APPLICATION OF EFFLUENT FROM ANAEROBIC DIGESTION OF BIOMASS TO CONDITION THE SOIL: A REVIEW OF THE LITERATURE

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ABSTRACT

Literature Review: Anaerobic digestion technology has significant potential in the treatment of organic waste, with varying levels of efficiency depending on the approach taken to the process. In addition to biogas production, it is also possible to obtain the digestate from anaerobic digestion, a nutrient and carbon-rich product, which is a relevant source for soil biota and fertility. Applying digestate to the soil helps in the recovery of degraded and contaminated areas due to its richness in nutrients and organic matter. When applied, it initiates the colonization of plants, colonies of fungi and bacteria, mineralizes nutrients, and promotes environmental recovery. Anaerobic digestion, when integrated with other processes such as composting, gasification, and pyrolysis, can enhance the capacity to sequester carbon in stable forms in the soil, thus reducing greenhouse gas emissions and increasing the potential for biomass (raw material) energy utilization.

Study Objectives: To review the existing literature regarding the application of digestate as a soil conditioner and its benefits to plants (crops).

Materials and Methods: Original articles related to the application of digestate in soil were selected through a search on the Web of Science and Science@Direct databases from the CAPES periodical portal.

Conclusion, Results, and Implications: The selected articles present results indicating that digestates can be used as soil conditioners, leading to increased organic matter, microbial activity, nutrients, physical quality, and plant benefits, thus contributing to the circular economy. However, there is a need for further studies related to the agronomic responses of digestate application to plants.

Keywords: Anaerobic Digestion, Soil Enrichment, Biomass, Stable Forms of Carbon, Humic, Fulvic Acids.

RESUMO

Referencial teórico: A tecnologia da digestão anaeróbia possui elevado potencial no tratamento de resíduos orgânicos, tendo diferentes níveis de eficiência dependendo da abordagem dada ao processo. Além da produção do biogás é possível obter também, o digerido da digestão anaeróbia produto rico em nutrientes e carbono, fonte relevante para a biota e fertilidade do solo. Os digeridos aplicado ao solo ajuda a recuperar áreas degradadas e contaminadas, por ser rico em nutrientes e matéria orgânica, quando aplicado inicia povoamento de plantas, colônias de fungos e bactérias, mineraliza nutrientes e promove recuperação dos ambientes. A digestão anaeróbia quando integrada a outros processos (compostagem, gasificação e pirólise), podem potencializar a capacidade de fixação de carbono em formas estáveis no solo, proporcionado a redução das emissões de gases de efeito estufa e aumenta o potencial de aproveitamento energético da biomassa (matéria prima).

Objetivos do estudo: Revisar na literatura o que se tem de estudo a respeito da aplicação dos digeridos como melhorador do solo e, quais os beneficiados as plantas (culturais).

Material e método: Através de busca nas bases Web of Science e Science@Direct do portal de periódico da CAPES foram selecionados artigos originais que abordavam estudos relacionados a aplicação dos digeridos no solo.

Considerações finais, resultados e implicações: Os artigos selecionados apresentam resultados que apontam que

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Application of Effluent from Anaerobic Digestion of Biomass to Condition the Soil: A Review of the Literature

1 INTRODUCTION

Anaerobic digestion is an ancient technology; its use since the 10th century BC in hot baths in Assyria is reported (Reichert, 2005 and Lora Grando et al., 2017). In China, vestiges of the use of anaerobic digestion were found more than 3,000 years ago (2010).

The process of anaerobic digestion consists of the degradation of complex organic matter in the absence of oxygen by anaerobic bacteria (Abbasi et al., 2012). In this process, the conversion of organic matter into biogas and methane occurs (Silva & Trevisan, 2019). During anaerobic digestion, the following steps occur within the digester (reactor): hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The previous stages cause various physical and chemical reactions in the primary organic matter (biomass), causing the degradation of their complex fractions, transforming them into simple substances (Rodrigues et al., 2015). Depending on the input of the raw material (feed to the digester (reator)), it classifies the process anaerobic digestion into: continuous and discontinuous, in the continuous process, the dynamics of the raw material within the digester (reator) are considered, being therefore characterized by the lower concentration of total solids (low load); already in the discontinuous process, known as batching, usually the primary organic matter (biomass) reaches levels of up to 40% total solids (high load), and remains permanently inside the digester until the necessary time of the process (hydraulic retention time) (Reichert, 2005). After the end of the anaerobic digestion process, it has as its product the CH₄-rich biogas (energy) (methane) and the digestate of anaerobic digestion (bio-fertilizer). CH₄, the main gas that makes up biogas, in relation to climate change (global warming), is, on average, 25 times more pollutant than carbon dioxide, so burning is necessary (William, 2007 and Lilian et al., 2023). CH₄ can be used in power generation (motor generator), effectively replacing non-renewable fuels (mainly fossil fuels).

