THE IMPROVEMENT OF BIOWASTE MANAGEMENT AND UTILISATION OF A GREENHOUSE TOMATO PRODUCTION PLANT: A CASE STUDY

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ABSTRACT

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Abstract

Agricultural waste that is daily generated in immense quantities poses an environmental, social as well as an economic burden if left untreated. The transformation to a sustainable circular bio-economy model is promoting the elimination of the mismanagement of agricultural waste by its valorisation though multiple different processes. For small and mid-size farmers anaerobic digestors for biogas production or aerobic composters for biofertilizer production are available and promising solutions. Not only do the farmers eliminate costs of waste treatment but can potentially attain further profit from products of employed technologies. The main aim of this research is to analyse and evaluate the current situation of waste management in a small agri-food production company, Agro GTV, and propose sustainable innovative solutions on how to improve its biowaste management with the application of circularity measures, to reduce costs and increase the efficiency of waste management based on the research and new developments in the area.

Key words
Biowaste, Biogas production, Composting, Circular economy, Biowaste management

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LIST OF ABBREVIATIONS

Ammonia (NH_3)
Anaerobic digestion (AD)
Biochemical methane potential (BMP)
Bulk container (BC)
Business to customer (B2C)
Carbohydrates ($C_6H_{12}O_6$)
Carbon dioxide (CO_2)
Carbon monoxide (CO)
Capital Expenditure (CapEx)
Chemical oxygen demand (COD)
Circular economy (CE)
Continuous stirred tank reactor (CSTR)
Cumulative methane production (CMP)
Direct plant costs (DPC)
General Systems Theory (GST)
Greenhouse gas (GHG)
Hydrogen (H_2)
Hydrogen sulphide (H_2S)
Industrial Ecology (IE)
Internal rate of return (IRR)
Intergovernmental Panel on Climate Change (IPCC)
Life cycle assessment (LCA)
Lipids ($C_{12}H_{24}O_6$)
Long-chain fatty acids (LCFAs)
Methane (CH_4)
Municipal solid waste (MSW)
Net present value (NPV)
Nitrogen (N_2)
Nutrient film technique (NFT)
Organic loading rate (OLR)
Proteins ($C_{13}H_{25}O_7N_3S$)
Sustainable Development Goals (SDGs)
The European Union (EU)
The organisation for economic co-operation and development (OECD)
Total kjeldahl nitrogen (TKN)
Total costs (TC)
Total Plant Costs (TPC)
Total Solids (TS)
Volatile fatty acids (VFAs)
Volatile solids (VS)
Water vapour (H_2O)

1 INTRODUCTION

1.1 Agriculture and sustainability

Agriculture affects ecosystems in a number of ways e.g., pollution, soil erosion, eutrophication, loss of biodiversity. Technological advancement and innovation in agricultural practices have led to intensification of production leading to higher productivity. However, the intensification has also significantly increased impacts on the environment as well as human health through agrochemicals, especially fertilizers and pesticides (Talukder et al., 2020; Chopin et al., 2017; Lampridi et al., 2019). According to IPCC (2023), the agricultural sector is responsible for approximately 23% of global greenhouse gas (GHG) emissions. Moreover, half of the habitable land and about 70% of global freshwater is used in agriculture. Undoubtedly, the industry contributes to one of the greatest global challenges, climate change. At the same time, agricultural productivity across the globe is also subject to climate change and is vulnerable in the context of a rapidly growing population and demand for food (Talukder et al., 2020; Chopin et al., 2017). According to projections, the world's population is expected to reach 9.8 million in 2050 and it is estimated that human society will require two times the Earth's resources to meet the demand for food, water, and energy (Lampridi et al., 2019).

Sustainability in agriculture has been a common concern for researchers already since the 1960s. By recognising its impacts on the environment, health and economy, and its pervasive use of natural resources, the idea of sustainable agriculture has been developed. Firstly, it focused mostly on the environmental aspects but later expanded into economic, social, and political dimensions as well (Talukder et al., 2020). Today, agriculture has been recognised as one of the many necessary ways to achieve Sustainable Development Goals (SDGs), especially number 1 - No poverty, 2 - Zero hunger, 12 – Responsible consumption and production, and number 13 – Climate action (UNDP, 2023; Talukder et al. 2020). As Latruffe et al. (2019, p.123) stated, *"the application of the concept of sustainable development in agriculture is of interest both for the sustainability of the agricultural system itself and its contribution to sustainable development."* However, for that to be possible, a shift in the agricultural industry is necessary. It can be accomplished through significantly broader sustainable food system strategies. The issue of whether current agricultural practices can provide equitable, healthy, and sustainable food for the ever-expanding population is now not just a query but a worldwide challenge (Talukder et al., 2020).

Important inquiries pursued by scientists and researchers primarily revolve around enhancing existing practices to ensure greater sustainability, identifying sustainable agricultural systems, and determining if agriculture can support ecosystems and improve the quality of life for both producers and consumers (Talukder et al., 2020; Chopin et al., 2017; Lampridi et al., 2019). The scientific community has been exploring the definition of sustainable agriculture however it seems like a challenging task since agricultural practices involve many case-specific variables that should be considered in sustainability assessment (Lampridi et al., 2019; Pandey, 2014). Lampridi et al. (2019) and Hayati et al. (2011) argue that sustainability is a dynamic, complex concept that is difficult to be generalized and to some extent, what is defined as sustainable depends also on the perspectives of the analysts. To this day, there is not yet established one standardized methodology for agricultural sustainability assessment as part of a unified concept of sustainable development. It is however useful to understand what variables play a role in the most widely used tools for such assessment, e.g., life cycle assessment (LCA). The variables involved are for instance crop type, machinery, fertilizers, location, transportation, cultivation process, waste management, economic viability, etc. (Lampridi et al., 2019).

1.2 Circular economy in agriculture

As already mentioned, in order to support the global population of tomorrow, a change in the food system needs to happen. It is time for society to cooperate on building a sustainable food system where growing, eating and disposal of food is not a burden but creates benefits for people, the environment, and the economy (Jurgilevich et. al., 2016). Scholars suggest that building a circular economy for food offers a solution to achieve this (Jurgilevich et. al., 2016; PACE, 2021). Since agriculture is a major part of the food system, the circular economy needs to be incorporated there as well.

Essentially, circular economy means to reuse, repair, refurbish and recycle existing materials and products; what was once considered waste becomes a resource (Jurgilevich et. al., 2016). In that sense, aiming towards a circular economy in agriculture implies prevention and reduction of the amount of waste generated, better recycling and sustainable management of nutrients, re-use, utilisation of by-products, and a shift from high input to more ecological principles in agriculture production systems (Bikra Vea et al., 2018; Jurgilevich et. al., 2016). As mentioned before, food production of today is very resource-intensive, wasteful and pollutes the environment. There is however a great potential for agriculture to go beyond the reduction of negative impact and to contribute to the regeneration of natural systems (PACE, 2021). If managed effectively, it could keep soil healthy and water clean, store carbon and provide homes for a wide range of biodiversity both above and below the ground. For this to happen, a major shift in what and how we grow is necessary (PACE, 2021). Apart from the suggestions to adapt our diet, production methods should be changed to include more resource-efficient and regenerative methods such as agroforestry, permaculture, and vertical or hydroponic farming (PACE, 2021).

According to MacArthur (2013), only less than 2% of nutrients in food by-products and human waste from cities are recycled back into agriculture. These materials are, however, valuable resources and should be used productively for instance as energy source, fertilizer, insect feed, textile or plastic raw material. In turn, this would also reduce the costs of waste disposal for various stakeholders involved in the value chain (PACE, 2021).

It is important to recognize that waste from food production that was once considered just waste and would end up landfilled, can create value. This waste can be used in new productive ways, or ways that have been largely forgotten. When looking at waste as new raw material, it can be transformed into valuable resources, and nutrient-rich fertilizers and can be turned into fuel (Bikra Vea et al., 2018; PACE, 2021). Collected organic waste can be composted and used for anaerobic digestion in biogas production (Jurgilevich et. al., 2016).

There is a great opportunity in reframing materials that are currently being wasted, and develop new business models and markets to facilitate their use. In fact, this is becoming a critical step towards the circular food system, as it will help to close the loop (Jurgilevich et. al., 2016). This could be achieved by increasing investments and sponsorship, both governmental and private sector, to innovation programs where new technologies can be brought to market to make productive use of agricultural waste (Jurgilevich et. al., 2016; PACE, 2021).

1.3 Aim and structure of the research

In this Master's thesis, a major focus is given to agricultural waste management and circular economy. The purpose of this research is to analyse and evaluate the current situation of waste management in a chosen case company, Agro GTV. The main aim is to propose sustainable innovative solutions on how to improve its biowaste management with the application of circularity measures, to reduce costs and increase the efficiency of waste management based on the research and new developments in the area. Hence, we have formulated the main research question "*What are the two best possible circular-economy solutions for the improvement of biowaste management in Agro GTV?*" and a sub-question "*Is small-scale biowaste processing feasible in the case of Agro GTV?*".

The case company Agro GTV is a small company located in Slovakia that runs a greenhouse tomato production plant using hydroponic systems. The results of our research will provide Agro GTV with two scenarios including the overview of the proposed solutions, techno-economic feasibility evaluation, legislative requirements, and social as well as business impacts. These results can be utilised in the future for further research or as a preliminary outline for waste management improvements in similar companies. Accordingly, a case study was selected as the optimal research design where all data used for analysis were provided by the company.

The thesis is structured in the following manner. Firstly, a theoretical framework with a focus on key concepts and theories is provided. Secondly, the methodology of this study is explained, and the case company is introduced. The next chapter on results and analysis presents the two suggested scenarios for bio-waste management improvements and their analysis, based on which, the preferred scenario is selected. To conclude the thesis discussion and conclusions consist of the interpretation of results, comparison with previous research, study limitations, as well as the implications and applications in the wider context.

2 THEORETICAL FRAMEWORK

In this chapter, a theoretical background for this thesis will be provided. Multiple different topics and fields of study are related to this research therefore an overview of them is provided separately in three sections. They all, however, play an important role in this study and the fact that they are interlinked will become more obvious by the end of this chapter. Firstly, three key concepts will be introduced. The second section will be dedicated to biogas production and in the third section, the process of composting will be reviewed.

2.1 Key concepts

This chapter starts with the introduction of three key concepts. Agricultural waste management and issues regarding sustainability will be discussed as well as the concept of circular economy and bioeconomy will be presented.

2.1.1 Agricultural waste management

Food is one of the basic needs for human survival. It is fundamental for our health, environment, society and economy. And yet, the current food system is wasteful, resource-intensive and highly polluting (Holden et. al., 2018; Jurgilevich et. al., 2016; PACE, 2021). The food system including agriculture is facing many sustainability challenges not only in Europe but also globally. Climate change, population growth with increasing demand for food, biodiversity loss and unsustainable food production practices are all indicators that there is a need for a transition towards more sustainable practices (Jurgilevich et. al., 2016).

With the growing human population, the demand for food has been naturally increasing too. Due to the need to meet such a demand, agricultural productivity has also been increasing globally since the middle of the twentieth century (Balogh, 2020; Hongdou et al., 2018; Kulcu, 2014). Nonetheless, this has resulted in inadequate and unsustainable agricultural methods that contribute to environmental decline (Hongdou, 2018). In the context of the prediction that the world population will reach more than 9 billion by 2050, many are concerned. It is important to support the global population of tomorrow however to achieve that, a change in the agriculture system is required. The world, including Europe, is experiencing many challenges such as unsustainable exploitation of natural resources, global warming, unpredictable severe changes in climate, and biodiversity loss (Diacono et. al., 2019). Overcoming them requires radical changes in resource use, people’s lifestyles as well as innovation in agriculture.

According to the literature, agriculture is one of the major contributors to climate change (Balogh, 2019). It is estimated that approximately 30% of the global emissions released into the atmosphere come from agricultural activities which negatively affect the environment and the climate. GHG emissions originating from agriculture primarily consist of methane and nitrous oxide, whereas the majority of carbon dioxide emissions arise from the practices linked to agricultural production (Balogh, 2020). The production process might include many activities with a destructive effect on the environment. These might involve improper land utilization, the excessive usage of pesticides and chemical fertilizers, or the deployment of agricultural machinery (Balogh, 2020; Hongdou et al., 2018).

Even though the emissions have been rising yearly since 1990 at a global level, the impact of agriculture and its intensity varies among countries and continents (Verschuuren, 2016). Moreover, it varies among different types of agricultural activities such as crop cultivation, the use of machinery, livestock farming, forestry or waste management. Waste management plays a crucial role when it comes to making the agriculture industry more sustainable.

An agricultural waste management system can be defined as a *"planned system in which all necessary components are installed and managed to control and use byproducts of agricultural production in a manner that sustains or enhances the quality of air, water, soil, plant, and animal resources"* (Obi et al., 2016, p. 960). The system is formed by six basic functions - production, collection, storage, treatment, transfer, and utilisation (Figure 1 below).

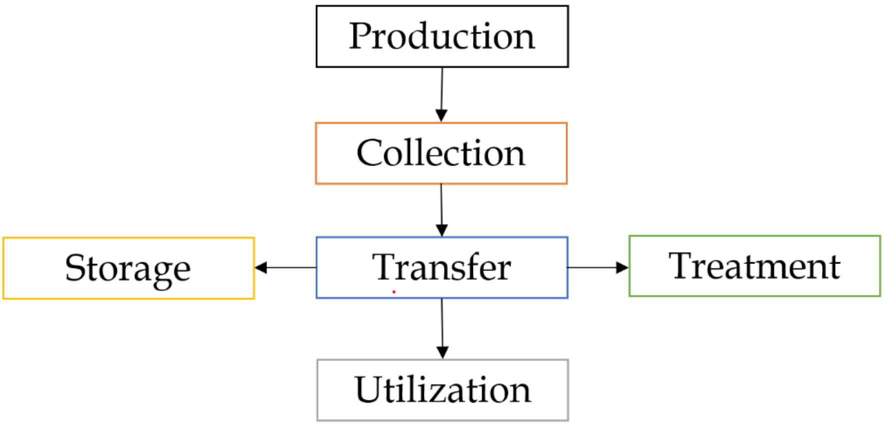


Figure 1: Agricultural waste management functions (Obi et al., 2016)

Production refers to the quantity and characteristics of waste originating from agriculture. A comprehensive analysis of production includes the type, consistency, volume, location, and timing of the waste generated (Obi et al., 2016). *Collection* refers to the initial capture and assembly of waste generated, starting from the point where it originates or is deposited. Obi et. al. (2016, p. 960, 961) highlights that the agricultural waste management plan "*should identify the method of collection, location of the collection points, scheduling of the collection, labor requirements, necessary equipment or structural facilities, management and installation costs of the components, and the impact that collection has on the consistency of the waste."*

The storage function involves temporarily storing or containing waste. A storage facility provides control over the regulation of the timing of system functions such as waste treatment or disposal which could be affected by weather or disrupted by other operations (Obi et al., 2016).

Treatment refers to any function that minimizes contamination or toxic potential of the treated waste, including biological, chemical, and physical treatment, and maximizes its capability for further reuse (Obi et al., 2016). In this context, preliminary treatment encompasses prior waste analysis, anticipation of waste characteristics post-treatment, and the choice of treatment process type, estimated scale, and associated management expenses (Mamo and Zewide, 2022).

Transfer pertains to the movement of waste throughout the system, commencing from the collection phase and extending to the utilisation stage (Mamo and Zewide, 2022).

Utilisation involves the application of waste for additional advantageous purposes. This encompasses recycling reusable waste and reintroducing nonreusable waste products back into the environment. (Obi et al., 2016; Thakur et al., 2021).

The notion of waste minimization decreases the amount and negative effects of waste disposal by reducing waste generation, reusing waste products with simple treatments, and repurposing discarded materials by utilising them as valuable assets to make new products (Obi et al., 2016; Thakur et al., 2021). This is commonly referred to as the '3R' method of reducing waste, reusing, and reusing materials and items through the process of recycling (see Figure 3 below). Certain waste materials have the potential to serve as valuable resources for the production of other goods or even the same product, thereby enabling the recycling of the same resource (Thakur et al., 2021). By reusing waste, it offsets the need to harvest new, comparable products, leading to the preservation of fresh resources and a reduction in the generation of waste.

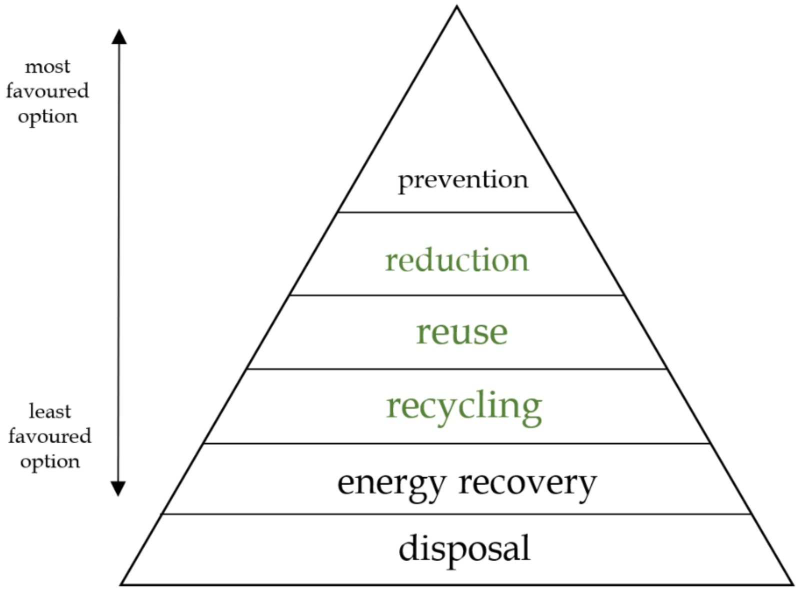


Figure 2: The 3Rs Hierarchy (Obi et al., 2016)

Overall, the 3Rs save fresh resource exploitation, add value to already exploited resources, and, most crucially, reduce the amount of waste and its harmful impacts (Obi et al., 2016; Mamo and Zewide, 2022). The 3Rs principle aims for effective and efficient reduction of waste generation by choosing to utilize items with a limit to the quantity of waste generated, repetitive usage of items or parts of items with still useful features and making use of garbage as a resource (Obi et al., 2016; Mamo and Zewide, 2022).

Inappropriate management of agricultural wastes negatively impacts the environment. Traditionally, the approach to agricultural waste management has been discharged to the environment with or without treatment (Obi et al., 2016). This has often resulted in contamination of water, soil and air, land resources as well as transmission of hazardous materials. To achieve a sustainable future, it is necessary to encourage waste reduction, reutilisation, recycling, and regeneration. When agricultural wastes are effectively managed and utilized, they have the potential of evolving into a sustainable resource for enhancing value and playing a significant role in ensuring energy security and ecological balance. Properly utilizing agricultural wastes can foster economic progress, preserve resources, promote circular economic practices, and safeguard human well-being (Awogbemi and Von Kallon, 2022). Achieving this requires improved technological utilization, incentivization, a shift in mindset and attitudes, and enhanced strategies for managing agricultural waste systems (Obi et al., 2016).

Every year, millions of tons of agricultural waste are generated. Environmentalists, governments, and other stakeholders continue to have legitimate concerns about the disposal and management of these wastes. These wastes are a burden to the environment, a health risk, and a source of habitat contamination when improperly disposed of and managed. Agriculture wastes can still be turned into valuable goods in a way that is economical, sustainable, and beneficial for the environment (Awogbemi and Von Kallon, 2022).

2.1.2 Circular economy

This section presents the second key concept, circular economy. As stated by Ghisellini et al. (2016), the concept of Circular Economy (CE) can be traced back to various schools of thought and its introduction is attributed to two environmental economists Pearce and Turner (1989). They have studied the linear and open-ended aspects of modern economic systems by detailing how natural resources influence the economy by supplying inputs for production and consumption as well as functioning as a sink for outputs in the form of waste (Geissdoerfer et al., 2017). Ghisellini et al. (2016) and Geissdoerfer et al. (2017) point out, that the work of Pearce and Turner (1989) was influenced by Boulding's (1966) work, which characterised the earth as a closed, circular system with a finite assimilative capacity, and concluded that the economy and the environment should coexist in equilibrium.

Ghisellini et al. (2016) acknowledge that CE has roots in the General Systems Theory (GST) and Industrial Ecology (IE) too. Due to the complexity and the degree of interdependence of relationships between organisations and environments, it is important to examine the behaviour of an economic agent or organisation within the context of the economic relationships between other agents in an economy. Consequently, holistic thinking, systems thinking, complexity, organisational learning and human development are important premises of CE, all of which promote GST.

