reach optimal methane yields in the digester (Ferreira et al., 2013, 2014). With lower straw methane yields the AD_1 scenario would we notably worsen in terms of climate and financial performance. There is some uncertainty related to straw with its availability. The collection potential of straw varies regionally and is constrained by competition with other uses (Scarlat et al., 2010). The collection potential is affected by the uncertainty regarding soil improvement benefits from leaving straw in the field. Attempts to maintain SOC could also limit the collection potential of straw (Johnson et al., 2010).

The exclusion construction of machinery from the LCA with the assumptions made regarding the use of excess heat from the PY process can cause some level of uncertainty for the results (Leppäkoski et al., 2021; Marttila et al., 2021). In this study, the exclusion of transportation machinery from the financial analysis was justified based on the assumption that the spreading of manure and digestate would include the same investments in all the scenarios. Transportation of goods also found to have minimal environmental impacts in related LCA studies (Leppäkoski et al., 2021; Marttila et al., 2021; Luhas et al., 2022) but could weaken the profitability of the treatment options, especially in smaller scale applications. The study results were partly sensitive to the assumption made regarding district heat (Table 8). In this study, a thermal dryer was assumed to utilize excess heat from the PY, with 50% of remaining heat used to replace district heat. With increased heat demand of the dryer, the climate impacts of the PY scenarios could increase as less excess heat would be available to replace district heating. The present study did not consider the N_2O emissions from storaging of the digestion prior to spreading on fields which could have altered the climate impacts of treatment options to some extent.

Co-application of AD and PY helps farmers reduce their resource dependence on imported goods such as fossil energy, while diversifying their revenue streams and thereby alleviating levels of uncertainty related to financial profitability. By generating additional income from the production of biochar, biogas, and organic fertilizers, the co-application of AD and PY can increase resilience in the market by minimizing vulnerability to input price fluctuations. This highlights the importance of also considering qualitative indicators such as security of supply when evaluating the best approaches for managing agricultural sidestreams in future research. Moreover, the trade-offs between different treatment options in terms of multiple environmental indicators and consideration of the co-application of PY and AD as a carbon sequestration method in carbon markets should be assessed. Some of the techno-economic benefits of the co-application of AD and PY, recognized in earlier literature (Pan et al., 2019; Song et al., 2021; Tayibi et al., 2021), were not considered in this study. Although immediate improvement in the profitability against the field application of manure was not documented in this study, by considering potential for reduced lag phase, healthier functioning of AD, or utilization of AD excess heat, could result in more financially competitive operational models, which could be addressed in future research.

While spreading untreated manure on fields presented a financial advantage, this solution has limitations, such as local legislation related to high pathogen, heavy metal, or organic pollutant levels of manure (Ruuskanen et al., 2016; Muurinen et al., 2017; Liu et al., 2018; Enbuske et al., 2020). Additionally, poorly treated manure can reduce the N reserves of the soil and weaken its fertilizing effect (Myllymäki et al., 2014). Finland's sparse population also concentrates local livestock production heavily in certain areas, which can lead to some locational abundance of manure fertilizer (Peltonen and Hagelberg, 2019). If the amount of generated manure on a farmland is too large to use locally, farmers may have to deal with additional transportation costs to utilize the excess manure in other locations. Applying manure fertilizing serves solely the fertilization purpose, making the business-as-usual model more vulnerable to market fluctuations and stricter legislation, to which operational models with more diverse product portfolios would not be as strongly exposed to.

For the agricultural and other rural entrepreneurs, this research demonstrates the potential to achieve reductions in their climate impacts and reduce dependency on imported goods and energy by investing in the co-application of AD and PY technology. The authors, on the other hand, acknowledge that adoption of these technologies may pose challenges for individual farmers, particularly in terms of initial investment costs and technical expertise. Therefore, further education of farmers on the benefits of the co-application and on how to implement this approach effectively is necessary for its successful operation. Acknowledging the increasing concerns related to rising levels of GHG emissions, policy makers should consider strengthening governmental support mechanisms for implementing sustainable technologies that would increase domestic carbon sinks. This study highlights the importance of supportive legislation through financing options and tools, such as tax incentives and low-interest loans, as carbon market prices were shown to significantly affect the financial performances of different treatment options.

5 Conclusion

This study examined the financial and climate impacts of the co-application of AD and PY in the management of agricultural sidestreams. The results present that although this solution might not be financially most profitable for the entrepreneur, it presents potential as an effective way for agricultural operators to reduce their emissions while increasing their product portfolio and revenue streams. Establishment of AD-PY solutions instead of a single AD is estimated to increase profitability and reduce emissions. In addition, two trade-offs between financial and climate impacts were recognized; digestating straw in this system leads to improved profitability but incinerating it for heat energy would increase emissions within the system. On contrast, addition of biochar to AD process decreases the profits but lessens the impact on climate.

It is recognized that holistic assessments considering financial and environmental implications of technologies and solutions are required for recognizing best practices for sustainable low-carbon economy. Although co-application of AD and PY is not yet the most profitable solution on the market, it presents potential for cost-effective reduction of GHG emissions for the future where suitable legislation or technological development has taken place. Overall, the insights in this paper could guide decision-making processes for individual entrepreneurs and policy-makers in the agricultural sector, aligning sustainability and financial viability in operational practices and policies guiding them. To conclude, the co-application of AD and PY aligns with the principles of a circular bioeconomy by closing the loops of waste streams, thereby supporting in providing solutions for sustainable operational models for rural waste management.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

MMa: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. JH: Conceptualization, Data curation, Investigation, Methodology, Writing – review & editing. VU: Conceptualization, Methodology, Supervision, Writing – review & editing. LL: Conceptualization, Supervision, Validation, Writing – review & editing, Project administration. MMi: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Validation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2024.1426890/full#supplementary-material

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