The digested species also known as digestate, digestate, biogas sludge, biofertilizer, among others, are sources of nutrients and carbon (forms of humic and fulvic acids) that can be used in plants (crops) (Aquino & Chernicharo, 2005).

Anaerobic digestate has the following advantages when used as soil conditioners: it increases the potential for fixation of recalcitrant carbon (fractions of greater permanence capacity) and minerals (nutrients) needed by plants (agricultural crops); it can replace in part or all (non-organic) mineral fertilizers, significantly reducing the use of fertilizers from non-renewable sources; it can help in the recovery of degraded and contaminated areas, favoring the microbiological activities of the soil and by separating the solid and liquid fractions of the digested and integration with other methods of biomass treatments (organic waste) can enhance the potential as reported by the authors Coban, Miltner and Kästner (2015), Siegmeier; Blumenstein; Möller (2015), Riding et al. (2015), Siegmeier, Blumenstein and Möller (2015), Barra Caracciolo et al. (2015), Grave et al. (2015), Verloop et al. (2015), Cestonaro et al. (2015), Buller et al. (2015), Garcia-Sánchez et al. (2015), Tampio, Salo and Rintala (2016), Muscolo et
Integration with other processes, such as composting, gasification and pyrolysis, can reduce the production of greenhouse gases, increase the potential for renewable fuel generation and modify the characteristics of digested fuels, providing different properties and applications, as reported by the authors Di Maria, Segoloni and Pezzolla, (2016), Monlau et al. (2016), Antoniou et al. (2019), Miliotti et al. (2020), Celletti et al. (2021) and Wang and Lee (2021).

Thus, within this context, the objective of the present work was to carry out an integrative bibliographic review research using the Prisma methodology, the use of digerides as soil conditioner and its benefits to plants, holistically analyzing the whole process and the technologies involved. The studies have shown results that favor the use of digestate in the soil, as an alternative or complement to conventional fertilizers and as a potential means of fixing carbon in the soil, but also, we see the need for more research, the application of digested plants (crops), integration with other processes of treatments of organic waste (biomass) and with different sources of organic waste (biomass) correlated to different processes of digestion, these being determinants in the compositions of the digested.

2 METHODOLOGY

2.1 Systematic Literature Review

The possibility of using digestate from anaerobic digestion as a potential soil conditioner and its benefits to plants, i.e. as a soil enhancer and nutrient source, led to the following research questions: "How much does digestate contribute to improving soil characteristics (physical, chemical and biological), fixing carbon, benefitting plants (crops) and the environment?”, based on the model Population, Intervention, Comparison, Outcome (PICO), used in Evidence Based Practice (PBE) and recommended for systematic reviews (Santos et al., 2007). The present paper opted for a review based on the PRISMA methodology, consisting of a broad analysis of the studies, contributing in the discussions of the methods and results, in a systematic and orderly manner, with objectives to cover as much as possible of works related to the research theme. The method makes it possible for the author to carry out a list of the items that make up the data before submitting the articles to a systematic review, assisting the researcher during the realization of the review process (Galvão et al., 2015).

The search and selection of the articles related to the theme were carried out via the web in the journal portal of CAPES/MEC in two databases Web of Science and ScienceDirect. Using the descriptors in the English language with their various combinations related: anaerobic digestion, anaerobic reactor, bioreactor, co-digestion, with emphasis on: biofertilizer, organic fertilizer, digested material, sludge, digested, biogas slurry, degraded substrate, and their effects on the ground, soil, soil, and benefits as plants, vegetables, vegetation, crops, agriculture, cultivation and subjected to search engines; after the inclusion and exclusion criteria of works were applied, the articles published, in english by the broadest scope of the language, available in full, that addressed the theme; as a strategy for extracting information, for each article selected, the following information was extracted: title of the document, author(s), the source, year of publication and application of digested in the soil. After reading the titles and abstract, the recovered works were documented in review driving forms and selected on the basis of the predetermined criteria, repeated works were documented once. The selected articles, published between 2015 and 2021, by the criteria for reading the title and summary, were included in this revision, for full reading and the results were presented in a global and systematized way, that is, by summaries of the observed results. The process of research and selection of the material for analysis is made explicit in Figure 1.
2.2 Analysis of Obtained Articles

After selection criteria, inclusion and exclusion of the works, were selected and discussed the articles related to the theme of the present research.