IE and CE are both founded on the concept of closing energy and material loops to make a reduction in the industry's environmental effect commercially viable (Baldassarre et al., 2019). Ghisellini et al. (2016) further elaborate that CE builds on IE's notions for analysing and optimizing industrial processes, scaling them up to an economy-wide system to create a new model of economic development, production, distribution, and product recovery. However, CE aims to decouple economic growth and resource use by redesigning goods and processes to optimize the value of resources throughout the economy.

The Ellen MacArthur Foundation (MacArthur, 2013) is credited for furthering the development of CE and the most renowned definition, which frames CE as *"an industrial economy that is restorative by intention and design"* (2013, p.14). Geissdoerfer et al. (2017) conducted an extensive literature review and based on the ideas of Geng and Doberstein (2008), Webster (2015), Yuan et al. (2008), and Bocken et al. (2016) defined CE as *"a regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling"* (Geissdoerfer et al., 2017, p. 759).

The main appeal of CE lies in its promises to reconcile environmental and economic goals by lowering resource usage while simultaneously encouraging economic growth. Theories about sustainable development come and go, but CE has had a lot of success in terms of policy, business, and civic engagement (Hobson et al., 2018, as cited in Baldassarre et al., 2019)

CE applies several principles from nature such as repurposing of waste (further production), the use of renewable energy sources, systems thinking, resilience through diversity and cascading flows of materials and energy (Jurgilevich et. al., 2016). In other words, it is the opposite of the current linear economic model, the so-called 'take-produce-consume-discard model', that assumes an abundance of resources and unlimited disposal of waste to drive economic growth. The essence of a circular economy is to reuse, repair, refurbish and recycle existing materials and products; what was once considered waste becomes a resource (Jurgilevich et. al., 2016).

One of the potential benefits of CE that will bring us closer to a sustainable model of the economy is its aim to decouple economic growth and resource use by redesigning goods and processes to optimize the value of resources throughout the economy (Ghisellini et al., 2016). CE also focuses on addressing problems such as *''supply risk, problematic ownership structures, deregulated markets, and flawed* *incentive structures lead to increasingly frequent financial and economic instabilities for individual companies and entire economies"* (Geissdoerfer et al., 2017, p. 757).

CE cannot guarantee 100% recycling according to Ghisellini et al. (2016), due to the entropy law. An economic system can not be entirely circular, with goods and energy returning to raw materials indefinitely. Also, the lack of appearance of issues like disassembly, disposal without negative environmental impacts, ease of distribution and return, durability, reliability, and customer success should be addressed as well, due to the pertinence of these issues in the context of CE.

2.1.3 Bioeconomy

Thirdly, following the circular economy, bioeconomy is presented here. A concept of the bioeconomy can be understood as a part of the green economy (Kleinschmit et al., 2014) which is defined as *"one that results in improved human well-being and social equity, while significantly reducing environmental risks and ecological scarcities"* (UNEP, 2010). The concept of bioeconomy is based on the notion that natural resources are finite and must be utilised efficiently (Kleinschmit et al., 2014). McCormick and Kautto (2013) state that the bioeconomy meets a multitude of requirements for economic, social, and environmental sustainability by supplying the essential elements for chemicals, energy, and material production from renewable biological resources. It represents a fundamental shift from fossil fuels to biomass, which directly influences systemic changes in socio-economic, agricultural, energy and technical systems. Consequently, one of the characteristics of the bioeconomy is a large transformation in contemporary production and consumption systems. Major influencing factors of the bioeconomy are *"government policy, regulatory conditions, intellectual property rights, human resources, social acceptance and market structure"* (McCormick and Kautto, 2013), which entail intricate interactions and feedback, making factor isolation and analysis extremely difficult.

The roots of bioeconomy can be found in the discourse of ecological modernization which argues that through technological progress, biotechnology, economic growth, and development can coexist with environmental protection (Kleinschmit et al., 2014). In the political context, the concept of bioeconomy alters depending on how and by whom it is used. As Staffas et al. (2013) present, the EU strives towards a bioeconomy utilising biomass as a resource, whereas the OECD and the USA are concentrating their efforts on the process of transforming raw materials into value-added goods through biotechnology and life sciences. Bio-based goods and bioenergy are the main products of the bioeconomy, while biorefineries are the key technology that will be used to replace petroleum-based refineries (Kamm and Kamm, 2004).

The European Commission has conducted a public consultation with organizations connected to the bioeconomy through 35 position papers (*Bio-Based Economy in Europe: State of Play and Future Potential Part 2*, n.d.). The position papers revealed considerable support for a recycling economy that emphasizes the use of renewable resources; places energy consumption at the end of the chain;

follows the reuse and recycling of materials; and fosters synergies between food, materials, and fuels (McCormick and Kautto, 2013).

The potential benefits of the bioeconomy are greenhouse gas emissions reduction, lower dependence on fossil fuels, efficient utilisation of natural resources, improved food security and new forms of employment in urban as well as rural areas, and the establishment of non-food markets for agricultural production (McCormick and Kautto, 2013). Creating new markets, aside from food markets, for agriculture along with alternative income sources for farmers can lead to a revival of rural areas dependent on agriculture. The bioeconomy to 2030: Designing a Policy Agenda - OECD (2009) also highlights the potential benefits of bioeconomy and biotechnology in tackling worldwide issues such as the supply and sustainability of food, animal feed, and fibre production; water quality; renewable energy; health of the population and animals.

Bioeconomy has received criticism because its development is tightly bound to the specific preferences of those designing the developmental pathways. Hence, McCormick and Kautto (2013) argue that this can result in self-serving policy changes towards the utilisation and support of preferred biotechnologies for the profit of a select few organisations. Another concern presented by Smolker (2008) is that by mare substation of fossil energy by biomass energy we are not addressing the real problem of unsustainable energy resources. Large-scale agriculture, industrial monocultures and genetically modified crop varieties can only partially supplement the growing energy demand. NGOs also voiced their concerns regarding land erosion, biodiversity loss, water use, food scarcity and actual benefits of genetically modified crops in connection to the utilisation of large amounts of biomass (McCormick and Kautto, 2013).

2.2 Biogas production

This section introduces the theoretical background on technological and chemical intricacies of biogas production, broken down into an overview of the process, feedstock characteristics, process parameters, biogas upgrading and digestate.

2.2.1 Overview of the process

The overview of the process explains how biogas can impact mitigation measures in the fight against climate change and lays out the basic chemical processes associated with each of the five consecutive steps in biogas production.

One of the most financially feasible forms of renewable energy that addresses socioeconomic and environmental concerns is biogas (Deublein and Steinhauser, 2011; Karlsson et al., 2017). Biofuels have a role to play in the fight against climate change, greenhouse gas (GHG) emission reduction and subsequent protection of public health (Aghbashlo et al., 2018; Onthong and Juntarachat, 2017). The European Union (EU) Renewable Energy Directive (2009) says that when used as a compressed gaseous biofuel, biomethane from the organic fraction of municipal solid waste has a notional reduction in GHG emissions of 80% of the fossil fuel it replaces (Browne and Murphy, 2013). Compared to other first-generation liquid biofuels, these savings are substantial (Korres, 2010).

Browne and Murphy's (2013) analysis reveals that 2.8% of the transportation sector's renewable energy sources may come from food waste. Methane (CH_4) and carbon dioxide (CO_2) are the predominant components of biogas, accompanied by smaller amounts of water vapour (H_2O), hydrogen sulphide (H_2S), hydrogen (H_2), ammonia (NH_3), carbon monoxide (CO), nitrogen (N_2) and siloxanes are also present (Valijanian et al., 2018; Onthong and Juntarachat, 2017). According to Rajaeifar et al. (2017), anaerobic digestion (AD) of organic materials results in the production of biogas, which consists of approximately 60% methane (Mata-Alvarez, 2003). AD is carried out by a sophisticated microbial population through a series of intricate biochemical processes. Before getting injected into the gas grid or used as engine fuel, biogas needs to be upgraded to biomethane (Sahota et al., 2018).

Due to high organic matter concentration, food wastes have a significant potential to produce biomethane (Mirmohamadsadeghi et al., 2019), whereas agricultural waste has potential due to its abundance (Abreu et al., 2019). The availability of the resource is determined by both the quantity of food waste accessible for AD and the specific amount of methane produced from that waste (Browne and Murphy, 2013). Based on the reports of the Food and Agriculture Organization of the United Nations (2019) globally, almost 33% of the food we eat—or 1.3 billion tonnes annually—is wasted with estimated direct economic impacts of around US$ 750 billion (Peixoto and Pinto, 2016). Instead of feeding landfills, food waste can be turned into energy as it is a nutrient-rich source. High moisture content, volatile solids and salinity are the main reasons for high emissions of GHG from food waste and its subsequent foul odour, vermin attraction, as well as groundwater contamination (Yasin et al., 2013). Every stage of the food supply chain, encompassing activities such as agricultural processing, sorting, storage, distribution, sales, preparation, cooking, and serving, result in the generation of food waste (Xu et al., 2018). However, processing businesses and retailers account for the majority of the sources of food waste generation (Mirmohamadsadeghi et al., 2019). Municipal solid waste (MSW) is comprised 20 to 54% of general food waste according to data from different countries (Yasin et al., 2013). Figure 3 illustrates biogas production under anaerobic conditions going through four distinct phases, including hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Ghodrat et al., 2018; Al-Masri, 2001).

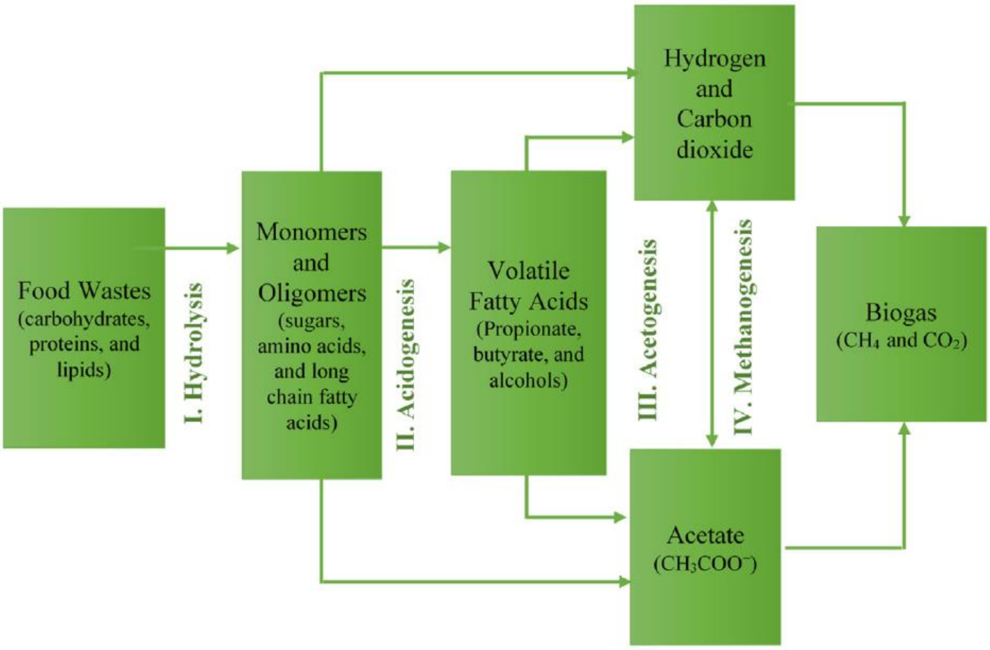


Figure 3: Biogas production from food wastes through AD (Mirmohamadsadeghi et al., 2019, p. 2)

Eq. 1 from Deublein and Steinhauser (2011), depicts the bioconversion reaction of food waste into biogas. It is a modified version of the original Buswell equation from 1952, for the estimation of products from the decomposition of a typical organic matter. The modification allows for computation of the biochemical methane potential (BMP) (Browne and Murphy, 2013).

Eq. 1

$$C_cH_hO_oN_nS_s + wH_2O \rightarrow mCH_4 + nNH_3 + s\,H_2S + (c - m)\,CO_2$$

where $m = \frac{1}{8}(4c + h - 2o - 3n - 2s)$ and $w = \frac{1}{4}(4c - h - 2o + 3n + 3s)$

The composition of food waste can be broken down into biodegradable and non-biodegradable compounds. Mirmohamadsadeghi et al. (2019) explain food waste's main degradable components are carbohydrates ($C_6H_{12}O_6$), proteins ($C_{13}H_{25}O_7N_3S$), and lipids ($C_{12}H_{24}O_6$). The various microbial consortia in charge of each stage work in syntrophic interactions with the microbial consortia in charge of the subsequent phases. When hydrolysing microorganisms expel exoenzymes such as amylase, cellulase, xylanase, lipase, and protease, hydrolysis begins. The hydrolytic enzymes attach to the outer layer of the substrate, gradually breaking down polymers into water-soluble monomers and oligomers (such as glucose, fatty acids, glycerol, and amino acids). Meanwhile, additional reduced products, such as alcohols and higher volatile fatty acids (VFAs), undergo further oxidation through a symbiotic relationship between acetogenic bacteria and methanogens, other fermentation products like acetate, hydrogen, and carbon dioxide can be utilised directly by methanogenic microorganisms producing CH_4 and CO_2 (Karellas et al., 2010). The hydrogenotrophic methanogens can also utilise lactate as an alternate source of hydrogen (Abreu et al., 2019). When producing biogas from waste streams containing highly resistant components like lignocellulose, the hydrolysis stage is often the step that limits the overall rate of the process. Although lignin-based compounds may be digested without pre-treatment, they are not biodegradable (Sahito and Mahar, 2014). In the subsequent acidogenesis step, the liberated monomers and oligomers are broken down into short-chain fatty acids (such as propionate, butyrate, acetate, and lactate), along with alcohols and gaseous secondary products (NH_3, H2, CO_2, and H_2S). In the first two phases, facultative anaerobic microbes can devour the unwanted oxygen, and the anaerobic environment is created for microorganisms that must be anaerobic. The organic molecules created in the previous step are transformed into acetic acid, hydrogen, and carbon dioxide in the third stage. Finally, under strictly anaerobic conditions, methanogens facilitate the conversion of CO_2, methyl compounds, or acetate into methane. The rate-limiting phase in the AD of readily decomposable feedstocks with minimal buffering capacity is methanogenesis (Rozzi and Remigi, 2004). The largest gas production of AD is accomplished between 29 and 40 days (Al-Masri, 2001).

The effect of substrate on AD processes is frequently illustrated through BMP tests, Filer, Ding and Chang (2019) further elaborate that through BMP analysis the appropriate foundation is chosen, and the crucial variables are optimised. BMP is estimated via batch analyses in a laboratory setting (Krause et al., 2018). Nevertheless, it should be mentioned that the theoretical potential of methane may be derived by taking into account the elemental compositions of the substrate and the stoichiometric reaction Eq. 1 (Mirmohamadsadeghi et al., 2019).

AD is a complex process dependent on the stability of process conditions that are influenced by multiple factors like feedstock characteristics and process parameters (Almasi et al., 2018; Mirmohamadsadeghi et al., 2019). Factors influencing AD are described in the following section 2.2.2 Feedstock characteristics and 2.2.3 Process parameters.

2.2.2 Feedstock characteristics

This subsection explains the importance of feedstock characteristics and how they influence AD as well as the design of a digester. The nutrient content of the feedstock is one of the decisive factors on whether AD can at all occur, while particle size and inhibitory compounds are secondary factors that can be managed through pre-treatment or proper reactor monitoring (Deublein and Steinhauser, 2011; Mirmohamadsadeghi et al., 2019; Agyeman and Tao, 2014; Zhang et al., 2014; Alkaya and Demirer, 2011).

Nutrient content plays a distinct role in how the AD process happens. Carbon, nitrogen, phosphorus, and sulphur are among the macronutrients present in AD. The main source of carbon in AD comes from organic compounds (Zhang et al., 2013a). It is advised to keep the C: N ratio in the 16–25: 1 range. However, it has been claimed that abnormal numbers, such as the C: N: P: S ratio of 1000: 20: 5: 3, would be sufficient for AD to go forward (Deublein and Steinhauser, 2011;

Mirmohamadsadeghi et al., 2019). This could be explained by the fact that anaerobic microbes do not require a lot of nutrients since their biomass does not increase very much (Mirmohamadsadeghi et al., 2019). Almomani (2020) found that the Co-AD of various agricultural solid waste (ASW) and cow manure ratios revealed how mixed substrates include a balanced C: N ratio and unvarying substrate texture within a reasonable % of moisture content (MC). These circumstances serve to reduce the possibility of inhibition, provide balanced C, O, N, and H content, raise the reaction rate, and boost the generation of biofuel.

The maximum cumulative methane production (CMP) is produced when the C: N ratio is less than 25, according to several studies (Hassan et al., 2016; Ndegwa and Thompson, 2000). Chong et al. (2016) found out that micronutrients have a role in co-precipitation, enzymatic activity, and biochemical processes and serve as the building blocks for the development of microorganisms. These micronutrients or trace metals are iron, cobalt, nickel, zinc, selenium, tungsten, magnesium, chromium, and molybdenum.

Iron plays a growth-promoting role in the production of ferredoxins and cytochromes, two essential elements in cell metabolism. Iron also lessens the corrosion-causing effects of H_2S in biogas. The stability of the AD process with larger organic loadings depends on the element cobalt. Mirmohamadsadeghi et al. (2019) further add that nickel is essential for the development of all methanogenic archaea and is necessary for the production of cofactor F_{430}. Methanogens require zinc in order to produce carbonic anhydrase. Different metalloenzymes are engaged in the AD process depending on the methanogenic pathway (acetolactic or CO_2/H_2 pathways), and as a result, different micronutrients are needed.

In general, adding more micronutrients can enhance AD performance. However, the AD process can be inhibited by high micronutrient concentrations (Chong et al., 2016). With micronutrients, other biological compounds can be introduced to the AD process. This approach is called bioaugmentation and it includes specific bacterial or fungal strains, microbial consortiums, or enzymes (Mirmohamadsadeghi et al., 2019; Kapoor et al., 2020). The concentration of microorganisms in digesters can be raised by the addition of metal cations and micronutrients, therefore the process needs to be well monitored.

The new method of adding calcium and magnesium as nanoparticles can prevent digester foaming, however, concerns remain regarding the economics and environmental impacts of nanoparticles (Zhang et al., 2019a). Chemical additives that can boost biogas generation include certain adsorbents. Enhancing the volume and characteristics of biogas, along with maintaining process stability, can be achieved through the use of substances like pectin, activated carbon, silica gel, kaolin, and bentonite, gelatine, tale powder, and polyvinyl alcohol, which act as adsorbents have been used as additives (Desai and Madamwar, 1994; Mirmohamadsadeghi et al., 2019). Furthermore, the addition of activated carbon to the co-digestion of food wastes and chicken manure aids in the removal of antibiotics and increases methane generation (Zhang et al., 2019b; Al-Masri, 2001). Onthong and Juntarachat (2017) explain that soybeans and papaya peels are ideal feedstock because of their macronutrient composition, consisting mainly of easily biodegradable materials. Forty per cent of the protein, 20% of the lipid, 35% of the carbohydrate, and 5% of phospholipids, vitamins, and minerals are found in soybean seeds (Liu, 1997). These parameters are significantly more ideal compared to for example rice straw which is majorly composed of 31.7% cellulose (Onthong and Juntarachat, 2017).

Secondly, *particle size* plays a role as well. It has been demonstrated that food wastes with smaller particle sizes have a greater surface area accessible for the first adsorption of exo-enzymes, accelerating the breakdown process and enhancing biogas generation (Agyeman and Tao, 2014; Mirmohamadsadeghi et al. 2019). Equalizing the necessary retention durations for various chemicals is the major benefit of food waste comminution (Palmowski and Müller, 2000). However, it should be noted that severe foaming and process failure were observed in the occurrence of too-fine particle sizes in the reactor systems (Zhang and Banks, 2013).

Metals in high concentrations are considered *inhibitory compounds* as they interfere with the structure and operation of enzymes, which has been supported by Mirmohamadsadeghi et al.'s (2019) review. They further develop the case as in food waste, there are significant concentrations of light metals, particularly Na and K ions, which may be cause for concern in case of their inhibitory properties. Moreover, lipids possess a significant theoretical methane potential (1014 lkg-1 VS), and their fermentation results in the production of long-chain fatty acids (LCFAs), which, at high concentrations, can prevent the generation of methane. Myristic and lauric acids have been shown to have the most significant inhibitory effects on AD (Vallado et al., 2011). Moreover, LCFA mixtures are more problematic and stronger inhibitors than singularly occurring LCFA compounds (Lalman and Bagley, 2002). The addition of active inoculum or co-substrate, discontinuous feeding or co-digestion of lignocellulose-rich waste can mitigate the inhibitory effects of LCFAs and VFAs (Zhang et al., 2013b; Haider et al., 2015). It has been demonstrated that the co-digestion of green biomass, such as agricultural residues and other plant components, stimulates the AD of food wastes and increases biogas production (Zhang et al., 2014; Alkaya and Demirer, 2011). Co-digestion of food wastes and lignocelluloses from ruminant nutrition (Al-Masri, 2001) also contributes to the creation of perfect conditions, including the right balance of nutrients, pH, and buffering power (Barua et al., 2018) while the methane yield can improve up to 43% (Pagés Díaz et al., 2011; Ghosh et al., 2020). The ammonia also poses a problem because the ammonia (NH_3) - ammonium (NH_4^+) balance shifts toward inhibiting ammonia at higher pH and temperature levels, and the inhibitory action of ammonia rise (Mirmohamadsadeghi et al., 2019). Rinzema et al. (1988) noted a 10% AD inhibition at a substrate Na^+ concentration of 5 g/l and complete inhibition at concentrations equal to or greater than 14 g/l. Although it has been proven by Barakat et al. (2012), Bondesson et al. (2013) and Almomani (2020) that Na^+ is very unlikely and only happens in very specific circumstances.

2.2.3 Process parameters

Process parameters are adjustable variables in the AD. Parameters are either calculated (retention time, organic loading rate, moisture content, feeding frequency) or selected (inoculum type, process configuration, pre-treatment, temperature) according to given feedstock characteristics (Mirmohamadsadeghi et al., 2019). In case the parameters are suboptimal the reaction will cease to exist, therefore, it is crucial to interlink the outcomes of the feedstock characteristics analysis with the development of process parameters for a specific AD reactor (Gerardi, 2003).

One of the key process parameters of AD that have an internal balancing mechanism is *pH*. Mirmohamadsadeghi et al. (2019) found that the pH range of 6.8 to 8.0 is the most suitable for the methanogenesis stage, while Farquhar and Rovers (1973) suggest a slightly lower pH range of 6.4 to 7.2. With the build-up of VFAs pH drops, when ammonia builds up, the pH rises. Two natural buffering systems exist the carbonate equilibrium (preventing too low pH values) Eq. 2 and ammonia/ammonium equilibrium (preventing too high pH values) Eq. 3. Ammonia is produced when proteins, peptides, and amino acids are digested (Benabdallah et al., 2009). A decrease in the content of ammonia in the substrate also influences bacterial growth (Almomani, 2020). The case of propionic acid concentrations rising, pH values falling, and CO_2 concentrations rising in generated biogas are all indicators of acidification. In the case of natural mechanism failure, ash can be added to combat the unregulated rise of CO_2 (Mirmohamadsadeghi et al., 2019). Ash increases methane synthesis by absorbing CO_2, as well as by boosting coenzyme F_{420} activity (Yin et al., 2019).

Eq. 2

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^- + H^+ \leftrightarrow CO_3^{2-} + 2H^+$$

Eq. 3

$$NH_3 + H^+ \leftrightarrow NH_4^+ \quad \text{and} \quad NH_4^+ + OH^- \leftrightarrow NH_3 + H_2O$$

Temperature is of great significance for the AD process. Based on research Mirmohamadsadeghi et al. (2019) explain that the process is carried out at thermophilic (55–70°C) or mesophilic (32–45°C) temperature regimes. The maintenance of stable temperatures in digesters is crucial as thermophilic methanogens are particularly responsive to changes in temperature. Mesophilic digesters can operate at normal performance consistency within temperature changes of ± 3°C. Thermophilic AD exhibits advantages over mesophilic AD due to the increased growth and breakdown rates (by roughly 50%). Further advantages of thermophilic AD are no need to disinfect the fertiliser, less oxygen solubility, less ammonia build-up inhibition, and greater ability to ease the inhibition brought on by high organic loading rates. As well the highest yield of biogas was reached by Co-AD of a cow manure-water combination at 50 °C, followed by 60 °C and 40 °C (Sambo et al., 1995). However, mesophilic AD is more prevalent as a result of straightforward process management and possesses some considerable advantages such as greater resistance to environmental fluctuations, enhanced sludge dewatering characteristics, and faster rates of food waste solubilization at lower temperatures (Zhang et al., 2014; Bharathiraja et al., 2016; Benabdallah et al., 2009). It is also considered to be a more stable process for food waste owing to its elevated organic content (Guo et al., 2014). An overview of the DRANCO dry fermentation and anaerobic digestion process for energy crops is shown in the flow diagram below, see Figure 4. Almomani (2020) revealed that there may be a direct correlation between temperature stability and mixture ratio based on his study. When fed a substrate containing ASWs and cow manure, Reactor 4 had the greatest CMP at a constant temperature with substrate mixture AWS: cow manure (70:30), followed by R3 (50:50), R2 (30:70), R1 (0:100), and R5 (100:0). He also advocates for maintaining a temperature range of 30 to 55 °C, considering the energy costs associated with heating the AD process and the operational challenges in managing AD at high temperatures.

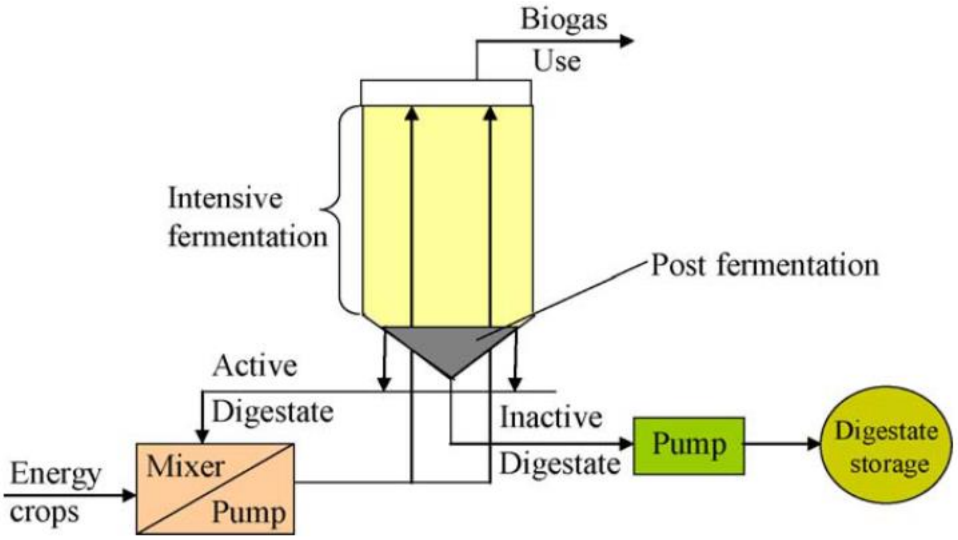


Figure 4: Basic flow diagram of the DRANCO dry fermentation, anaerobic digestion process applicable for energy crops (Karellas et al., 2010, p. 1276)

The most significant process variable impacting the yield and pace of methane generation is the duration of the *retention time* (Gerardi, 2003). The ideal retention period is influenced by the proportions and contents of the feedstock mixture, organic loading rate, and temperature. Therefore, in these digesters, a minimum retention duration of 10 to 15 days is required to prevent biomass wash-out (Mirmohamadsadeghi et al., 2019). The typical retention period in mesophilic anaerobic digesters is 15 to 30 days (Mao et al., 2015). Anaerobic digesters' startup periods should last up to three months to generate the necessary concentration of biomass for maximum efficiency (Chandra et al., 2012). Through hydraulic retention time (HRT) (see Eq. 4) and solid retention time (SRT) (see Eq. 5) it is possible to articulate the retention time (Mirmohamadsadeghi et al., 2019).

Eq. 4

$$HRT = \frac{digester\ volume}{a\ flow\ rate\ of\ substrate}$$

Eq. 5

$$SRT = \Delta t\ of\ solid\ microorganisms\ retention\ in\ the\ digester$$

Organic loading rate (OLR) stands for the number of volatile solids (VS), or chemical oxygen demand (COD) provided daily to each unit volume of the digester and is a crucial parameter that affects AD process stability, performance, and cost. (Dhar et al., 2016; Mirmohamadsadeghi et al., 2019). The amount of methane produced per litre of a digester fed with food waste increased by 479% with an increase in the OLR from 1.8 to 5.0 kg-VS/m^{3}d. while the highest yield was reported at the OLR of 8.0 kg-VS/m3 d. (Morken et al., 2018; Liu et al. 2012). Recirculating effluent offers a resolution for the process inhibition caused by the accumulation of VFAs in the case of an unregulated increase in the ORL (Mirmohamadsadeghi et al., 2019). Astals et al. (2013) and Rajagopal et al. (2013) agree that ORL together with the biodegradability index and balanced nutrients are the key components in regulating methane generation and determining the efficiency of the AD process.

Mechanical mixing and biogas recirculation are used for low and high solids operations, respectively (Igoni et al., 2008) as biogas production can be enhanced by mild *agitation* (Deublein and Steinhauser, 2011). The removal of metabolic products, particularly the H_2-blocking layer, the prevention of foaming, the disruption of the temperature gradient, and the eradication of floating and sinking layers all depend on proper mixing in digesters (Mirmohamadsadeghi et al., 2019).

The role of hydrogen in the AD process can both indispensable and inhibitory. Mirmohamadsadeghi et al. (2019) argue that for the AD process to function naturally during the methanogenesis stage, a well-balanced *hydrogen concentration* is necessary. Hydrogen, on the other hand, functions as an inhibitory substance during the acetogenesis stage. Therefore, for the AD process to be successful and to maintain a balance in the hydrogen content, acetogenic and methanogenic microbes must coexist together. The substrate and microbial consortiums have an impact on the maximum permissible hydrogen concentration (Deublein and Steinhauser, 2011).

Moisture content is the variable that differentiates the submerged, less than 15% solid concentration, and solid-state AD process (Mirmohamadsadeghi et al., 2019). The submerged process is characterised by lower inoculum requirements, shorter retention times, larger methane yields, and increased VS reduction. Achmon et al. (2019) have successfully performed a solid-state AD of grape and tomato pomace with a solid content of 28%. By co-digesting food waste and green waste, a change from submerged AD (5-10% TS) to solid-state AD (15-20% TS) boosted methane volumetric productivity as well as methane production. However, raising the TS to 25% resulted in overloading, inhibition, and the production of significant quantities of ammonia (Chen et al., 2014). According to Almomani (2020), the general pattern shows the maximum production for the %MC in the range of 34% to 48%, which dropped by raising the %MC over 50%, there is a clear correlation between the %MC and the CMP. If the addition of organic matter and the range of the %MC is controlled the %CH_4 may be enhanced for all substrates Bollon et al. (2011) demonstrated an increase in biochemical acetate degradation rates by 6 times (from 290 mgCOD/kg to 2000 mgCOD/kg). The study concludes that diffusion restrictions inside the substrate are the primary cause of this improvement. Browne and Murphy (2013) also found in their study that higher yields of CH_4 were associated with wet samples of food waste. This notion is also supported by Onthong and Juntarachat (2017) who concluded from their experiments that wetter samples of food waste such as papaya peels and soybean residue generated more biogas and subsequently CH_4 than other drier samples.

The amount of *inoculum* has a direct impact on AD's start-up phase (Motte et al., 2013). Among the most commonly applied forms of inoculum are livestock dung, inoculum sourced from a farm-scale digester fed with a mixture of cattle slurry and grease trap waste (80:20 ratio), and inoculum obtained from a digester fed with chicken manure, anaerobically digested food waste, sludge acclimated to food waste (Mirmohamadsadeghi et al., 2019). These materials are frequently utilised as inoculum since they are a rich source of microorganisms (Eze and Agbo, 2010). According to Kong et al. (2016) and Browne and Murphy (2013), the best inoculum for the AD process is the sludge acclimated with the substrate and conditions of the identical process. On the other hand, cow dung is the animal inoculum that produces the most methane from food waste, compared to other livestock inoculums (Dhamodharan et al., 2015) and should be kept at the temperature of 4 °C to prevent biological activity (Almomani, 2020). While Gaur and Suthar (2017) claim based on their research that combining various inoculums might increase biogas generation. For an already functioning digester, a viable option is to recirculate the digestate. Reusing digestate increases microbial density along with activity and marginally boosts biogas output by reintroducing the washed-out microbial biomass into the digester (Mirmohamadsadeghi et al., 2019; Kapoor et al., 2020). The sludge supernatant recycling shows a notable impact on the methane output of solid-state AD, particularly when in traduces in the start-up phase and the already inhibited processes as the reaction restarter (Li et al., 2019).

Process configuration has an impact on AD efficiency and is divided into two categories, batch (Capson-Tojo et al., 2017), continuous or semi-continuous (Nguyen et al., 2017; Karellas et al., 2010) configurations that can be performed in single (Ariunbaatar et al., 2015) or multiple stages (Li et al., 2018). According to recent studies, the two-stage digesting process, with the acetogenic and methanogenic phases separated from the hydrolytic and acidogenic steps has many benefits (Montgomery and Bochmann, 2014) like the possibility of creating hydrogen as a by-product, a larger methane yield, a faster production rate, a shorter hydrolytic retention time, a higher OLR, and a more stable process (Mirmohamadsadeghi et al., 2019). However, the expense of such a complicated system is a major drawback (Montgomery and Bochmann, 2014). In contrast, single-stage processes need less capital investment and are more resistant to technological failures (Kiran et al., 2014). Almomani (2020) also recognised the necessity of proper base and reactor design for optimal CH_4 production with bearable costs. Karellas et al. (2010) note that recent developments in AD technology have been made to accommodate the conversion of energy crops or organic wastes. Reactors/digestors can therefore be categorised based on plant size, see Table 1. Mirmohamadsadeghi et al. (2019, p. 5) found that all mentioned types of reactors as follows are suitable for biogas production: "*ASBR: Anaerobic sequencing batch reactor, CSTR: Continuous stirred tank reactor, APFR: Anaerobic plug-flow reactor, ACR: Anaerobic contact reactor, UASB: Up-flow anaerobic sludge bed reactor, UASS: Up-flow anaerobic solid-state reactor, ABR: Anaerobic baffled reactor, ICR: Internal circulation reactor, LBR: Leach bed reactor, HF-AnMBR: Hollow fibre type anaerobic membrane reactor.*" Figure 5 outlines possible configurations of anaerobic digesters. However, Karellas et al. (2010) argue that reactor type selection is influenced by waste characteristics, specifically particulate solid contents or total solids. Angelidaki and Ellegaard (2002) as well support this notion and explain that CSTRs are often used to handle high total solids feedstocks and slurry waste, whereas high-rate biofilm systems such as anaerobic filters, fluidized bed reactors, and UASBs are used to treat soluble organic wastes. Table 2 in Appendix 1 contains information on substrates and recommended digester configurations (Karellas et al., 2010).

Table 1: Digestor differentiation based on volume

Digestor design	Volume m^3	Specifications
Horizontal digester	50–150	• excellent mixing conditions • appropriate for the most compact facilities • treatment of cow and poultry manure or feedstocks with higher TS (energy crops)
Upright standard agricultural digesters	500–1500	• internal heating system • one or more exterior motors for mixing • double-membrane • top gasholder roof • a treatment capacity of up to 10,000 m^3/year • a hydraulic retention time of 3 to 80 days
Upright large digester	1000–5000	• pre-heating of input material • centrally located roof mixer that is continuously running • a hydraulic retention time of 20 to 30 days

		• treatment capacity 90 000 m^3/year

Source: Karellas et al. (2010)

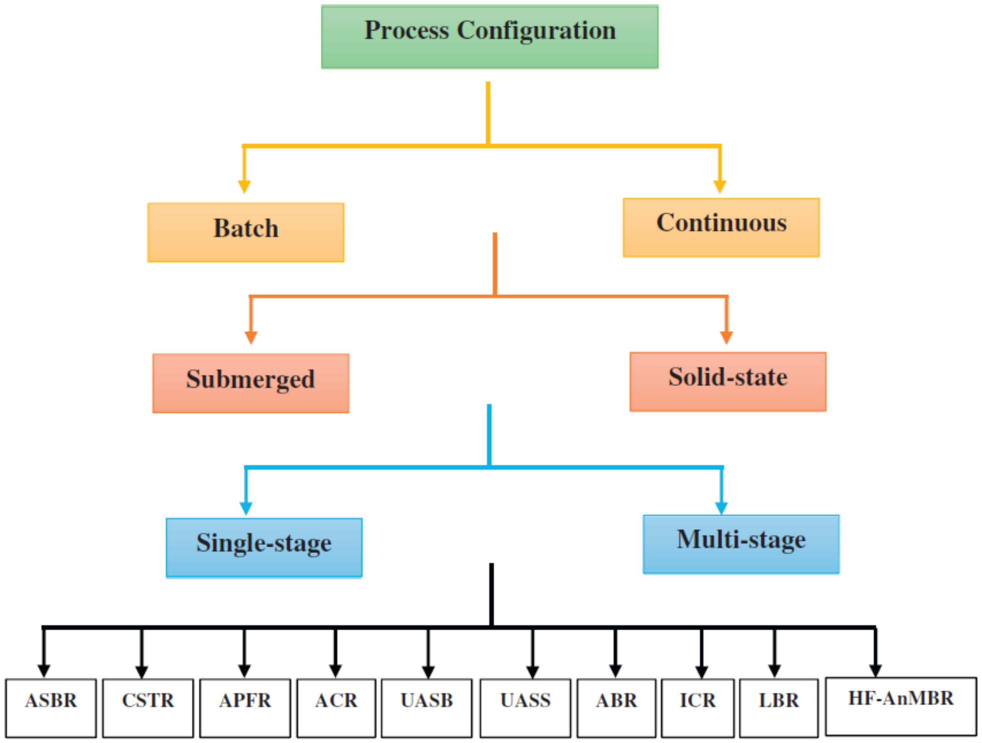


Figure 5: Different configurations of anaerobic digesters for AD of food wastes (Mirmohamadsadeghi et al., 2019, p. 6)

Increased *feeding frequency* can lead to more methane being produced and fewer LCFAs being present in the effluent (Mirmohamadsadeghi et al., 2019). This notion is also supported by the study of Svensson et al. (2018) who found that increasing the feeding interval to 10 per day resulted in 20% growth of methane production compared to one-off daily digester feeding.

Pre-treatment can raise the methane concentration in biogas and increase the biodegradability of food waste. The rate-limiting phase in the AD process, hydrolysis, is frequently sped up by pre-treatment. Food waste can be pre-treated using a variety of techniques, including mechanical, thermal, biological, and chemical ones (Mirmohamadsadeghi et al., 2019). All methods of pre-treatment actively affect food waste solubilisation, and particle size reduction is also a consequence of mechanical and chemical pre-treatments. Generally, basic physical processing, such as milling, is the most effective and economical pre-treatment for food waste (Zhang et al., 2019a). More advanced and technically demanding pre-treatments such as using ultrasound-assisted pre-treatment have demonstrated promising outcomes when employed in the co-digestion of food wastes, cow dung, and sludge, leading to increased volumetric methane outputs and reduced retention times (Quiroga et al., 2014). Almomani et al. (2019) have explored the enhancement of biogas production via pre-treatment with advanced oxidation employing Fenton, ozone, and ozone combined with Fe (II) and H_2O_2. The number of soluble materials was raised by 3-6 times, which sped up the pace at which the treated substrate was broken down. This led to a 23–30% increase in the total amount of methane produced and an 11.2-25% enhanced digestion effectiveness ($\%\eta_{AD}$). According to semi-batch studies, combining fresh and pre-treated substrate in a 50:50 ratio increased both the specific methane generation (1.7 times) and volatile sold reduction (79%) with a favourable impact on sludge dewaterability (Astals et al., 2013). The improvement in the CMP following the alkalinity treatment is also showing promise and may be attributed to $NaHCO_3$'s capacity to dissolve the complex Li in the ASWs (Almomani, 2020). Easy-to-break-down compounds (such as CE and HCE) along with intricate and less readily degradable substances Li are both included in the substrates employed in the feeding of the AD process (Yang and Wang, 2019). Implementing the chemical treatment enables the $NaHCO_3$ to attack the substrate, breaking down CE and HCE into smaller molecules (i.e., improving the Bio_{sub}), allowing the polysaccharide and Li to be released from their bond and releasing the biodegradable cell content for bacterial usage (Chenet al., 2009; Almomani and Bhosale, 2020). As a result, the substrate's % of AD_{biodeg} increases, and the CMP improves with the best outcomes reported when 1.0 g $NaHCO_3$/gVS of alkalinity treatment was used (Almomani, 2020). Unfortunately, pre-treatments with acids and alkalis have the drawbacks of causing corrosion and soap formation, respectively (Sumphanwanich et al., 2008; Mouneimne et al., 2003). Therefore, in the case of lignocellulosic feedstocks, Kapoor et al. (2020) suggest hydrothermal pre-treatment to solubilize hemicellulose and Li, hence lowering the probability of inhibitor formation, such as furfural.