2.2.1 Characteristic of anaerobic digestion technology

The use of anaerobic digestion technology is not recent and has been developing and expanding its use worldwide, as it is considered a sustainable alternative technology. Rodrigues, Blans and Scindwein (2015), state that the anaerobic digestion process is economically viable because it brings highly significant environmental gains from the production of biogas that has potential for energy production (methane) and from the production of digestate that can be used as biofertilizer (organic fertilizer), after verifying the absence of contaminants (heavy metals and pathogenic micro-organisms).

Anaerobic digestion is a relatively simple process as it occurs by transforming complex organic waste into simple organic matter under conditions of absence of free oxygen. Riding et al. (2015) and Costa et al. (2015) detailing the process of anaerobic digestion, the complex organic matter (raw material) is initially transformed into volatile acids, and then the conversion of these into organic acids, carbon gas, hydrogen, and at the end in the gaseous end product the biogas that is made up of 60% CH4, 40% (CO2, N2, H2, O2, HS), the main one in energy generation being CH4.

The anaerobic digestion process comprises four stages: pre-treatment, digestion of waste, biogas recovery and waste treatment (Reichert, 2005). Pretreatment is usually required to homogenize the raw material, and systems can be continuous or discontinuous. In continuous systems, the load can be high (15% to 25% total solids) or low (less than 15% total solids), while in discontinuous anaerobic digestion systems (batches), the raw material can contain up to 40% total solids and remain in the digester for the time needed (Costa et al., 2015). Reichert (2005);) states that several pre-treatment methods have positive effects on anaerobic digestion,
including chemical, mechanical, biological and thermal processes. Treatment time in the digester has greater influence than temperature during the process (Wirth et al., 2015). Kinnunen, Craggs and Rintala (2014) they state that the mesophilic temperature range (20 to 40 °C) is widely used due to the lower need for control and greater guarantee of the process, while higher thermophilic temperatures (50 to 55 °C) are more effective in producing CH₄ and accelerating the process, but require greater control. In addition, fermentation performance varies with different raw materials, depending on the pH conditions (Jimenez et al., 2020). For optimal degradation of the raw material in the digester, pH values should be maintained between 4.5 and 9, varying according to the stages of the anaerobic digestion process (hydrolysis, acidogenesis, acetogenesis, methanogenesis) (Latif et al., 2017).

Rodrigues, Blans and Schindwein (2015) and Ferreira (2021) they highlight that both the system and the anaerobic digestion process influence the efficiency of biogas production. The composition of the raw material and the number of divisions of the stages of anaerobic digestion can affect the composition of the digestate. Single-stage anaerobic digestion occurs in a single compartment, while staged digestion divides the phases into more than one compartment (e.g., hydrolysis and acidogenesis in one compartment and acetogenesis and methanogenesis in another).

Siegmeier, Blumenstein and Möller (2015) note that anaerobic digestion converts about 35 to 40% of total dry organic matter into CH₄ and CO₂. In addition, anaerobic digestion reduces pathogenic microorganisms in the raw material, and the resulting digestate may present different concentrations of pathogens and heavy metals, with a tendency to decrease and mobilize depending on the raw material (biomass). O’Connor et al. (2021) the risk to plants (crops) in the application of digestate from anaerobic digestion in the soil varies depending on the origin of the raw material.

The use of biogas (methane) in energy generation contributes to the reduction of air pollution (greenhouse effect), since CH₄, the main component of biogas, is burned. It is regarded as a gas with a high potential for greenhouse effect, about 25 times more powerful than CO₂ (William, 2007). The energy use of biogas can be carried out in various ways, from domestic uses, such as in ovens and refrigerators, to heating in productive systems of animal production (cattle, pigs and poultry), as well as its combustion in motor generators for generating electricity. The purification of biogas increases the content of CH₄, increasing its energy power (Rodrigues et al., 2015).