2.2.4 Biogas upgrading

The last step in the process is turning biogas into biomethane, a purer form with fewer drawbacks but additional associated costs (Kasikamphaiboon and Khunjan, 2018). This step is optional as it is common in the commercial production of biomethane for fuel, though not in the case of private homes or community use.

The use of biogas for generating power and/or heat is well-known around the world and Kapoor et al. (2020) explain that biogas gains combustibility from CH_4 but loses calorific value due to CO_2's incombustibility, which restricts its use and transportability. The presence of water vapour, hydrogen sulphide, siloxanes, and other substances in biogas results in equipment corrosion and reduces heating value. Therefore, it becomes crucial to extract CO_2 and other corrosive elements from biogas to expand its range of uses. Biogas cleaning involves the elimination of contaminants like H_2S and moisture, and it may be employed in straightforward processes like the generation of heat and electricity. Upgrading is the process of removing CO_2 from biogas. It raises the calorific value (heating value) of biogas by up to 39 MJ/m^3 and enhances its quality. As a by-product $bioCO_2$ can be processed and utilised in places where fossil-based CO_2 is already used, such as greenhouses, the cultivation of algae, the fumigation of grains, the manufacture of chemicals, etc. Various methods are commercially available for biogas upgrading based on physical and chemical absorption, adsorption, membrane separation, and cryogenic separation (Kasikamphaiboon and Khunjan, 2018).

Water scrubbing is the most well-known and most often used biogas upgrading process (Thrän et al., 2014). It is based on how easily gases dissolve in water. Compared to CH_4, CO_2 and H_2S are more soluble in water (Kapoor et al., 2017). Kapoor et al. (2020) found out that it is typically advised to pre-separate H_2S before water scrubbing even though this method concurrently dissolves H2S in water. The process mechanics are as follows: biogas is compressed at 8–12 bar and introduced from the bottom into the scrubbing system. Water is sent into the scrubbing column from the top. Over randomly packed packing material, a counter-current interaction occurs between the gas and the water. This leads to an extended duration of contact and mass transfer between the gas and the water. (Bauer et al., 2013). In downflowing water, CO_2 is absorbed, and biomethane with a purity of more than 90% CH_4 is produced while the water that has been exposed to CO_2 and H_2S is directed into a flash column to obtain CO_2-rich gas (Kapoor et al., 2020).

According to Kapoor et al. (2020), *organic scrubbing* is similar to water scrubbing, except to absorb CO_2 and H_2S from biogas, organic solvents such as methanol and dimethyl ethers of polyethene glycol are used in place of water. The system is more compact and requires less pumping because H_2S and CO_2 are more soluble in organic solvents than in water. However, due to the demand for high temperatures, the regeneration of used organic solvents is difficult and energy intensive. Even higher temperatures are required for solvent regeneration if H_2S is not eliminated before the upgrading procedure. Therefore, it is typically advised to remove H_2S beforehand before the upgrading procedure in order to minimise reducing energy requirements (Persson, 2003). In the process of organic scrubbing raw biogas is cooled to 20 °C and compressed to 7-8 bars before being channelled into the absorption column from the bottom for upgrading (Kapoor et al., 2020). To improve gas solubility, the organic solvent is refrigerated before being channelled into the absorption column from the top (Bauer et al., 2013). In the desorption column, the wasted solvent is regenerated by heating it to 80 °C and depressurizing it to 1 bar (Bauer et al., 2013; Sun et al., 2015). The grade of the biomethane produced by this method can reach 98% (Bauer et al., 2013).

Chemical absorption uses solvents such as mono-, di- or tri-ethanolamine and alkaline salt solutions since CO_2 and H_2S are highly soluble in chemical solvents, so chemical absorption offers the benefit of removing both gases from biogas at once (Kapoor et al., 2020). During the procedure, a column filled with packing material is utilized for absorption. Biogas is introduced from the bottom of the column at a pressure of around 1-2 bar, while the amine is injected from the top in a counter-current manner (Petersson and Wellinger, 2009). From the biogas, CO_2 is exothermally absorbed into the amine solution that is directed to a stripping column equipped with a boiler, which is designed to heat it to temperatures ranging from 120 to 160 °C (Khan et al., 2017). Even though chemical absorption yields 99% pure biomethane, its biggest drawback is the enormous energy required for the regeneration of the used chemical solvent (Kapoor et al., 2020).

The second most often used technique for refining biogas is *pressure swing adsorption* (PSA). According to Augnelletti et al. (2017) and Kapoor et al. (2020), it relies on the selective adsorption of gas molecules onto the external area of adsorbents like carbon molecular sieve, activated carbon, and zeolites 13X and 5A. The bigger molecules of CH_4 are separated from the CO_2 and H_2S by a sieving process and because H_2S's adsorption is irreversible, pre-separation is advised (Zhou et al., 2017). According to Kapoor et al. (2020) PSA process is initiated with compression, biogas is directed into the adsorption column where CO_2, N_2, O_2, H_2O, and H_2S are selectively held onto the surface of the adsorbent, whilst CH_4 flows through without being retained and is collected from the column's top. The biogas stream moves to the subsequent column when the first column becomes saturated with retained gases. By releasing a gas combination that contains considerable volumes of CH_4 and CO_2, as well as a pressure drop, the saturated adsorbent is regenerated (Bauer et al., 2013). Hence, this gas combination is reintroduced to the PSA intake to reduce CH_4 losses, which makes this technique beneficial in terms of low energy requirements and capital expenditures (Augelletti et al., 2017). Biomethane yields are reported at an average concentration of 96–98% CH_4, although CH_4 recovery is limited (Bauer et al., 2013).

Kapoor et al. (2020) summarised that *membrane separation* depends on the selective permeability of membranes, like polyimide and cellulose acetate that are suitable for biogas upgrading. The particular membranes have a higher diffusion coefficient and carbon dioxide solubility compared to that of CH_4. There are two ways to carry out the upgrading: dry (gas/gas separation) and wet (gas/liquid separation). In any case, it is essential to remove moisture and H_2S beforehand to prevent corrosion and energy loss. When biogas is upgraded, CO_2 and H_2S pass through the membrane to the side where permeation occurs while CH_4 is kept and pumped into the membrane system at 5 to 20 bars (Bauer et al., 2013). CH_4 is kept at high pressure while CO_2 passes on to the low-pressure side (Kapoor et al., 2020). The best design to lower CH_4 losses is the three-stage with a sweep which generates biomethane with a 98% concentration of CH_4 (Basu et al., 2010). The significant expense and CH_4 losses of this membrane technology are two significant drawbacks (Kapoor et al., 2020).

The *cryogenic separation process* creates involves converting biogas into liquefied CH_4 and isolating it from CO_2 by utilising the concepts of low temperature and high pressure (Muoz et al., 2015). When dehydrated biogas gets pressurized to 80 bars and then gradually cooled to -110 °C, refined and liquefied biomethane is produced that is isolated from CO_2 and other pollutants (Ahmed et al., 2016). Even though this technique yields biomethane and bioCO_2 in their purest forms, the expense and high energy need are the main drawbacks (Kapoor et al., 2020).

2.2.5 Digestate

The liquid and solid residues of the AD are referred to as digestate. Kapoor et al. (2020) explain that a possible substitute for costly mineral fertilisers based on fossil fuels, on the other hand, digestate is made from agricultural waste. Digestate composition is influenced by agri-waste content, inoculum, operational parameters including pH and temperature, pre-treatment, and process design. Due to ammonia synthesis and VFAs breakdown, the digestate often has a somewhat alkaline pH. The initial TKN (Total Kjeldahl Nitrogen) concentration determines the amount of $N\text{-}NH4^{+}$ in the digestate. The digestate contains trace levels of macronutrients such as P, K, and S as well as the elements Co, Fe, and Se (Monlau et al., 2015; Li et al., 2018; Zhou et al., 2018), while also being rich in macro elements and heavy metals making it suitable as a fertilizer (Koszel and Lorencowicz, 2015). Biogas digestate has the potential to be used in different ways like soil amendment or enrichment and may be processed and sold as commercial fertiliser or dried and used as animal bedding (Kapoor et al., 2020). Though, before use, the digestate has to be mechanically processed and then centrifuged to separate solids and liquids (Paolini et al., 2018). It is now realistically possible to separate the digestate into several streams, including solid N, P-fertilizer, liquid N, K-fertilizer, and dischargeable water, using modern membrane technology (Gienau et al., 2018).

2.3 Composting

After recognizing the issues associated with agricultural waste and demonstrating the potential of a circular economy for achieving a sustainable future, the process of composting and associated challenges will be reviewed in this section.

2.3.1 Overview of the composting process

The conversion of waste into valuable resources has received a great amount of attention in recent years (Bian et al., 2019; Kulcu and Yaldiz, 2014; Sharma et al., 2019; Fermoso et al., 2018). A significant impact of biomass availability on the circular economy has been acknowledged, as it can be effectively transformed into various bioproducts and energy. A study by Saravanan et al. (2023) elaborates on how advanced methodologies have the capacity to convert biomass into value-added products and various energy forms, contributing to the circular bioeconomy framework. For the conversion of biowaste into bioproducts and bioenergy both biological and physico-chemical methods can be employed (Saravanan et al., 2023). Physicochemical methods for instance include hydrothermal carbonization, gasification, and pyrolysis whereas biological methods are fermentation, composting, and anaerobic digestion.

Composting is a process commonly used for the valorisation of biomass, therefore it plays an important role in the management of organic waste. It usually involves a transformation of organic biowastes into useful bioproducts such as biofertilizers (Saravanan et al., 2023; Kulcu and Yaldiz, 2014; Sharma et al., 2019). It is a natural process that breaks down organic matter into a nutrient-rich soil amendment that can be used to improve soil fertility and plant growth. According to Mengqi et al. (2021), the majority of agricultural waste contains abundant organic matter, along with significant levels of nutrients such as nitrogen, phosphorus, potassium, and other essential elements required by crops. For the production of organic fertilizer, it is an excellent source. As Fermoso et al. (2018) point out, for a long time, composting has been suggested as a low-cost solution for managing agricultural waste (Fermoso et al., 2018). By mineralization and humification, organic waste is transformed into stable humic compounds during composting. In addition, pathogens are eliminated through the heat generated during the thermophilic phase. However, although being a sustainable way of returning the nutrients back to the agricultural sector, according to the economic benefit derived from composting is generally relatively low.

The stability and maturity of the compost, which are influenced by several factors, can determine its quality (Bian et al., 2019). Therefore, the management of composting parameters, such for instance thermal phases, transformation time and moisture, is key for composting optimization. The following parameters may be successfully optimized to speed up the process and produce high-quality products. Firstly, the thermal phases influence microbial activity and determine the potential eradication of undesired pathogenic bacteria. (Bian et al., 2019; Kulcu and Yaldiz, 2014). Secondly, a brief conversion period can cause inadequate breakdown of high-molecular-weight organic matter, and on the other hand, too long of a time may result in nutrient loss. Thirdly, vegetable waste can contain moisture levels as high as 85% or even more, providing the opportunity to regulate the overall moisture content of the mixture. Insufficient moisture can lead to reduced microbial activity, while excessive moisture can impede gas diffusion and prove detrimental (Bian et al., 2019). Fourthly, the consumption of oxygen within the pile by microorganisms can lead to the development of anaerobic conditions, which, in turn, slow down the decomposition, decreased temperatures lead to generation of unpleasant odours. Therefore, it is important to ensure a consistent air circulation within the composting pile, to hinder the development of anaerobic environment (Kulcu and Yaldiz, 2014).

2.3.2 Challenges associated with composting

Generally, composting agricultural waste is considered to be a useful way to reduce waste, enhance soil quality, and decrease greenhouse gas emissions (Bian et al., 2019; Kulcu and Yaldiz, 2014; Sharma et al., 2019; Fermoso et al., 2018; Saravanan et al., 2023). However, several challenges and problems can arise when composting agricultural waste (Sharma et al., 2019).

Some of the challenges include for instance contamination, nutrient imbalance, odour, space requirements, management requirements and economic viability. Firstly, agricultural waste can contain contaminants such as pesticides, heavy metals, and pathogens that can be harmful to human health and the environment. If these contaminants are not properly managed during composting, they can remain in the compost and contaminate soil or water when the compost is used (Sharma et al., 2019). Secondly, different types of agricultural waste have different nutrient content, and if the composting process is not properly managed, the resulting compost may have an imbalanced nutrient content that can harm crops or cause pollution when applied to soil (Sharma et al., 2019; Bian et al., 2019). Thirdly, composting agricultural waste can produce strong odours that can be unpleasant for nearby residents or workers. Proper management and control of odours are necessary to avoid complaints or regulatory issues (Kulcu and Yaldiz, 2014). Fourthly, composting requires space for the compost piles or bins, as well as space for equipment and processing facilities. Agricultural waste can be bulky and take up a lot of space, which can be a challenge in areas where land is scarce or expensive (Sharma et al., 2019). Fifthly, composting requires careful management to ensure that the composting process proceeds smoothly and efficiently. This includes monitoring moisture levels, temperature, and turning the compost regularly to promote aeration and decomposition. The management requirements can be challenging for small-scale farmers or those with limited resources (Sharma et al., 2019). Sixthly, composting agricultural waste might not always be a low-cost solution, especially if the process requires specialized equipment or facilities. The economic viability of composting may depend on factors such as the availability of subsidies, the price of alternative waste management options, and the demand for compost in local markets (Fermoso et al., 2018; Kulcu and Yaldiz, 2014).

2.4 Theoretical framework summary

Here, a summary of the theoretical framework is presented, where the issues associated with the agricultural industry were introduced, mainly in the context of waste management. In short, the world is currently facing many challenges associated with climate change. With a rapidly growing population, the demand for food has been naturally increasing too. As a result, agricultural productivity has intensified, causing damage to the environment. According to the literature, agriculture is one of the major contributors to climate change (Balogh, 2019). It is estimated that approximately 30% of the global emissions released into the atmosphere come from agricultural activities. Therefore, it has become apparent that a shift towards more sustainable practices is needed. When it comes to making the agriculture industry more sustainable, improving waste management plays a crucial role. (Balogh, 2019).

The concepts of circular economy and bioeconomy were introduced above as they are interlinked. CE is a response to the traditional linear model of production and consumption, where resources are extracted, turned into products, and ultimately discarded as waste. In a CE, materials are kept in use for as long as possible, and waste is minimized through the use of recycling, reuse, and repair. The goal is to create a closed-loop system where resources are conserved, waste is reduced, and the environment is protected. The potential benefit of CE that will bring us closer to a sustainable model of the economy is its aim to decouple economic growth and resource use by redesigning goods and processes to optimize the value of resources throughout the economy (Ghisellini et al., 2016).

This case study is based on notions of circularity that are integrated into solutions for abundant biomaterial considered waste. CE is considered an umbrella term for different types of economies such as bioeconomy, sharing economy and service economy since the conceptual boundaries are not clearly defined (McCormick and Kautto, 2013; Buera and Kaboski, 2012; Acquier et al., 2019). From the text above we can infer that all endeavours that depend on biological resources are referred to as being part of the "bio-economy" (Leal Filho, 2018). By combining the core ideas of CE and bioeconomy we end up with a new concept of the bio-circular economy that is built on the idea of zero waste, where resources are not solely converted into value-added goods, but also the resulting waste streams are managed in a sustainable manner (Kapoor et al., 2020). The concept of bioeconomy is based on the notion that natural resources are finite and must be utilised efficiently (Kleinschmit et al., 2014). It has the potential to offer numerous benefits, including increased resource efficiency, reduced dependence on fossil fuels, and greater food availability.

A sustainable bioeconomy must meet three requirements: an enduring foundation of resources, sustainable production and consumption methods, products, and a circular flow of materials (Kumar et al., 2019; Barros et al., 2020). As Kapoor et al. (2020) and Kushwaha et al. (2022) stress an Agri-based circular economy may be reached by utilising all of AD's products, and the problems of waste, energy, and nutrient recycling can be resolved in a sustainable and circular way, see Figure 6. In a cascade agri-waste system, anaerobic digestion is a key phase that produces digestate, also known as biofertilizer, and biogas, a sustainable energy source. As mentioned above biogas production under anaerobic conditions goes through four distinct phases, the hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Mirmohamadsadeghi et al., 2019; Al-Masri, 2001; Ghodrat et al., 2018) that is carried out in digesters. Figure 7 shows a simplified flow diagram of a generic anaerobic digestion plant based on organic feedstocks.

By converting the agri-waste into value-added product streams that are then utilised as the basis for the development of new goods and by-products, a closed loop is created that maximises the energy, financial, and environmental advantages. Bioeconomy and circular economy have been and are largely supported by legislation and political discourse (Staffas et al., 2013; Kleinschmit et al., 2014; Geissdoerfer et al., 2017). With the European Union, the second-largest democratic electorate in the world, devoting almost half of its efforts to attaining zero carbon emissions by 2050, leveraging policy is crucial now more than ever to transition to a circular economy (European Commission, 2019).

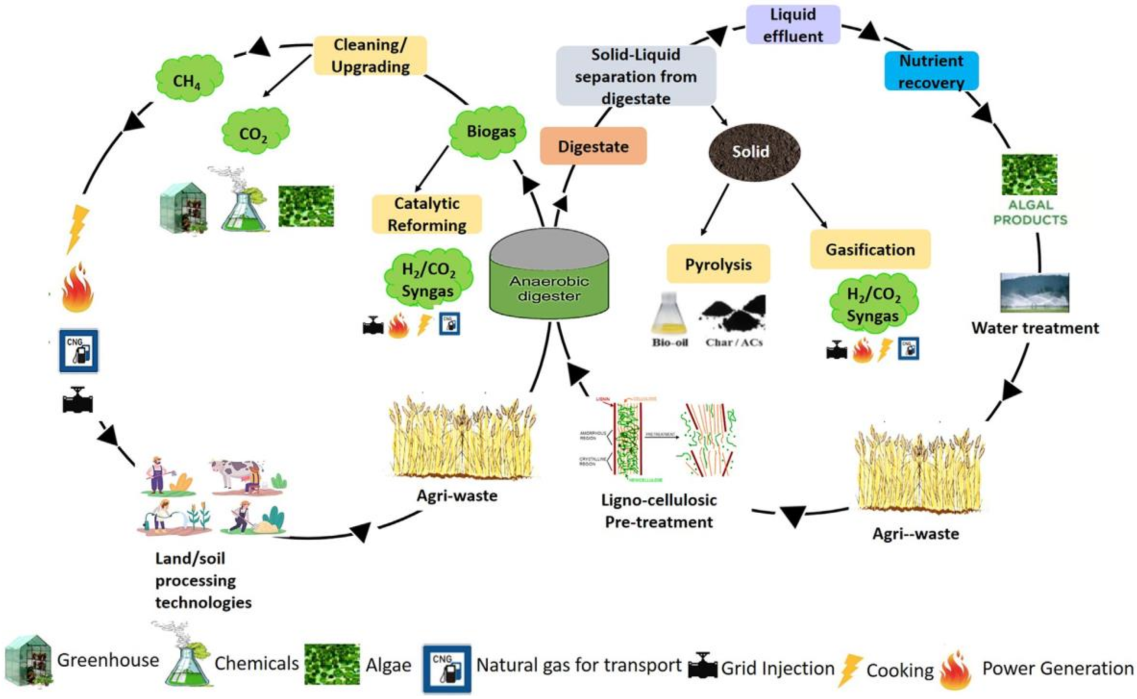


Figure 6: The concept of Agri-waste based circular economy (Kapoor et al., 2020, p. 3)

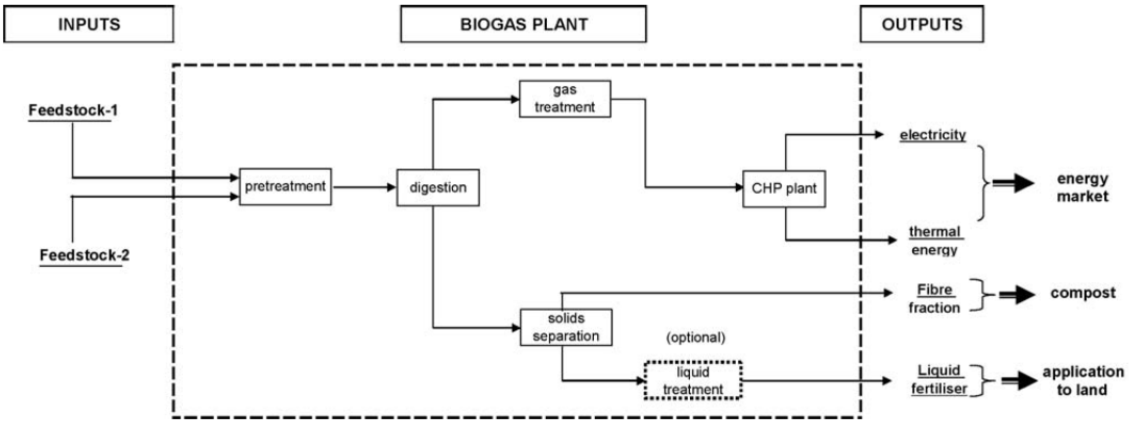


Figure 7: A simplified flow diagram of a generic anaerobic digestion plant based on organic feedstocks (Karellas et al., 2010, p. 1274)

Overall, biogas production is a promising and rapidly growing technology with the potential to provide a sustainable source of energy and improve waste management in many regions of the world. According to Deublein and Steinhauser (2011) and Karlsson et al. (2017), biogas is one of the most financially feasible forms of renewable energy that addresses socioeconomic and environmental concerns.

Similarly, composting is a widely employed process for the valorisation of biomass. It usually involves a transformation of organic biowastes into useful bioproducts such as biofertilizers (Saravanan et al., 2023). It is a natural process that breaks down organic matter into a nutrient-rich soil amendment that can be used to improve soil fertility and plant growth. Generally, composting agricultural waste is considered to be a useful way to reduce waste, enhance soil quality, and decrease greenhouse gas emissions (Bian et al., 2019; Kulcu, 2014; Sharma et al., 2019; Fermoso et al., 2018; Saravanan et al., 2023).

Moreover, companies should take into account that their operational cost could be reduced, and an additional stream of revenue created in the instance of agri-waste valorisation since they correctly handle their own waste products and may benefit from selling heat and power as well as using a stabilised biofertilizer (Karellas et al., 2010).

3 DATA AND METHODOLOGY

In this chapter, the methodology of our research will be outlined. The purpose of the research, the content of the research, an overview of the research design, methodology and other relevant information will be provided as well as the case company will be introduced.

3.1 Main purpose and overview of the research design

The main purpose of this research is to analyse and evaluate the current situation of waste management in Agro GTV and propose sustainable innovative solutions to reduce costs and increase the efficiency of waste management based on the research and new developments in the area. The results of our research will provide Agro GTV with two scenarios including the overview of the proposed solution, techno-economic feasibility evaluation, legislative requirements, social and business impacts. These results can be utilised in the future for further research or as a preliminary outline for waste management improvements in similar companies. Accordingly, we have selected a case study as the optimal research design.

Crowe et al. (2011) and Baxter and Jack (2008) found out that the case study approach facilitates thorough examinations of complicated phenomena within the context of real-world scenarios. In the fields of business, law, and policy, the methodology of case study is widely acknowledged for its value and gives the researcher a chance to respond to "how" and "why" inquiries while also considering how the context of a phenomenon affects it. According to Crowe et al. (2011) to ensure the quality of a case study it should be conducted in the following manner:

1. *Case definition* – requires consideration of the body of current literature as well as an understanding of the theoretical difficulties and unique setting. Importantly, every case should establish predetermined boundaries that outline the type of information to be collected, the primary focus for data collection and analysis, the extent (encompassing the context and timeframe of the case study), and the relevant subject matter.
2. *Data collection* – should accumulate various sources of evidence by utilising a range of quantitative and increasingly frequently qualitative techniques. Employing multiple data sources, also known as data triangulation, is recommended to enhance the internal validity of a study. An underlying assumption is that information obtained through different methods should lead to comparable findings, and examining the same issue from various perspectives can contribute to better comprehension of the phenomena.

3. *Analysis, interpretation, and conclusion* – are the consecutive last steps of a case study. A fundamental framework approach proves to be a valuable method for managing and examining extensive datasets. It comprises five phases: initial familiarization, thematic framework choice, indexation, charting, outlining, and interpretation. However, the case study should not be "pressed to suit" the specific theoretical framework in use should not serve as a constricting barrier, nor should theoretical perspectives restrict creative thinking. It's vital to equip the reader with sufficient background information when presenting findings. This helps them understand the methodologies employed and the rationale behind the conclusions.

We have specifically selected the exploratory case study type as this particular kind of case study is used to investigate circumstances where the intervention being assessed has no obvious, singular set of results (Yin, 2003). For presenting our conclusions we have opted to use an approach of scenarios. As Balarezo and Nielsen (2017) present in their article scenario planning has been adopted as a viable method in research related to economics, business and related fields. We have opted to outline the two most probable scenarios that will utilise specifically the technology of biogas production, composting, and processing of hydroponic growing mats. The two scenarios will be assessed based on their techno-economic and legislative feasibility. To conclude our case study we will select one scenario with the highest potential for implementation.

3.2 Data acquisition and methods

To conduct exploratory research, we have gathered secondary data. The majority of the secondary data came from online journals, e-books, and other sources, company records, as well as printed publications. We have used databases of Google Scholar and the Web of Science focusing on sources from the last 3 to 5 years. However, we have opted to use certain older materials as their contents were still relevant and cited in current research. The most relevant sources were found under search terms like biowaste management, circular economy, bioeconomy, biogas production, anaerobic digestion, composting, and food waste valorisation. The research design reflects the complexity of the case study and preliminary formation of research questions as well as selecting the researched technologies. Technologies were selected based on consultation with the assistant agronomist of Agro GTV Ing. Gabriela Košičarová.

We have visited Agro GTV on 3 separate occasions all of which were supervised by Ing. Gabriela Košičarová. During the first visit, we have been introduced to the overall design of the greenhouse. The main focus was put on agricultural waste production. Especially how is the waste produced, gathered and disposed of. The first visit served the purpose to formulate scenarios and select suitable technologies for waste valorisation.

The second visit happened one month after the initial visit and consisted of presentations of proposed scenarios and a two-hour-long interview with Ing. Gabriela Košičarová. In the interview, we inquired about the current and future strategies of Agro GTV in waste management.

Before the third visit, which was scheduled again after a month, we completed our literature review and compiled questions and data requests necessary to advance in our research such as what the area of the greenhouse and floor plan with the surrounding land disposition is; what are varieties of tomatoes that are currently grown and in what quantities; how is harvest conducted and in what frequencies based on the lengths of growing seasons; what cultivation treatments are used in terms of fertilisers and hydroponic setup; how much organic waste generated and on what bases it is measured; how much waste is generated in total during the year; how often is organic waste collected; how is waste handled and disposed of; what are costs associated with waste disposal.

Due to the nature of this case study, we did not opt to gather any primary data as company records and publications were sufficient for analysis and further formation of conclusions.

3.2.1 Economic evaluations

To establish whether any of our proposed scenarios is economically feasible we have selected multiple economic performance indicators used to assess the soundness and attractiveness of long-term investments like the net present value, internal rate of return, and the payback period.

Net Present Value

According to Fernando et al. (2022a), the difference between the present value of incoming cash inflows and outflows over a specific timeframe is referred to as the net present value (NPV). To assess the potential profitability of a proposed investment or project, NPV is utilized in capital budgeting and investment planning. This method helps in evaluating the profitability of the project or investment. The project's NPV is calculated using the following equation:

$$NPV = \sum_{t=0}^{n} \frac{R_t}{(1+i)^t}$$

where: R_t = net cash inflow – outflows during a single period

i = discount rate or possible return from alternative investment

t = number of time periods

Internal rate of return

Fernando et al. (2022b) explain that in financial analysis, the internal rate of return (IRR) is a metric employed to determine the profitability of potential investments. IRR represents the discount rate that sets the NPV of all cash flows to zero in a discounted cash flow analysis. The same equation is used for NPV calculations and IRR calculations. The IRR does not accurately reflect the actual financial value of the project. An investment is more favourable to make the greater the internal rate of return is. A least acceptable return, sometimes known as "the hurdle rate," is assessed to see if the estimated IRR exceeds it (Karellas et al., 2010). The project's IRR is calculated using the following equation:

$$0 = NPV = \sum_{t=1}^{T} \frac{C_t}{(1 + IRR)^t} - C_0$$

where: C_t = net cash inflow during the period t
C_0 = total initial investment costs
IRR = the internal rate of return
t = number of time periods

Payback period

Kagan (2020) defines the payback period as an approach that is frequently used for approximating investment returns. It assists in determining the period required for an investment's initial costs to be recovered. The investment is more lucrative the faster the returns. Although this indicator has uses in various sectors, estimating the payback period is important in capital and financial budgeting. It may be used to estimate the return on investment for energy-efficient technology like solar panels and insulating materials, including upkeep and modifications.

$$Payback\ Period = \frac{Cost\ of\ Investment}{Average\ Annual\ Net\ Cash\ Flow}$$

3.2.2 Sizing of the biogas plant

According to Energypedia (2021) the amount, kind, and quality of the biomass that is available, as well as the temperature at which it is being digested, determine the size of the biogas plant. It's important to think about the following facts. To properly size the digester and additional components like the gas holder we will employ the following equations.

Digester volume and substrate input

The size or volume of the digester, denoted as V_d, is determined based on the chosen retention time (RT) and the daily substrate input amount (S_d). (Energypedia, 2021).

$$S_d = biomas\ (B) + water\ (W)\ [m^3/d]$$

$$V_d = S_d * R_T\ [m^3 = m^3/day * number\ of\ days]$$

Digester loading rate

The daily total solids input TS/d or the daily volatile solids input VS/d, along with the digester volume Vd, are used to compute the digester loading Ld (Energypedia, 2021). The TS is used to assist in identifying which digester is sufficient for the quantity of feedstock coming in, and the VS may be thought of as a measurement of the organic matter (Nelsom, 2010).

$$Ld_T = \frac{TS/d}{Vd}\ [kg/(m^3d)]$$

$$Ld_V = \frac{VS/d}{Vd}\ [kg/(m^3d)]$$

3.2.3 Additional applied theory

Dry fermentation

During our research on local contractors, we came across an alternative technique called "*Dry fermentation*". According to Červená et al. (n. d.), dry fermentation is a younger process compared to wet fermentation, but some of its types already promising applications in practice. In addition, dry fermentation is typically divided in accordance with the dry matter content of the substrate into a dry process (25 - 45% dry matter) and a high dry matter process (over 40% dry matter). Garage type fermenter (see Pictures 1 and Figure 8 below) is the most suitable for dry technology. It is a structurally simple device for processing high-dryness substrates with a batch method and filling the fermenter by using a front loader. This technology works with dry matter of up to 60%, which is very interesting from the point of view of the management of rotten products. The main advantage of dry fermentation is a smaller amount of digested sludge (digestate), i.e., its greater concentration, and at the same time a smaller consumption of process water for dilution and subsequent smaller problems with its utilisation as a by-product.

Picture 1: Garage-type Fermenter (Pietzsch, 2007)

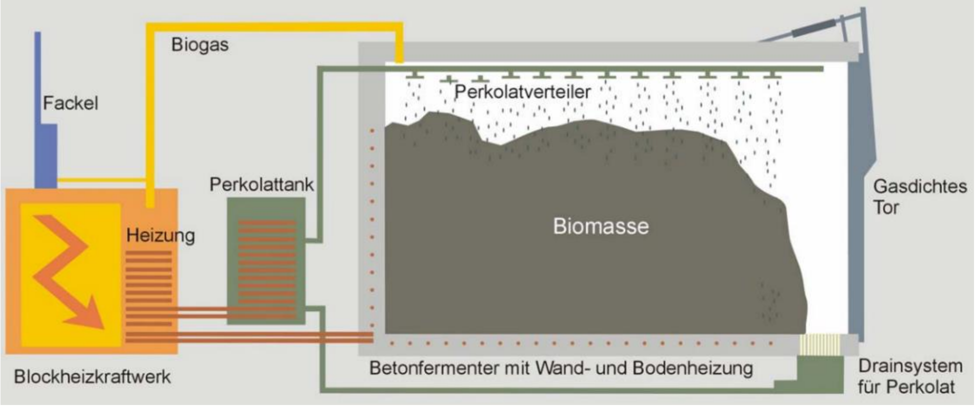


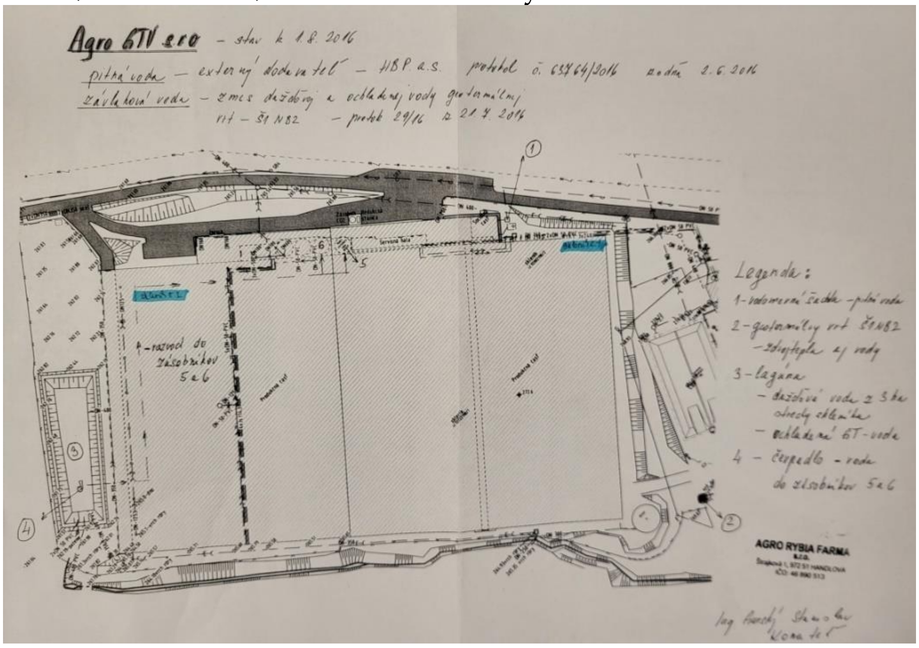
Figure 8: Dry fermentation process (Pietzsch, 2007)

3.3 Case company

For this study we have selected the following Slovak case company Agro GTV, located in the Prievidza region, that runs a greenhouse tomato production plant, using hydroponic systems. The aforementioned company is a part of the larger corporation Hornonitriaske bane Prievidza a.s. (HBP a. s.). HBP a. s. was previously a nationally owned coal mining company, then privatised in the year 1996, and registered as a joint-stock company (Kvašňák, 2017; Finstat, n.d.). HBP a. s. is the main supplier of brown coal for the coal powerplant in Nováky. As the EU is moving towards green energy the Nováky power plant is to be shut down and the coal mining is to be ceased by the year 2023 (TASR, 2022). Considering upcoming changes HBP a. s. is shifting its focus towards already existing other business ventures, one of which is Agro GTV.

Agro GTV has under its operation a greenhouse of 2.8 ha divided into two growing areas of 1.5 ha and 1.3 ha. For graphical representation please refer to Picture 2 below. In the year 2022, 100 000 singular tomato plants were planted in seven different varieties of Marinice, Presence Imperoso, Bellioso, Brioso, Annasun, Tomimari Mucho, and cherry tomatoes. This year all together was planted

97 228 individual tomato plants in four distinct varieties of Prospano Rz F1 (62 440 pc), Amelioso Rz F1 (20 680 pc), Lucioso Rz F1 (13 780 pc), Hyrule Rz F1 (328 pc). Each growing season planted varieties are selected based on the demand of wholesale customers. The average yearly production yield is 1 100 000 to 1 200 000 tons reached in the growing season (January- December). The length of the growing season and ripening time is dependent on the amount of light, temperature, fertilisation, and tomato variety.



Picture 2: Floorplan of Agro GTV (2023)

Hoidal et al. (2022) explain the basics of hydroponic growing systems as follows: plants may be grown without using soil all year round. Water requirements are lower in hydroponic systems than in conventional soil-based farming. Furthermore, hydroponic cultivation facilitates faster growth and higher yields compared to conventional soil-based growing methods. The basic requirements for starting a hydroponic production are the means of securing the selected plant species, suitable containers, water, appropriate nutrient-rich fertiliser, and a light source. Artificial lighting and appropriate temperature promote quicker growth if plants are grown inside. Hydroponic systems are installed both indoors and outdoors.

In Nováky the greenhouse consists of only a hydroponic system. Agro GTV uses growing mattresses (Grodan GT master mineral felt mattresses) made of mineral fibre to serve as a substrate, which holds the plant roots and captures nutrients. In the foreseeable future, the transition to cultivation with coconut mattresses is planned. The cultivation is based on a groove system that uses the Nutrient film technique (NFT) see Figure 9 below. Drip irrigation and nutrition work on the principle of a capillary supply system of nutrients from the distribution pipe directly to the growing boxes. The excess nutrient solution flows through the sloped metal gutters fixed on a metal frame back into the storage tank, where it is cleaned and then used for the next irrigation. Picture 3 below shows the whole growing system directly in the greenhouse in Nováky. Usage and ratios of agents constituting the nutrient solution comply with all legal requirements of the Slovak Republic as well as the European Union. Table 3 in the appendix lists all the fertilizers and the content of key elements expressed in percentages.

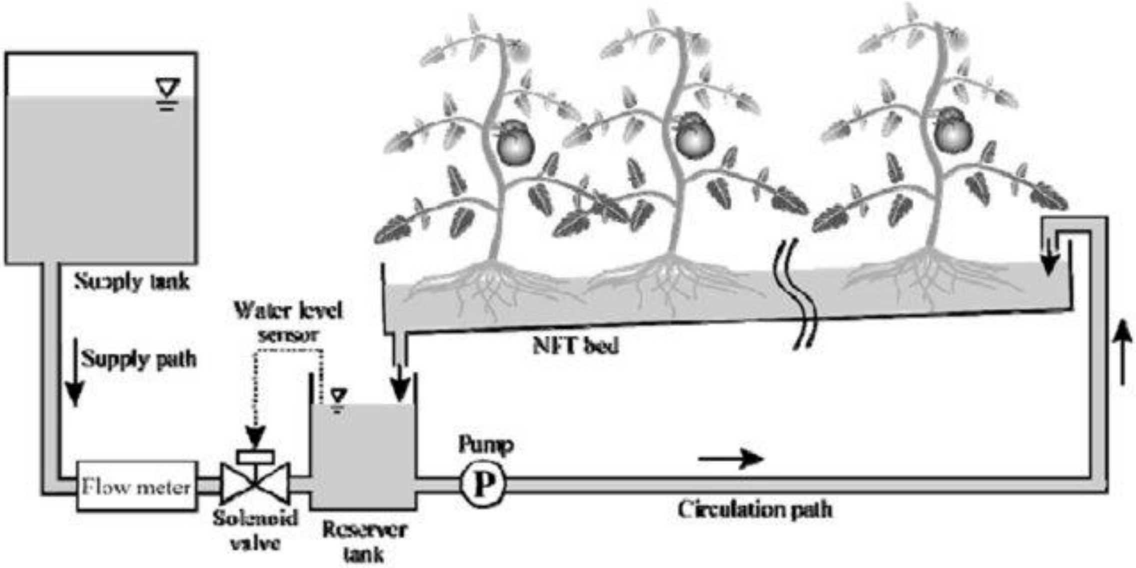


Figure 9: Model of groove system using NFT(Nomiyama et al., 2017, p. 30)

Picture 3: Agro GTV tomato greenhouse section 1 (HBP a. s., 2023)

Since it is an agricultural production, biowaste is produced daily coming mainly from leaves. Biological waste is also generated both during the picking of tomatoes, where non-standard ones are discarded, as well as during the sorting of tomato fruits for the sale of free fruits, if it does not meet the quality characteristics, it is then discarded in containers Bio-waste is collection cycles depend on the individual work operations in the greenhouse and the growth phase of individual tomato varieties. A bulk container (BC) with waste tomatoes is dispatched about once a week while collected fallen or removed lower leaves are transported to the compost site approximately 3 times a week, again adjusted based on how quickly the collection container is filled and then transported by the contractual company Vepos s.r.o Nováky to a processing facility or composting site. Table 4 below lists the amount of waste produced in the past year based on category.

Table 4: Types of waste per year

Waste type	Volume in t/year
Waste plant tissue	162.5
Leaves	200
Mixed packaging	1.83
Plastics and rubber	1.94

Source: Agro GTV (2023)

Costs associated with waste disposal are dependent on many factors including the amount of waste, nature of waste, transportation costs, contractual terms and conditions, local taxes, waste fees and many more. Thus, every year the final cost of waste disposal for Agro GTV varies, but it should be noted that it is on a rising trajectory. Tables 5, 6 and 7 below outline the associated costs for the year 2022 to better understand the economic implications. Fees refer to the waste fee paid under the laws of the Slovak Republic, the p. Z. z. 329/2018 and the reclamation fee 312/2018.