We can see that, in addition to the energy importance in the production of biogas (methane), anaerobic digestion generates digestate from anaerobic digestion that can contain high nutritional value and the efficacy of its effects can be increased when the solid and liquid fractions are separated or integrated with other treatment processes as stated Tampio, Salo and Rintala (2016). Thus, the solid fractions can be applied directly to the soil or can be used in the processes of composting, gasification and pyrolysis that raise even more their agronomic properties and greater energy use; the liquid fractions can be applied to the soil mainly as a source of nitrogen and potassium. Anaerobic digestion is a technique currently used on a large scale for the treatment of various organic residues (raw materials), producing environmental and economic gains in energy by the use of biogas and digestate.

2.2.2 Digested from anaerobic digestion as soil conditioner/enhancer and plant benefits

The anaerobic digestion process produces digested anaerobic digestion, nutrient-rich material, and organic matter. Mendes; Giorgo (2016) soil organic matter is mainly derived from plant and animal organisms, with a species-to-species composition and within the same species, depending on plant age and the presence of animals in the soil. Soil organic matter plays a crucial role in the stability, mechanical strength, structure, biodiversity, water retention and
supply of soil nutrients. Losses of organic matter can be aggravated by human activities, such as deep soil mechanization, which accelerates erosive processes, and the excessive use of non-organic fertilizers in crops. Riding et al. (2015) emphasize the importance of conserving and increasing soil organic matter, as it is essential for diverse ecosystem services, including environmental regulation and food production, decomposition and climate change mitigation.

Tampio; Salo; Rintala (2016) highlight the importance of the transition to more efficient production systems as a key strategy to reduce environmental pressures and preserve soils, avoiding erosive processes and loss of organic matter. The application of techniques, such as the recovery of environmental services in drainage basins, the creation of carbon sinks and the regulation of water, are promising for soil conservation. Jimenez et al. (2020a) emphasize that the use of digestate from anaerobic digestion in agriculture is recognized as an effective way to reduce greenhouse gas emissions by recycling materials, including the return of organic matter and nutrients to soil. Both energy from biogas and biofertilizers produced from digestate can partially or completely replace mineral fertilizers, playing a key role in the restoration of organic matter and nutrients to soil. The digested ones may also promote an increase in the density of microorganisms that are beneficial for the growth of plants, raising their agronomic potential.

Digests from anaerobic digestion can be considered as a source of nutrient supplementation to crops. Siegmeier; Blumenstein; Möller (2015) digested fertilizer may be used as an alternative fertilizer which, under certain conditions, may replace NPK fertilizers of non-organic origin. The application of digerides to soil can have several positive agronomic effects due to the presence of organic matter and organic nutrients readily degradable in readily available mineral forms. This can result in improvements in crop quality and productivity, as well as benefit crop rotation and spontaneous plant control. It also contributes to plant health and the maintenance of soil organic matter, and is an important source of nutrients in organic farming systems. Tampio; Salo; Rintala (2016) they point out that the agronomic characteristics of the digestate are related to the content and quality of the organic matter, the quantity of nutrients available and the organic matter available, which benefits the structure of the soil, microbial activity, nutrition, humidity and the accumulation of carbon in the soil and in plants.

The authors Riding et al. (2015) they highlight that digestate applications may vary according to the composition of the waste (biomass) used in anaerobic digestion. Therefore, it is crucial to know the raw material (biomass) and the anaerobic digestion technology used to classify digested foods. The generalization of digestate is challenging due to the potential heterogeneity of the by-product (biomass) in terms of chemical and physical properties. In relation to the composition of the raw material (biomass), it may contain residual organic material, such as lignin and cellulose, which cannot be digested by anaerobic digestion, which may call for the application of other processes for treating the raw material.

Siegmeier, Blumenstein and Möller (2015) have observed that digerides resulting from anaerobic digestion show higher levels of nitrogen, especially ammonia (NH₃), compared to undigested residues. This highlights the importance of digested foods as a source of this nutrient for plants, reducing dependence on conventional, non-organic sources. Nitrogen is a limiting factor for plant growth, particularly in organic agriculture, making digested crops a relevant source for this production system.