Table 5: Waste disposal costs of plant tissue for the year 2022

Date	Volume in t	Amount in EUR
31/01/2022	12.04	445.48
25/05/2022	15.87	634.80
30/06/2022	35.52	1,420.80
25/07/2022	16.29	651.60
31/08/2022	41.05	1,642.00
30/09/2022	34.08	1,363.20
31/10/2022	11.64	465.60
30/11/2022	5.10	204.00
07/12/2022	10.62	424.80
Sum	**182.21**	**7,252.28**

Source: Agro GTV (2023)

Table 6: Waste disposal costs of mixed packaging for the year 2022

Date	Volume in t	Amount in EUR	Fees in EUR
04/04/2022	2.02	98.62	26.94
20/12/2022	1.27	68.20	16.94
Sum	**3.29**	**166.82**	**43.88**

Source: Agro GTV (2023)

Table 7: Other associated waste disposal costs for the year 2022

Period	Rent of a BC in EUR	Transport of BC in EUR	Manipulation with BC in EUR	Mileage in km	Other in EUR
01/2022	34.10	46.25	19.60	46.80	
02/2022	30.80	48.58			137.29
03/2022	31.10	48.58			
04/2022	34.30	48.58	35.70	85.80	
05/2022	34.10	48.58	30.60	70.20	
06/2022	33.00	48.58			
07/2022	34.10	48.58	91.80	210.60	303.48
08/2022	34.10	48.58	66.30	156.00	
09/2022	33.00	48.58	61.20	140.40	
10/2022	34.10	53.42	20.40	46.80	
11/2022	33.00	53.42	10.20	23.40	
12/2022	34.10	53.42	20.40	115.20	
Sum	**399.80**	**595.15**	**356.20**	**895.20**	**440.77**

Source: Agro GTV (2023)

4 RESULTS AND ANALYSIS

In this chapter, the proposed solutions for making the current biowaste management of Agro GTV more sustainable will be presented. In line with the circular economy principles, two different scenarios are proposed and further explained. For both scenarios, biogas plant and composting, the techno-economic and legal feasibility are analysed as well as barriers to implementation. These two scenarios were selected because according to previous research, they are generally the most widely used techniques for organic waste valorisation while simultaneously they are in line with an action plan for the transformation of the region where Agro GTV is based (pwc, 2021).

4.1 Scenario 1: Biogas plant

The first scenario is named "Biogas plant" since the main biowaste utilisation process is anaerobic digestion. As the name suggests the final product is biogas and the secondary product is digestate. This scenario aims to valorise the biowaste of Agro GTV and turn it into heat for raising the temperature of the greenhouses, which will get the internal conditions closer to the ideal and enhance the properties of the grown produce. Digestate can be sold and turned into additional income for the company. Scenario number one is structured into subsections as follows: description of the proposed solution, techno-economic feasibility, sources of supplementary funding, legislative requirements for biogas production, and barriers to implementation.

4.1.1 Description of the proposed solution

Based on the literature research and analysis of the case company Agro GTV we have gone through a selection process of standardised reactor configuration contingent on the feedstock type. The selected digestor design is CSTR (continuous stirred-tank reactor) with a standard structure employing the co-digestion submerged AD process with less than 15% solid concentration (Mirmohamadsadeghi et al., 2019) in a single-stage digestor, as it is a more practical method of extracting methane from unprocessed tomato plant waste (TPW) (Ruiz-Aguilar et al., 2022). Mechanical mixing enhances biogas production by mild agitation (Deublein and Steinhauser, 2011), removes metabolic products (H_2-blocking layer), prevents foaming and the disruption of the temperature gradient, while eradicating floating and sinking layers (Mirmohamadsadeghi et al., 2019). Tomato plants contain a relatively small amount of lignocellulose. The majority of the plant's biomass is composed of water, followed by carbohydrates such as cellulose and hemicellulose (Ali et al., 2020). Hence, hydrolysis will not be a rate-limiting step as the majority of the compounds in TPW can be digested without pre-treatment and are biodegradable (Sahito and Mahar, 2014). Tomato plant micronutrient composition includes 23 types of minerals, of which iron, zinc and nickel are present in trace amounts (Ali et al., 2020). Iron plays a growth-promoting role in the production of ferredoxins and cytochromes and lessens the corrosion-causing effects of H_2S in biogas (Chong et al., 2016). Nickel is essential for the development of all methanogenic archaea and is necessary for the production of cofactor F_{430}, while zinc is required for methanogens in order to produce carbonic anhydrase (Mirmohamadsadeghi et al., 2019).

The most suitable inoculum for co-digestion of AWS is cow or pig manure for more balanced C: N ratios; creates consistent texture and MC; reduces chances of inhibition by LCFA and VFAs (Zhang et al., 2013b; Haider et al., 2015); provides balanced C, O, N, and H content; raises the reaction rate; and boost the generation of biofuel (Almomani, 2020; Zhang et al., 2014; Alkaya and Demirer, 2011). The other benefits of co-digestion like nutrient balance, buffering power, pH control and methane yield boost are described more closely in the theoretical section.

The most commonly occurring results of tests for the Substrate to Inoculum (S: I) ratio is between 0.5 and 1, and when the S: I ratio rises, the yield of methane generation is significantly impacted (Raposo et al. 2006; Zhou et al., 2011). Nevertheless, to achieve the highest biogas production yield, Pellera and Gidarakos (2016) advise conducting separate tests for each feedstock to determine the S: I ratio since the quantity of inoculum greatly relies on the substrate parameters. The aforementioned 0.5 and 1 are only considered rough guidance for making estimates.

Thanks to the literature review of studies on biogas yield from tomato plants, done by Camarena-Martínez et al. (2020), it is evident that the suitable temperature range is 35 °C to 37 °C (mesophilic reactor temperature). The advantage of a mesophilic digester is that it can operate at normal performance consistency within temperature changes of ± 3°C (Mirmohamadsadeghi et al., 2019). Since the digestor would be operated by the employees of the greenhouse straightforward process management resistance to environmental fluctuations, enhanced sludge dewatering characteristics, and faster rates of food waste solubilization at lower temperatures (Zhang et al., 2014; Bharathiraja et al., 2016; Benabdallah et al., 2009) are important aspects that made us choose the mesophilic AD. The average methane production of mesophilic AD ranges from 130.3 ml/g VS to 415.4 ml/g VS (Camarena-Martínez et al., 2020). This is further verified by Ruiz-Aguilar et al. (2022) who reported in their findings that obtained methane production from TPW was 365.4 ml/g VS. Methane made up 66.1% of the biogas on average. The methane yield from TPW is very similar to Nkemka et al.'s (2015) results from corn silage 358 ml CH_4/g VS. We will further use an average of methane yields we have collected from other studies equalling to a more conservative measurement of 280 ml CH_4/g VS.

Digester volume is estimated to be 100 – 150 m^3 based on the calculations where daily input of biomass and its availability and retention times are considered. The most common hydraulic retention time in Austrian plants of similar size based on local farms is 82 days (Walla et al., 2003). As we have to take into account certain drops in biomass production throughout the year and eminent increases at the end of the growing seasons. The reactor should accommodate these changes as well as the space for the gas storage chamber. Figure 10 below shows a cross-section of the selected CSTR digestor that can be scaled to any preferred size. The fundamental construction of the digestor does not change. This digestor type is commonly used in Europe for more than 40 years, specifically on a smaller scale, localised at individual farms (Ploechl and Heiermann, 2006). Figure 10 below depicts a vertical digester, even though it is more common to have smaller digestors from 50 – 150 m^3 as horizontal structures (Karellas et al., 2010) To achieve greater surface area accessible for the first adsorption of exo-enzymes, accelerating the breakdown process and enhancing biogas generation (Agyeman and Tao, 2014; Mirmohamadsadeghi et al. 2019) we have decided to include as a pre-treatment a simple chopping machine. To avoid process failure and severe foaming caused by too-fine particle sizes (Zhang and Banks, 2013) we have disregarded the option with a grinder.

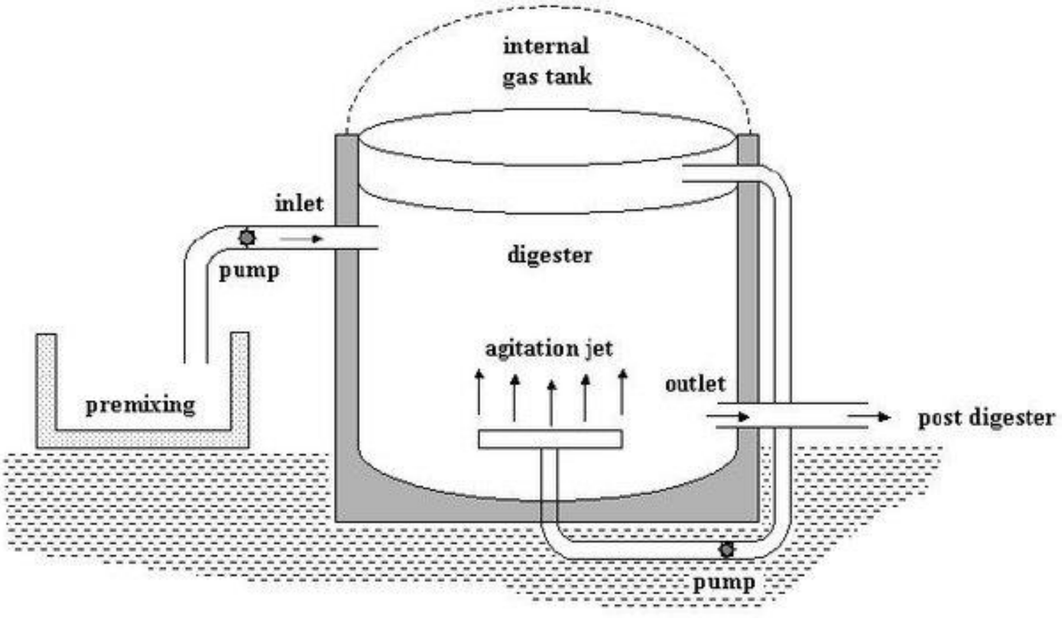


Figure 10: Digester for the wet anaerobic digestion (European example) by Ploechl and Heiermann (2006, p.5)

According to SGC (2012), 1 m^3 of pure methane has a calorific potential of 10kWh. The energy content of 1.1 l of petrol equals 1 m^3 of biogas with 97% purity. Figure 11 below compares volumes of biogas with 97% purity, petrol and natural gas compressed at 200 bars with energy content corresponding to 1 l of petrol. The significantly higher volume of biogas for the same energy content as petrol, explains the necessity of the internal hemispherical collection gas tank accounting for higher digestor volume.

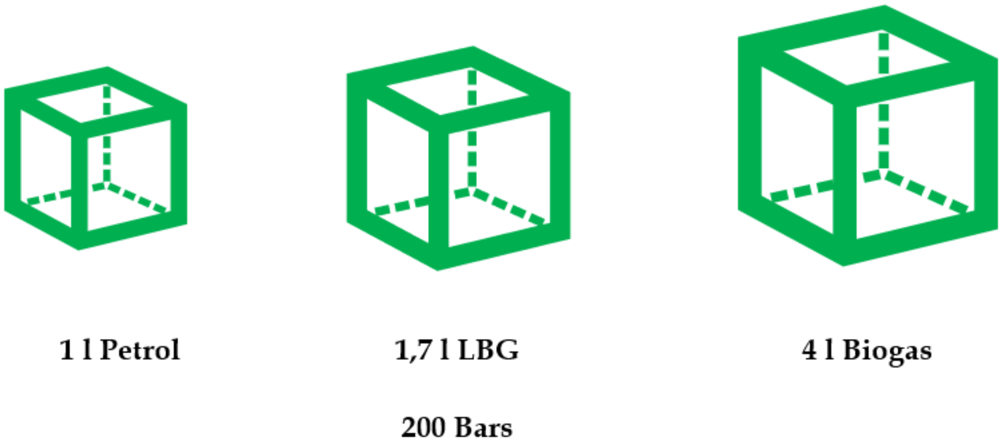


Figure 11: Comparison of the volume of liquified fuels pressurised to 200 bars (SGC, 2012, p. 9)

Tomatoes are similar to oranges, apples and pears in regard to water, nutrient, and cellulose content. Water should be added to the substrate to achieve a solids content of 4-8% which determines the substrate input (Energypedia, 2021). Ripe tomatoes have a water content of 90 – 95% (Hou et al., 2020) while the stems and leaves have a relative water content potential at full turgidity at 98%, while the average around the initial wilting is between 60 - 70% (Barr and Weatherley, 1962). The inoculum (cow/pig manure) has an average water content of 83% (Taylor, 1917; Lorimor et al., 2004). Hence the ratio of water to biomass cannot be calculated on average as the nature and mix of biomass changes with the growing season as well as the changing water content of the added inoculum from animal manure. Although, we can assume for the end of the growing season when the biomass would be constituted of equal parts of ripe tomatoes and plant bodies at the initial wilting stage. This constitution gives us a relative water content of 77.66 – 82.66% with a solids content of 22.34 – 17.34%. To reduce the solids content to the recommended range (target 6%) the substrate input would be constituted of biomass and water in ratio S_d = 100: 16.34 – 100: 11.34. To estimate methane production or reactor daily loading rate we have to know the TS and VS of feedstock. Figure 12 below shows the composition of ripe tomatoes. From there we can infer that ripe tomatoes are constituted of 4% organic matter, or in other words VS (Hamilton and Zhang, 2016) and TS including ash is 5%, which in our case amounts to 18.125 t/year.

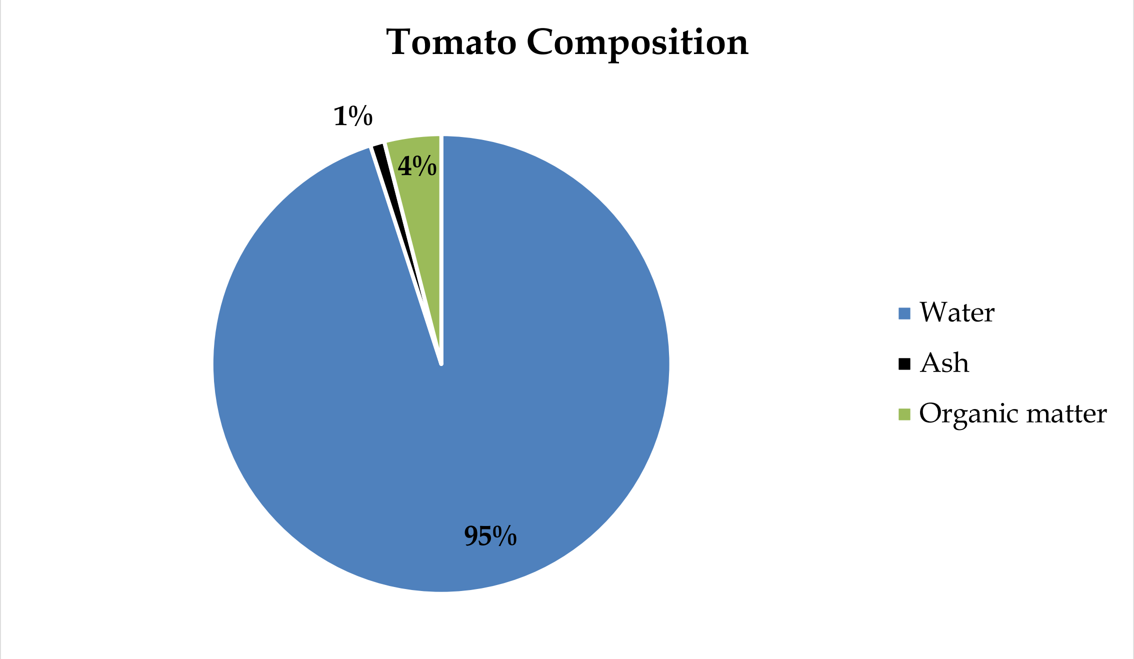


Figure 12: Tomato Composition (Sink and Wilkie, 2011)

Karellas et al. (2010) measured that pig manure has a satisfactory bio-methane production potential at 362.5 ml CH_4/g VS. Manure contains on average 4.3% organic matter and TS constitute 17%, which in our case amounts to 34 t/year. Hence, the constitution is similar to that of tomatoes. From the estimated amounts of TPW 14.5 t of VS and from inoculum 8.6 t of VS a year will be available for CH_4 production. As the amount of inoculum fluctuates based on the actual conditions in the digestor, we have opted to use the amount of 200 tones a year in the calculations as it is closer to the ideal ratio of 0.5: 1 and yet it accounts for a higher need of inoculum in case the amount of lignocellulose is significantly high around any given time (see Table 8). From the information gathered, we have calculated that the proposed digestor has the potential to produce 7 177.5 m^3 CH_4/ year from the available biowaste. To achieve a higher calorific value of the biogas and to prevent corrosion or depreciation of the heating equipment, water scrubbing as the most well-known and most often used biogas upgrading process (Thrän et al., 2014) was selected. However, new technology with activated carbon filters is also available (AAT Biogas Technology, n.d.). There is a possibility to boost the production of biogas from given feedstock by employing bioaugmentation (Mirmohamadsadeghi et al., 2019; Kapoor et al., 2020) or chemical additives (Desai and Madamwar, 1994) but the additional costs outweigh the pros. Although, activated carbon can be an inexpensive additive to remove antibiotics from the purchased manure in case the farm records higher application numbers (Zhang et al., 2019b; Al-Masri, 2001). From the information contained in Table 8, we have calculated the daily loading rates for reactor size 100 and 150 m^3, being Ld_T = 1.428 and 0.952 kg/m^3 d while Ld_V = 0.6301 and 0.42 kg/m^3 d respectively. Based on Svensson et al. (2018) and Mirmohamadsadeghi et al. (2019) the increased feeding frequency is advised and will correlate with the waste collection protocol at Agro GTV, which happens continuously throughout the day in batches upwards of 100 kg (Košičarová, 2023). As the organic loading is not excessive the stability of AD is not dependent on the addition of cobalt (Chong et al., 2016). Based on the amount of waste produced by Agro GTV and the calorific potential of methane the reactor is going to produce 7 177.5 m^3 CH$_4$/ year, which equals 71 775 kWh. Table 9 summarizes all estimated parameters mentioned in the text above. Filer, Ding and Chang (2019) and Krause et al. (2018) advise conducting BMP analysis to optimise crucial variables using batch samples. At the moment, we are unable to utilise BMP for our calculations. Though, it is advised to use BMP in a trial reactor, if Scenario 1 is selected.

Table 8: Produced biogas from TPW feedstock and manure

Input feedstock	Tones of TS/ year	Tones of VS/ year	m^3 CH$_4$/ ton VS	m^3 CH$_4$/ year
TPW	18.125	14.5	280	4060
Manure	34	8.6	362.5	3117.5
Total	**52.125**	**23.1**	**-**	**7177.5**

Table 9. Estimated parameters of the anaerobic digestor

Name of the parameter	The estimate	Unit
Digestor type	CSTR	-
Configuration	Sigle-stage	-
Inoculum type	Cow or pig manure	-
Inoculum amount	181.25 – 362.5	t/year
Feedstock type	TPW	-
Feedstock amount	362.5	t/year
Digestor temperature	35 - 37	°C
Digestor volume	100 - 150	m^3
Methane yield TPW	280	ml CH$_4$/g VS
Methane yield manure	362.5	ml CH$_4$/g VS
A substrate-to-inoculum ratio	0.5 - 1	-
Biomass to water ratio	100: 16.34 – 100: 11.34	-

Name of the parameter	The estimate	Unit
Ld_T	1.428 – 0.952	kg/m³
Ld_V	0.6301 and 0.42	kg/m³

Once the digestor is in full operation and produces high-quality digestate it is possible to recirculate it. Using digestate as inoculum increases microbial density along with activity and marginally boosts biogas output by reintroducing the washed-out microbial biomass into the digester (Mirmohamadsadeghi et al., 2019; Kapoor et al., 2020) as well as lowers the costs associated with inoculum procurement. Furthermore, Pelayo Lind et al. (2021) showed that plant-derived anaerobic bio digestate, when sieved, diluted to the right ammonium content, and then put under controlled nitrification before and/or during its application in recirculating hydroponic growth, is a beneficial nutrient solution. In BD-based hydroponic farming of bok choy, sufficient yields were attained while taking into account the system's bio circularity and the potential for enhanced crop quality. Yields increased by less than a week, giving results comparable to those of traditional hydroponic growing.

4.1.2 Techno-economic feasibility

This section examines the project's techno-economic feasibility, or in other words how feasible it would be to build and run an AD plant using the available organic feedstocks primarily from Agro GTV and possibly sources from the surrounding area. Our economic assessment will be based on the assessment done by Karellas et al. (2010) in their study. The anticipated total plant costs (TPC), and CapEx (the entire project cost including development and contingency) are the main focus of the evaluation of the plant. Additionally, a projected breakdown of the various expenses that make up total operating costs (TOCs), including feedstock prices (for co-digestion), is provided. Karellas et al. (2010) highlight that the decision often depends on the objective of the analysis. When evaluating the feasibility of biogas-to-energy projects, data such as the project's initial capital expenditure, projected energy production (both electricity and thermal energy), and annual sales of the compost fraction are considered. Meanwhile, operational costs typically encompass net operating expenses (including feedstock costs, energy crop expenses) and financing costs. Usually, an after-tax cash flow statement, proforma earnings statement, and debt redemption schedule are also created. Then, to assess the potential return, annual after-tax cash flows are contrasted with the initial equity investment. Another viewpoint would be to compute and compare before-tax, debt-free cash flows to the project's overall cost. The key merit indicators are net present value, internal rate of return, and payback period.

It is inherently difficult to estimate the capital costs for building an AD in general. From the literature review, it is apparent that capital costs may vary greatly due to technological differences in approaches of pre-treatment, digestor configuration or feedstock. We have to also take into account that capital cost calculation is also dependent on set boundaries. Table 10 shows how capital costs can be estimated at different levels based on defined boundaries. We have based our approach on that of Karellas et al. (2010) and incorporated capital costs into Total Plant Costs (TPC) which can be also referred to as "turn-key costs". TPC include the cost of both building and measuring equipment, construction, piping, engineering, commissioning, contingency and interest.

Table 10: Composition of capital costs

Cost component		The usual range of costs	The most used cost factor
Major unavoidable costs: - Construction - Building and measuring equipment - Piping - Engineering - Lagging - Civil and electrical works	Direct Plant Costs (DPC)		100% DPC
Engineering, design, supervision	DPC	10 – 20%	15% DPC
Management	DPC	5 – 20%	10% DPC
			125% DPC
Commissioning	Installed Plant Costs (IPC)	1 – 10%	5% IPC
Contingency	IPC	0 – 50%	10% IPC
Contractor's fees	IPC	5 – 15%	10% IPC
Interest during construction	IPC	7 – 15%	10% IPC
	Total Plant Costs (TPC)		**135% IPC** **169% DPC**

Source: Karellas et al. (2010, p.1278)

Červená et al. (n. d.) created an informative overview of the biogas plants in the Czech Republic and Slovakia starting from the year 1990. They have found out that an average plant turned out to have 500 kWh power output and required 2 100 000 EUR as an initial investment and expected return of investment within

10 years. However, it must be noted that a plant of this size has significantly higher associated costs with building, infrastructure, as well as personnel and surrounding buildings. The life expectancy of large-scale farms is over 20 years. However, on a business level the average investment costs are up to 2,5 times higher for plants with output smaller than 25 kW_{el} compared to plants with output greater than 200 kW_{el} (Walla et al., 2003). Birch Solutions (2021) suggest that a smaller facility that handles slurry and manure and comprises a basic digester and a CHP (Combined Heat and Power) system, could have a price tag ranging from £750 000 to £1 million, which equates to 847 552.06 - 1 130 069.42 EUR. This is further supported by Mashhadi et al. (2021) who highlight the necessity of minimum daily feedstock input of 18 tons of manure for overall operational rentability. In the case of commercial rentability, the input should be significantly higher. For comparison small home biogas digestors that produce 1.8 m^3 of biogas per day, cost 1 000 EUR (Freegas.cz, 2023). There is a large investment size gap between house devices and industrial or business size.

Capital Expenditure (CapEx) in our case is defied by combining TPC and concept development, contingency, pre-financing as well as required authorisations and licenses. Table 11 below shows the breakdown of estimated CapEx including development costs at 7.5% of TPC and possible contingency estimated at 5% of TPC based on findings of Karellas et al. (2010) and Muradin and Foltynowicz (2014) expressed in most expected percentages. Unfortunately, we were not able to acquire any real-time information online or model quotations from vendors. Companies based in Slovakia or the Czech Republic do charge hundreds or thousands of EUR for an estimate or require a DIČ – Daňové identifikačné číslo, which can be translated as the VAT identification number for enterprises, to prove a purchase intent. Therefore, we have taken the average percentages and reduced them by the percentage for civil works and infrastructure as the plant is intended only for internal use, as well as the ready existence of the traffic connection has to be taken into account.

Table 11: CapEx of a generic model biogas plant

Capital Cost items	The most used cost factor
Infrastructure	- 11%
Reception and pre-treatment of biowaste	9%
Inoculum	4%
Digestor and ancillaries	24.5%
Decanter	4%
Biogas cleaning system	10%

Capital Cost items	The most used cost factor
Other subsystems	4%
Cogeneration unit	21%
Total Plant Costs (TPC)	87.5%
Project development (7.5% of TPC)	7,5%
Contingency (5% of TPC)	5%
Total costs (CapEx)	**100**

From the obtained information we have concluded that the investment of Agro GTV into a small biogas plant is not techno-economically feasible. The reasons for this conclusion are the technical complexity, lack of available economic data and sizable initial investment.

4.1.3 Sources of supplementary funding

The European Union (EU) has many initiatives to support the transition to sustainable energy sources and in general to support agriculture. After all the food industry is one of the critical sectors keeping us alive while producing a significant amount of waste. According to the EU Taxonomy, agricultural activities that satisfy given requirements are deemed environmentally sustainable and may be eligible for financing from sustainable finance instruments (Celsia, 2023). The funding for biogas production is accessible through various programs and initiatives. Here are the key sources of EU funds specifically for biogas projects:

- Horizon Europe: The EU's research and innovation program, Horizon Europe, supports projects related to biogas production and technology development. It provides funding for research, demonstration, and pilot projects in the field of sustainable energy.
- European Regional Development Fund (ERDF): The ERDF promotes local or regional growth across the EU and can provide financial assistance for biogas infrastructure projects. It aims to promote sustainable and low-carbon solutions, including renewable energy production.
- Common Agricultural Policy (CAP): The CAP includes measures to support rural development, including funding opportunities for biogas projects. These funds can be accessed by farmers and rural communities for the construction and operation of biogas plants.

- European Structural and Investment Funds (ESIF): The ESIF encompasses several funds, including the ERDF and the European Agricultural Fund for Rural Development (EAFRD). These funds can be used to support biogas production initiatives in different regions, with a focus on promoting sustainable agriculture and rural development.
- LIFE Program: The EU's LIFE Program provides funding for projects in the areas of environment and climate action. Biogas projects that contribute to greenhouse gas reduction, circular economy principles, and waste management may be eligible for support through this program.

Horná Nitra, the region where Agro GTV operates, is also eligible for financial support dedicated to reviving dying regions and combating unemployment. These funds can come from the Next Generation EU; Fund for Just Transformation 2021 - 2027; European Structural and Investment Fund within the programming period 2021 - 2027; European Agricultural Fund for Rural Development; Community programs of the EU; National support mechanisms; European Investment Bank (EIB); State budget; regional and municipality budget. It is important to note that specific funding opportunities, awarded amounts, eligibility criteria, and application processes may vary over time. Thus, these funds are a feasible source of supplementary funding for building a biogas plant but have to be reviewed ahead of project planning to meet necessary deadlines or postpone plant erection based on the funding scheme time plan.

4.1.4 Legislative Requirements for biogas production

Since Slovakia is a part of the EU any activity falls not only under the jurisdiction of Slovak law but also that of the EU. Hence, we will below outline legislative requirements for biogas production coming from the EU and the Slovak Republic respectively.

Legislative requirements of the EU

Legislative requirements for biogas production on the EU level are extensive, but they mainly consist of associated legislation tied to environmental and biodiversity protection. The foundational concept behind the principle of primacy (also referred to as "precedence" or "supremacy") of EU law is that, if there is a dispute, EU law will have priority over the national law of an EU member state. Hence, national law is inferior to EU law (European Union, n. d.). This implies that none of the member states can institute national legislation that contradicts with EU law. Additionally, it means that any national law, even one that was passed before the EU law took force, might be superseded by an EU law (Citizens Information, 2022). Consequently, the below-listed legislative requirements of the EU that are connected to biogas production or those that govern the impacts associated with biogas production are of greater importance and are as well reflected in the national legislation of Slovakia.

- Legislative requirements of the EU use conditionality as an umbrella term for the Statutory Management Requirements (SMR) according to Article 4 and Annex III of the European Council (EC) Regulation No. 1782/2003 and Good Agricultural and Environmental Conditions (GAEC) standards according to Article 5 and Annex IV of the same regulation.
- Council Directive 79/409/EEC of 2 April 1979 on the protection of wild birds.
- Council Directive 80/68/EEC of 17 December 1979 on the protection of groundwater against pollution by certain dangerous substances.
- Council Directive 86/278/EEC of 12 June 1986 on the protection of the environment and especially the soil during the use of sludge in agriculture.
- Guideline Council Directive 91/676/EEC of 12 December 1991 on the protection of waters against nitrate pollution from biodegradable municipal waste sources (Nitrate Directive) Council Directive 92/43/EEC of 21 May 1992 on the protection of natural habitats, wild animals, and plants.
- Council Directive 91/676/EEC On the Protection of Water from Nitrate Pollution from biodegradable municipal waste sources. The Nitrate Directive is a set of measures aimed at reducing the possibility of pollution of water sources (surface and underground) by nitrates that can come from industrial fertilizers and farm fertilizers (manure, slurry, urea) when they are applied in excessive doses, at the wrong time, or when they are not properly stored.
- Since January 1, 2009, the system of cross fulfilment according to Article 51 of EC Regulation No. 1698/2005 has also been in effect for the payment of selected subsidies within the framework of the Rural Development Program of Slovakia funded by the European Agricultural Fund for Rural Development (EAFRD) (ENRD, 2022). According to the proposal of the EC Regulation, it should be applied in a three-year transitional period. Regulations guarantee transparency, equality of subjects, a non-discriminatory environment, competition, and the right to choose.
- Regulation of the European Parliament (EP) and EC No. 1228/2003 on the conditions of access to the network for cross-border exchanges of electricity.
- EP and EC Directive No. 2003/54/EC on common rules for the internal electricity market. Regulations requiring priority connection, priority access, priority distribution, and priority supply.
- EP and Council Directive No. 2001/77/EC on the promotion of electricity produced from renewable sources in the internal market.
- EP and Council Directive No. 2004/8/EC on the promotion of combined energy production based on the demand for useful heat in the internal energy market.

Legislative requirements of Slovakia

It is possible to do business in the energy industry only based on a business permit or confirmation of compliance with the reporting obligation. The Office for the Regulation of Network Industries (URSO) issues a business license and a certificate of compliance with the notification obligation to legal entities and private persons after meeting the conditions established by law (URSO, 2020). Act No. 250/2012 Coll. on Regulation in Network Industries gives URSO a mandate on setting tariffs and terms of their application in network industries, as well as terms of carrying out the regulated activities. The general legislative requirements of Slovakia tied to biogas production are as follows:

- Act No. 250/2012 Coll. on Regulation in Network Industries
- Act No. 251/2012 Coll. on Energy and Amendments to Certain Acts
- URSO Decree No. 446/2012 Coll. determines the format and dates for reporting outputs from the records, the method of maintaining records of expenses, revenues, assets, and liabilities, and the technique of keeping records of data that are the topic of accounting.
- URSO Decree No. 236/2016 Coll. establishes quality criteria for energy supply, distribution, and transmission.
- URSO Decree No. 18/2017 Coll. provides conditions for carrying out regulated operations in the power sector as well as pricing regulation of the industry.
- URSO Decree No. 278/2012 Coll. modified by Decree No. 233/2016 Coll., establishes quality criteria for gas storage, transmission, distribution, and supply.
- URSO Decree No. 223/2016 Coll. which establishes price regulation in the gas sector and as amended by Decree No. 206/2018 Coll.
- Act No. 188/2003 Coll. on the application of sewage sludge and bottom sediments to the soil
- Decree of the Ministry of Agriculture of the Slovak Republic No. 577/2005 Coll. and technical standard STN 46 5735 (46 5 735) Industrial composts regulate the requirements for the composition and quality of compost.
- Decree of the Ministry of the Environment the Slovak Republic No. 706/2002 Coll. classifies heat production equipment in terms of pollution source size according to the aggregate nominal heat input. This decree also regulates emission limits.
- Decree of the Ministry of the Environment of the Slovak Republic No. 705/2002 Coll. establishes the obligations of the operator in monitoring emissions.
- Regulation of the Government of the Slovak Republic No. 296/2005 Coll. cites the requirements for the quality of discharged water, establishes requirements for qualitative goals of surface waters and limits values of wastewater pollution indicators.

- Decree of the Ministry of the Environment of the Slovak Republic No. 284/2001 Coll. According to this, the Waste Catalog is developed and from which further legislation of waste treatment stems.
- Act No. 146/2023 Coll. concerning air protection
- Decree of the Ministry of the Environment of the Slovak Republic No. 706/2001 Coll. on the incineration of waste. Connected to Act No. 146/2023 Coll. from a process point of view, burning biodegradable waste is the same as burning any other type of waste.
- Fertilizers Act No. 136/2000 regulates the use of digestate defined as a secondary source of nutrients. Before applying for the digestate, the farmer is obliged to apply to the Central Control and Testing Institute for Agriculture in Bratislava (ÚKSUP) for a permit, which is valid for one year. The basis for issuing a permit is an analysis from an accredited laboratory, which indicates the content of dry matter, organic dry matter, pH value, nitrogen, phosphorus, potassium content and magnesium, values of the risk elements cadmium, lead, chromium, arsenic, nickel, and mercury, as well as microbiological parameters.

Legislation in the Slovak Republic is in many cases flawed or insufficient. Laws that have been developed or amended with biogas production in mind have applications only for large power plants. Here we list some examples of problematic legislation.

Even though in some countries (e.g. Sweden or Denmark) the legislation allows direct application of digestate to agricultural land in some cases, this is not possible in the Slovak Republic. The direct application of sewage sludge, which has similar properties to digestate, is regulated by Act No. 188/2003 on the application of sewage sludge and bottom sediments to the soil. Consequently, the digestate is most often further treated by aerobic processes, e.g. composting, for it to be legally used as a fertiliser.

Regulation of the Government of the Slovak Republic No. 296/2005 Coll. does not precisely set the limits for biogas plant or anaerobic digestor operation. Usually, the operator of the sewage network into which the wastewater is discharged is responsible for monitoring and treating the digestate wastewater, or the administrator of the recipient, if the operator has built its own aerobic level of wastewater treatment.

Under the Act No. 251/2012 Coll. on Energy and Amendments to Certain Acts the production of biogas or energy under one 1 MWh does not fall under this legislative act and is exempt from permit requirements. However, there are still permits associated with waste processing and procurement of manure.

4.1.5 Barriers to implementation

Politically motivated economic considerations are the primary impediments along with the insufficient amount of feedstock. Strong public opposition, which is mostly the result of a lack of trustworthy information about biogas, is another significant challenge encountered by biogas plants that rely on organic waste. Although the technique makes use of a biological mechanism that has been understood since prehistoric times, the technology is still somewhat fresh. The most frequent criticisms are on offensive odours (Červená et al., n. d.), health dangers, and environmental degradation. Resistance to change, inadequate access to reliable information about biogas and its production, the 'not in my backyard' effect, and the efforts of proactive opponents who rely on falsified data (often driven by personal motives) are some of the most notable among many causes of protests in Poland (Muradin and Foltynowicz, 2014).

The absence of regulatory laws governing renewable energy sources appears to be the largest obstacle. The building of biogas facilities has to be supported to ensure that they are profitable. The administrative load of the processes required to secure the necessary approvals deters investors as well. (Muradin and Foltynowicz, 2014).

One of the case-specific barriers is the price of erecting the AD digestor and keeping it in operation. The average investment costs are 2.5 times higher for plants with an output smaller than 25 kW_{el} compared to plants with an output greater than 200 kW_{el}.

Different metalloenzymes are engaged in the AD process depending on the methanogenic pathway (acetolactic or CO_2/H_2 pathways), and as a result, different micronutrients are needed (Mirmohamadsadeghi et al., 2019), which means that batch analysis of the of digesting sludge needs to be carried on a regular basis in the laboratory. This process ensures a seamless production process and the possibility to control the reaction through the addition of certain micronutrients as well as ensure a smooth initial start of the AD. Although, it ensures a better methane yield it is certainly expensive and, in our case, nearly impossible to carry out as such a facility is not in the vicinity of the Prievidza region.

4.2 Scenario 2: Composting

The second scenario is called "Composting" as we suggest setting up a composting system on-site where aerobic digestion will be the main biowaste utilisation process. The final product of the process will be a natural fertilizer that can be sold to other local producers. This will promote a circular economy within the company as its biowaste will be turned into a valuable resource and provide an additional income for Agro GTV. Scenario number two is structured into subsections as follows: description of the proposed solution, techno-economic feasibility, sources of supplementary funding, legislative requirements for composting, and barriers to implementation.

4.2.1 Description of the proposed solution

According to our research, composting is one of the most widely used techniques for biowaste management. However, for it to be effective, multiple criteria need to be met and whether the process is successful depends on several factors. During this study, we came across various alternatives in regard to composting agricultural biowaste. However, what we found to be the most suitable solution for Agro GTV is dry fermentation units produced by a Slovak company, the Green Machines a.s., which is based in Bratislava.

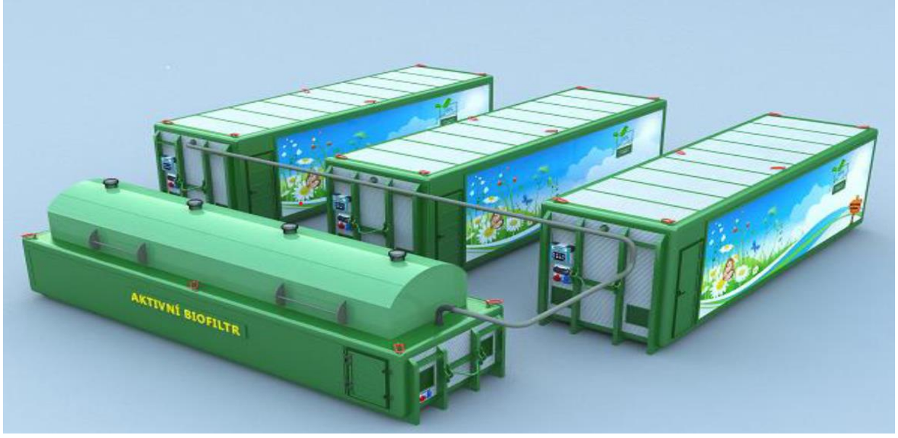
The dry fermentation units, biofermenters, made by Green Machines a.s. (see Picture 4 below) belong to the category of composting technologies, where the composting process itself is controlled in the closed space of the biofermenter, where controlled aerobic fermentation takes place. Therefore, the optimal conditions for a successful composting process are ensured at all times.

Picture 4: Biofermenter by Green Machines a.s. (Biofermentory, 2023)

Thanks to the closed space, the ongoing processes can be monitored and controlled. This way, there is also a significant reduction in the time required for the degradation and the transformation of the input raw materials into a final product. At the same time, negative impacts on the environment are minimized. This makes controlled aerobic thermophilic fermentation fundamentally different from typical composting plants (Green Machines a.s., 2023). A significant technological advantage of biofermenters is the fact that in a closed fermenter, it is possible to sanitize the substrates at temperatures between 50°C to 70°C. This results both in the destruction of pathogens and in the self-sanitization of the unit for a period longer than 58 hours. The final product of the aerobic fermentation process is compost for agrotechnical use. During fermentation, the biomass mixture turns black-brown due to the formation of humic acids. Additionally, a by-product of the fermentation is water vapour which is used to moisten a biofilter that minimises odour (Green Machines a.s., 2023).

Biofiltration is an integral part of any fermentation unit approved for commercial operations close to an inhabited area. Hence, Green Machines a.s. (2023)

use sophisticated technology of mobile biofilters. Biofilter is a part of the composting system that can be either integrated directly into the biofermenter or when the system consists of multiple composting units, depending on the required capacity, the mobile bio filter comes as a separate unit that connects the biofermenters (e.g. see Picture 5 below).



Picture 5: Composting system with three biofermenters and a biofilter (Biofermentory, 2023)

Air biofiltration is a technology that, due to recent and ongoing innovations and also low operating costs, is becoming an increasingly used technology for the elimination of volatile organic substances as well as some inorganic pollutants. Most often, biofilter technologies are used where there are medium concentrations of biodegradable substances, but where substances have a strong odour, even at very low concentrations (Green Machines a.s., 2023). Biofiltration is an effective method primarily used for removing concentrations of harmful and unwanted substances during the operation of composting plants. Biofilters are capable of removing even mixed contamination of organic and inorganic pollutants very effectively. The reduction of odour in the operation and the surroundings is another benefit for mobile biofilter applications (Green Machines a.s., 2023).