In a study evaluating the effects of the application of digerides on the soil and ryegrass crop (Lolium multiflorum Lam.) Tampio; Salo and Rintala (2016) they highlighted the strong agronomic characteristics of the digestate and their potential to increase crop productivity. The results of the tests indicated an increase in productivity of between 5% and 30% in relation to crops fertilized with non-organic mineral fertilizers. The source of the digestate's raw material played an important role in the nutritional characteristics and potential for carbon accumulation in the soil.

In the study by Barra Caracciolo et al., (2015), by comparing the capacity to mobilize
carbon in the soil with the application of digerides from pigs, cattle and compost in the presence and absence of the rosemary plant (Salvia Rosmarinus), it was observed that the addition of digerides from pigs significantly reduced the carbon concentrations only after 180 days of application when the plant (crop) was present. In this situation, the rhizosphere stimulated the microorganisms to use the fraction of carbon most available. Increased microbial activity due to the entry of organic matter readily mineralizable through digestate has resulted in higher nutrient contents and provided a better habitat for the development of microorganisms, due to increased soil porosity, water retention capacity and aggregate stability. These factors positively influenced the soil quality, making the digested effective soil conditioners Figure 2. The digestate's responses applied to the soil led them to behave like a soil conditioner.

**Figure 2** - The benefit of the application of digerides in the soil by the addition of soluble organic carbon (a) and total soluble N (b), in the presence and absence of a plant. (con. - control; pl - plant; digested - digested anaerobic digestion; bo - Cattle; ba - low; al - high; su - pig; c org so - C soluble organic; d - days and n to so - N total soluble).

**Source:** adapted from Barra Caracciolo et al. (2015).

Slepetiene et al. (2020) they point out that the separation of the solid and liquid fractions of the digested from the anaerobic digestion facilitates their transport and handling during application in the soil. The solid fractions of the digerides show high concentrations of organic carbon, indicating their potential as a supplement to organic carbon in the soil. The response in soil to the application of digestate depends on several factors, including particle size, degradation status, agronomic properties (pH, N, P and K), soil cover, agro-climatic conditions, treatment of the raw material (biomass) before and after digestion. The application of digerides influences the increase in soil pH, especially in acidic soils, and digerides function as soil conditioners, containing 3% to 32% organic matter, which is crucial to improve the agronomic characteristics of soils.

Grave et al. (2015) they argue that in terms of greenhouse gas emissions, the application of raw pig waste to the soil results in higher CO₂ emissions from the soil, due to the greater decomposition of crop residues, compared to the application of digestate from anaerobic digestion of pigs. This is because raw ejects have higher labile carbon content, total solids, and a low C/N ratio, while digested ejects have lower labile carbon content, total solids, and high C/N ratio. Soils treated with digested porcine animals reduce CO₂ emissions, contribute to the input of recalcitrant carbon, assisting in the reduction of CO₂ emissions and the accumulation of carbon in the soil, promoting the increase of soil organic matter and contributing to carbon sequestration.

Chiew et al. (2015) they claim that the remaining organic matter from the raw material...
digested during anaerobic digestion is incorporated into the soil, making digested animals potential carbon sequestrants when added to the soil. This is because the application of digestate reduces CO₂ emissions, retaining the carbon that would otherwise be released into the atmosphere. However, the carbon sequestration process is complex and depends on several factors, such as soil type, temperature, and microbial activity.

Grave et al. (2015) They point out that temperature, soil upwelling and the incorporation of crop remains are the main abiotic factors that affect CO₂ emissions in the soil. The application of digestate from anaerobic digestion reduces greenhouse gas emissions, provides nutrients readily available for crops and can serve as an alternative to fossil fertilizers (chemical fertilizers), as highlighted by Slepetiene et al. (2020).

Riding et al. (2015) point out that the application of digestate from anaerobic digestion in soil may be valuable for the increase of organic matter, but its inappropriate use may result in negative impacts, including imbalances in biological and chemical interactions leading to greenhouse gas emissions (CO₂, N₂O and CH₄). The stability of organic soil improvers after application is key to ensuring that carbon remains stable and that nitrogen is adequately supplied to crops. The in-depth knowledge about the organic correctives and the synchronization of the application with the growth stage of the plants can limit the emissions of N₂O and CO₂. Nitrogen and carbon cycling in the soil is directly linked to changes in the soil's carbon composition, affecting nitrogen turnover and exchange of nitrogen gas compounds. This process can lead to anoxic conditions and denitrification, justifying the investigation of the gaseous emissions of the digestate when applied to the soil.