The selection of appropriate biofermenters and their sizing was based on the information on the nature and volume of waste provided by Agro GTV and consultation regarding their specific needs with experts from Green Machines a. s. The recommendation correlated with our assumptions of using a set of two smaller biofermenters to meet the capacity demand and to ensure the possibility of operation where the use of biofermenters will become more flexible. During the high season when there is a higher amount of biowaste, both fermenters can be used at the same time. In the case of a low season, e.g. in winter months, only one unit at a time can be in use. During normal operation, one biofermenter is always filled and the other is emptied, thereby ensuring continuous processing of biowaste. One process cycle takes approximately 10 to 14 days (Green Machines a.s., 2023).

The dimensions of the chosen biofermenters are 5 x 2.5 x 2.5 meters per unit. Together, the two biofermenters will provide a capacity for composting up to 1 500 tonnes of biowaste per year. Considering that Agro GTV produced 360 tons of biowaste in 2022, these biofermenters will provide plenty of additional capacity. The capacity is, however, an estimate and should not be considered a definite number as it generally depends on the type of biowaste and its weight as well. Moreover, the high capacity could be used in the future as an opportunity to offer composting as a service to other producers in the area as well.

The proposed solution for biowaste management in this scenario comes with multiple advantages. The biofermenters are mobile, therefore there is no requirement for any building permit. It also provides additional flexibility for moving the units to another place if necessary as well as for adjusting the number of units according to future needs. For the proposed composting system to be set up at Agro GTV, only a paved surface and an electrical outlet is needed. Although there is also an option for the biofermenter to be supplied by renewable energy, e.g. solar panels, we have not considered this option for the purposes of this study as its feasibility would require further extensive research. Another advantage of the biofermenter is that there is practically no need for spare parts during the entire period of operation and there are especially low maintenance requirements. Biofermenters are normally filled with biowaste using a small loader operated by one person with easy access through the front gate.

4.2.2 Techno-economic feasibility

We have based our approach on that of Scenario 1 and listed capital costs as well as total costs (TC). TC include the cost of two biofermenters, a loader, biofilter, connecting pipes, one year's worth of electricity and approximate fueling and maintenance of the loader. Nor interest nor contingency is included as the financing can be internally managed or through funds from the EU. According to a quotation from Green Machines a.s., the purchase price of the two chosen biofermenters including a biofilter and a biowaste loader would be around 131 000 EUR, which gives us the CapEx (see Table 12). This price is, however, only of an informative character and should be understood as such, the price may be subject to change in the future. The same applies to the biowaste loader as the price is dependent on the current pricing of the seller in the given market.

Table 12: CapEx of biofermenter station at Agro GTV

Capital Cost items	Cost in EUR (without VAT)
Biofermenter with hygienisation (2x) 5 0000 x 2 500 x 2 500 mm	64 000
Belt skid steer loader	52 000
Biofilter midsize 4 000 x 2 000 x 2 000 mm	12 000

Capital Cost items	Cost in EUR (without VAT)
Connecting pipes for the bio filter	3 000
CapEx total	**131 000**

Total costs for one year of running the biofermenters were calculated by adding CapEx and variable costs. Variable costs account for loader fuel and overall maintenance but also the used electricity as it varies based on the outer conditions and the internal loading of the fermenting chamber. Green Machines a.s. (2023) say that the average electricity expenditure for such set-up is below 1 kWh. To account for unexpected complications, we have opted to use 1 kWh in our calculations. Based on the regulation of the government of the Slovak Republic no. 19/2023 Coll. from the 16th of January 2023, the price of electricity for subjects using up to 30 MWh of electricity is capped at 199 EUR/MWh. Fuelling and maintenance were estimated by the average running of one hour with consumption of 4 litres (JCB, n. d.) of diesel every calendar day, equalling 1 898 EUR. We have opted to stretch this number to 2 000 EUR to account for possible oil changes or changes of degraded consumables of the operating machinery. The above-mentioned cost items are summarised in Table 13, from where we can infer the total costs equalling 133 072.635 EUR accounting for the whole cost of the initial investment and the first year of usage.

Table 13: Total Costs of biofermenter station at Agro GTV for one year of running

Total Cost items	Cost in EUR (without VAT)
Biofermenter with hygienisation (2x) 6 0000 x 2 500 x 3 000 mm	64 000
Belt skid steer loader	52 000
Biofilter midsize 4 000 x 2 000 x 2 000 mm	12 000
Connecting pipes for the bio filter	3 000
Total costs (CapEx)	**131 000**
Electricity 365 kWh/year	72.635
Fuelling and maintenance of the loader	2000
Total Costs (TC)	**133 072.635**

To calculate the net present value, internal rate of return and payback period it is necessary to know the expected cash inflow. From the Green Machines a. s. (2023) we have received an estimation of possible revenues from the produced biofertiliser. Approximately 500 to 600 tons of feedstock can experience up to 15% weight reduction after process completion. From the research of Green Machines a. s. (2023), it is apparent that large consumers are willing to pay up to 200 EUR for a ton of biofertiliser. Thus, the return on investment is expected between the first and second year of operation with an operational capacity of 500 tons of feedstock.

We have taken the information from Green Machines a. s. (2023) into account and decided to calculate the parameters as well for the case of sale on the B2C (Business to Customer) market. In this case, the price of bio-composted fertiliser prices averaged 280 EUR per ton (Heureka, 2023). As well, we have opted to use in our calculations only the feedstock readily available to Agro GTV, being 360 tones.

To assess a project's or investment's potential profitability we decided to calculate the NPV. The NPV is calculated for the time period of five years with a discount rate of 10%, accounting for inflation and the cost of capital. The total present value equals 382 067.48 EUR, from which we have subtracted the initial investment of 131 000 to obtain the NPV of 251 067.48 EUR. Since the NPV is positive, it suggests that the investment is expected to generate more value than the initial investment, making it potentially profitable.

From NPV we can further calculate the IRR to assess the statistical rate of return and if the return exceeds the hurdle rate. We have calculated that the IRR equals 18.4%, which is within the bracket of 18 – 20%. Therefore, it can be considered as a good investment from the standpoint of IRR.

To assess the return on the investment timewise we have calculated the payback period. The calculation worked with net annual cash flow to account for the operational costs. The payback period hence equals 1.3 years, or in other words 484 days or 16 months. Again, from the investor’s point of view, it is a short-term investment that appears to be profitable early on.

From our perspective and from the results of carried out calculations we conclude that the investment of Agro GTV into biofermenters has potential and is sound. Hence, this scenario is techno-economically feasible.

4.2.3 Sources of supplementary funding

Sources of supplementary funding for this scenario are the same as discussed for the first scenario, namely in section 4.1.3. Though, securing funds for a smaller investment with a high utility and regional business potential is more likely to happen. Therefore, Agro GTV would be advised to pursue applications in the upcoming rounds of the EU fund allocations.

4.2.4 Legislative requirements for composting

Legislative requirements for setting up this composting system at Agro GTV and the subsequent commercial activity fall under two longstanding legislative acts of the Slovak Republic and an affiliated technical standard. From a practical point of view, there are no legal constraints to this scenario as Agro GTV has to already comply with the Fertilizers Act No. 136/2000 since the operations within the greenhouse require the use of synthetic fertilisers. EU legislation regarding fertilisers has been adopted and transposed to Slovak laws as safety in agricultural production is uniform across all member states. Further internal legislature connected to biofertilizer production is the Decree of the Ministry of Agriculture of the Slovak Republic No. 577/2005 Coll. and technical standard STN 46 5735 (46 5 735) Industrial composts regulate the requirements for the composition and quality of compost.

4.2.5 Barriers to implementation

From our research and the overall information from the entire section 4.2. we can conclude that Scenario 2: Composting does not face any major barriers to implementation. The only notable challenges could be gathering initial investment capital, time and resources that need to be allocated to prepare applications for EU funds of interest, allocation and preparation of land designated for the biofermenter structure, and training staff to operate associated machinery.

4.3 Final Assessment of Scenarios 1 and 2

Scenario 1: Biogas plant consists of one CSTR single-stage rector with a volume between 100 and 150 m^3. The main feedstock is TPW and the selected inoculum is cow manure suitable for mesophilic AD. The main benefits of this process are the simplicity of the AD reaction, minimal requirements for electricity, scalability, and low emissions of GHG and other air pollutants resulting in net positive environmental impacts. Negatives are mainly connected to the need for pre-treatment of agricultural waste, the complexity of the whole process, high initial investment, maintenance costs, land requirement, and the necessity to monitor and maintain the reaction. Assessment of techno-economic feasibility has shown that the selected technology is not a viable investment for Agro GTV with its limited availability of biowaste. Sources of supplementary funding from the EU do exist and are applicable. However, it is uncertain whether the funding will be available in the amounts necessary for the project to go forward. Legislative requirements for biogas production within the EU and Slovakia are extensive. Slovak law is in many cases unclear on the operation of smaller plants and forbids the use of digestate directly as a fertiliser. Legislative complexity is another negative associated with operating a biogas plant.

Scenario 2: Composting utilises a dry aerobic fermentation process carried out in an enclosed and controlled environment of a biofermenter with dimensions of 6 x 2.5 x 3 meters per unit. The selected setup of two biofermenters will provide a capacity for composting up to 1300 tonnes of biowaste per year. The main benefits of this process are significantly lower degradation time, minimal environmental impacts, no permanent land requirement, substrate sanitation, low maintenance costs, scalability, flexibility with set up, and with the use of biofilter minimal odour production. We have not identified any negatives or drawbacks of this technology. Assessment of techno-economic feasibility has proven that Scenario 2 is a viable investment for Agro GTV. Carried-out calculations show a plausible return on investment and payback period within a short time. Sources of supplementary funding from the EU are applicable and attainable as the necessary capital is not exceptionally high and is not constrained by extensive project planning, research, or licenses. There are no legal constraints or requirements for the operation of biofermenters within the EU and Slovakia.

Based on the evidence presented in sections 4.1 and 4.2 as well as the final comparison we have selected Scenario 2: Composting, as the preferred solution to improve biowaste utilisation at Agro GTV.

5 DISCUSSION AND CONCLUSIONS

In this Master's thesis, the main focus was on agricultural waste management of the case company Agro GTV which runs a greenhouse tomato production plant using hydroponic systems in Slovakia. The purpose of this study was to analyse the current situation and provide two best possible circular-economy solutions for the improvement of biowaste management in Agro GTV, and to assess if small-scale biowaste processing is feasible in the case of Agro GTV. With circular economy principles in mind, two different scenarios, the biogas plant and composting, were proposed as solutions for biowaste utilisation.

Both scenarios generally offer an effective way to follow a circular economy model of reusing materials and turning waste into a valuable resource. However, based on the thorough feasibility analysis of both scenarios, it was clear that the first scenario, the biogas plant, is not feasible. The main reasons against the adoption of this scenario are listed above in the final assessment section 4.3. The second scenario, composting, is the preferred solution in this case study. Not only because the initial costs are incomparably lower and the legislation is more favourable compared to the first scenario, but because it does offer an effective solution with multiple advantages. The proposed composting system provides a flexible solution as it can be designed to handle different volumes of waste. The significance of our findings lies mainly with Agro GTV as this research has proposed a viable option with an existing business case for the valorisation of their bio-waste. However, this research can serve as guidance for companies of comparable size or dealing with similar volume of bio-waste, on how to employ existing technologies in their waste management system.

From the assessment of the two proposed scenarios, it is evident that there are circular-economy solutions for bio-waste treatment. Nonetheless, small-scale viability has to be individually assessed. Complex and expensive technologies with a greater chance of unsuccessful treatment or a very low estimated rate of return on an investment, such as in our case the proposed biogas plant, are not viable options. Though, it should be noted that even the smallest biofermenter set-up exceeds the capacity of Agro GTV in terms of available feedstock. During our research, we were unable to find appropriately sized technical solutions. For both selected technologies micro-sized home setups are commercially available and then mid-range industrial technology can be found. Small-scale production is omitted. It begs the question if it is purely caused by a lack of demand caused by long-term dependence on centralised waste treatment, low profitability for technology producers or other unbeknown reasons.

In terms of biogas production as a circular solution our findings align with previous research of Karellas et al. (2010), Kapoor et al. (2020), Muradin and Foltynowicz (2014) who all explored the potential of biogas production from agricultural waste in their respective countries, Poland, India, and Greece. All mentioned authors agreed that commercial biogas plants are very expensive to build or maintain and the return on investment is expected to be around 10 to 15 years. We have concluded that small-scale biogas production is not viable in Slovakia at the moment, while Muradin and Foltynowicz (2014) arrived at the same conclusion in the Polish setting. Whereas Kapoor et al. (2020) see the potential of community biogas plants as the safe and circular valorisation of biowaste. The main differences between this case study and the research of Kapoor et al. (2020) are the price of materials, significantly warmer weather, and the legislative setting in India.

Composting is generally considered to be an effective method for biowaste utilisation, our findings are also aligned with previous research (Saravanan et al., 2023; Kulcu and Yaldiz, 2014; Sharma et al., 2019; Fermoso et al., 2018; Bian et al., 2019). The authors agreed that composting is a process commonly used for the valorisation of biomass, therefore it plays an important role in the management of organic waste. The literature showed a number of potential challenges associated with composting agricultural waste, however, our proposed solution, biofermenters, seems to be able to overcome or minimise all of them. For instance, the enclosed system of biofermenters allows for a fully controlled process of composting in ideal conditions which requires minimal management. Therefore, the potential contamination, nutrient imbalance, odour and management requirements are eliminated. Minimal space requirements and economic viability were also found to be advantageous in this case, as opposed to being a challenge in the previous research. Further alignment with previous literature is, however, difficult to find as this kind of solution has not been extensively researched yet.

The results of this case study reported herein should be considered in light of some limitations, namely a lack of available literature on the topics of small biogas production and applied studies utilising biofermenter technology. Furthermore, we were unable to acquire direct quotations or even estimates, for the purpose of research, from companies in Slovakia or the Czech Republic for a small biogas plant. All quotations were only available for already existing companies that are to provide tax identification. The contacted vendors wished to remain anonymous. Their reasons for not providing quotations were the time-consuming nature of the process and the current volatility of the market, which makes the previous quotations invalid. As well, they are contractually bound not to reveal any information regarding existing projects to protect business cases of biogas plant operators. The legislation imposed on the utilisation of digestate as an open-field fertiliser also potentially affects the amount of available literature on this topic. The legislative limit as well served as a natural boundary for the scope of this research.

Besides the presented limitations the findings of this research suggest some directions for future research. Firstly, there is a need to holistically address the exposed research gap in the valorisation of agricultural biowaste on a small scale concerning biogas production. Notably, the economic feasibility and technological intricacies of mesophilic and thermophilic anaerobic digestion in subzero external reactor temperature. While the results of this study suggested that the operation of a biogas reactor in the context of a smaller central European agri-food producer is not feasible, this topic still deserves much further scrutiny. Moreover, there is a possibility to explore the social phenomenon of the NIMBY (Not in My Back Yard) in relation to communal and small-scale biogas production at the current time. Secondly, there is a legal impediment to the use of AD digestate as fertiliser in Slovakia, even though it is allowed in other EU countries, and we are facing fertiliser shortages worldwide. Hence, we see a potential for research on the safety of the usage of digestate from AD as a commercial fertiliser for open-field energy and food crop cultivation. Last but not least, the existing literature on technological advances in biowaste valorisation explores the specifics and benefits of such technologies, singularly, only in theory and trials are conducted mostly in laboratory conditions alone. Thus, we see an opportunity for future research to establish links between existing technologies and their viability for different volumes of biowaste, climate, feedstock type, and their interchangeability or co-application.

The circular economy's fundamental benefit is the preservation of material and product value over a longer period. Kapoor et al. (2020) further elaborate that by virtue of the organisational, social, and technological revolution, the transition from a linear to a circular bio-economy is also projected to put in motion vigorous economic development and the creation of jobs. In this sense, it is crucial to support the circular economy at the local level in addition to the regional and national levels to make it sustainable and use its full potential. The selected scenario 2 utilising biofermenters not only provides a commercially viable final product but also the unused capacity of biofermenters that can be offered as a service to neighbouring municipalities, enterprises as well as to Prievidza District Committee of the Slovak Union of Gardeners who tend to produce larger amounts of biowaste in certain months. This way, Agro GTV will enhance the sustainability of its operation along with laying the foundations of a shared, circular economy in the whole region.

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APPENDIX

Table 2: Substrate-dependent reactor configuration

Substrate (organic feedstock)	Process of biogas production	Reactor configuration	List of equipment needed
Pig manure	Mono/co-digestion	CSTR[a] or plug-flow	Standard structure[b] + biogas desulphurization
Rape	Mono/co-digestion	CSTR or plug-flow	Standard structure
Sunflower (WCS)	Co-digestion	CSTR or plug-flow	Standard structure
Orange	Co-digestion	CSTR or plug-flow	Standard structure
Pear	Co-digestion	CSTR or plug-flow	Standard structure
Apple	Co-digestion	CSTR or plug-flow	Standard structure
Sweet sorghum	Mono/co-digestion	CSTR or plug-flow	Standard structure
Lucern	Mono/co-digestion	CSTR or plug-flow	Standard structure
Glycerol	Co-digestion	CSTR or plug-flow	Standard structure
Peas (WCS)	Co-digestion	CSTR or plug-flow	Standard structure
Barley silage	Mono/co-digestion	CSTR or plug-flow	Standard structure
Spring Wheat Grain	Mono/co-digestion	CSTR or plug-flow	Standard structure
Autumn Wheat Grain	Mono/co-digestion	CSTR or plug-flow	Standard structure
Hemp	Only with hydrolytic pretreatment	CSTR or plug-flow	Standard structure + hydrolytic pretreatment
Miscanthus	Co-digestion	CSTR or plug-flow	Standard structure

Substrate (organic feedstock)	Process of biogas production	Reactor configuration	List of equipment needed
Maize stalks	Co-digestion	CSTR or plug-flow	Standard structure
Sugar Beet	Co-digestion	CSTR or plug-flow	Standard structure
Barley grain	Co-digestion	CSTR or plug-flow	Standard structure
Grass, meadow	Mono/co-digestion	CSTR or plug-flow	Standard structure
Maize	Mono/co-digestion	CSTR or plug-flow	Standard structure
Maize grain	Co-digestion	CSTR or plug-flow	Standard structure + biogas desulphurization
Distillery waste	Co-digestion	CSTR or plug-flow	Standard structure
Bakery waste	Co-digestion	CSTR or plug-flow	Standard structure
Starch waste	Co-digestion	CSTR or plug-flow	Standard structure
Manure	Mono/co-digestion	CSTR or plug-flow	Standard structure
Straw	Co-digestion	CSTR or plug-flow	Standard structure
Willow	Only with hydrolytic pre-treatment	CSTR or plug-flow	Standard structure + hydrolytic pre-treatment
WWTP Sludge	Mono/co-digestion	CSTR or plug-flow	Standard structure

a CSTR, continuous stirred tank reactor
b Standard structure includes biomass storage tanks, homogenisation and feeding system, digestion tank and mixing system, gas cleaning, cogeneration unit and digestate tank

Source: Karellas et al. (2010, p. 1275)

Table 3: Fertilisers used by Agro GTV

Fertiliser name	Chemical formula	Content of key elements expressed in %
Ducanit (Calcium nitrate)	$Ca(NO_3)$	Ca 26.5%; N 15.5%
Potassium nitrate	KNO_3	K 38% - N13%
Ammonium nitrate	NH_4NO_3	N 35%
Magnesium nitrate	$Mg(NO_3)_2$	Mg 15,5% - N 10,8%
Calcium chloride	$CaCl_2$	Ca 27% - Cl 48%
Potassium chloride	KCl	K 50% - Cl 45%
Magnesium sulphate	$MgSO_4$	Mg 16 % - S 32.5%
Potassium sulphate	K_2SO_4	K 42% - S 18%
MKP potassium phosphate	KH_2PO_4	K 27.7% - P 22.7%
Manganese sulphate	$MnSO_4$	Mn 31%
Zinc sulphate	$ZnSO_4$	Zn 23%
Sodium tetraborate	$Na_2B_4O_7$	11% concentration
Copper sulphate	$CuSO_4$	Cu 25 %
Sodium molybdate	Na_2Mo_4	40% concentration
Nitric acid	HNO_3	53-55% concentration
Iron chelates	Fe	11% concentration
Hydrogen peroxide	H_2O_2	35% concentration

Source: Agro GTV (2023)