Verloop et al. (2015) emphasize that the process of decomposition of soil organic matter contributes to CO₂ emissions in the atmosphere, while carbon sequestration in soils mitigates these emissions. Management strategies, such as the use of organic fertilizers, have a significant impact on the dynamics of soil organic matter. Therefore, it is essential to understand the effects of soil and crop management on soil organic matter in a broad context. The application of digerides from high-load anaerobic digestion, with more than 70% organic matter, sequesters more carbon in the soil than organic fertilization with undigested organic waste.

Cestonaro et al. (2015) they observed that the composition of the digestate varies depending on the different sources of raw material (biomass) and their proportions at the start of the anaerobic digestion process. This variation affects the stability of the digested material as a source of nutrients, making it crucial that it does not behave as conventional sources of organic fertilizer (fresh dung) in the soil. The ratio of humic acids to fulvic acids (AH/FA) in the digestate varies with the input raw material, resulting in different AH and AF concentrations. During the digestion process, organic matter consumption occurs, leading the digested to different concentrations of more stable carbon fractions. Figure 3.
Slepetiene et al. (2020) they highlight that humic acids in digestate vary according to the source of raw material used in digestion, with the ratio of humic acids to fulvic acids (AH/FA) reaching 3.15 in the solid fractions of digestate. This represents 1.9 times more humic acids in the solid fractions compared to the unfractionated digerides, composed of the solid and liquid phase together. Therefore, digestate applied to the soil has the potential to stabilize and sequester carbon, contributing to the increase of organic matter in the soil.

However, Tambone et al. (2019) they concluded that, when studying digestate from biogas plants from different biomass mixtures at the start of the digestion process, there was no significant difference in the concentration of total organic carbon in the liquid fractions of the digestate. These liquid fractions, even though they have less total organic carbon than the solid fractions of the digestate, still contain concentrations similar to those found in traditional organic residues, untreated by digestion and used in crops. Furthermore, the C/N ratio is lower in the liquid fractions of the digested ones compared with the solid fractions, due to the high nitrogen content in their composition.

Coban, Miltner and Kästner (2015) they observed that about 60% of the carbon derived from the digerides remains in the soil with the passage of time after the application. This recalcitrant carbon is derived from the carbon fractions of the digerides and from the cell wall fragments of the microbial necromass contained in the digerides, contributing to the formation of soil organic matter. Fungi play a significant role in the renewal of labile carbon in the soil after the application of digerides.

Muscolo et al. (2017) they also state that the addition of solid fractions of digested soils in the soil increases the humic carbon content and microbial biomass compared to uncorrected soils with digested soils. The application of the liquid fraction of digerides increases the organic matter in the soil and the carbon/nitrogen ratio, with the increase in organic matter attributed to the presence of the solid fraction in the liquid fraction of digerides. Therefore, it is recommended to know the composition and concentration of both liquid and solid fractions.
when applying the digested ones in the soil for greater efficiency in the use of these materials. Figure 4.

![Figure 4 - Gains in soil organic matter (MOS), humic acids (AH), fulvic acids (AF) and Nitrogen (N), depending on the application of the liquid fractions (FL) and solids (FS) of the digested ones in%; where: Co - control; F - Factor (digested 60% animal manure (birds, cows and sheep), whey, corn silage and in lesser quantity with olive residues 20% and citrus pulp 20%); U - Uliva (digested from remains of 30% olives and 30% citric pulp and in a smaller quantity 40% with animal manure and corn silage); T - treatment; HC - humic acids; FC - fulvic acids; C/N - nitrogen carbon ratio.](image)

*Source:* adapted from Muscolo et al. (2017).

Riding et al. (2015) address the market of digestate from anaerobic digestion, highlighting challenges related to its variability of composition, uncertainty about environmental benefits, lack of regulation, equipment and technical information for land application. This contributes to the undervaluation and underestimation of digested people due to lack of knowledge and cultural issues. The future trend is a change in the commercial attitude towards this waste, looking for forms of recovery.

In relation to the use of digerides, Buller et al. (2015) they point to the scarcity of information about their effects on different ecosystems, particularly in agriculture, where their agronomic value is relevant. However, application in agriculture requires adequate management, processing and distribution techniques to avoid impacts such as soil acidification and eutrophication due to increased nutrient leaching. Local soil quality, weather conditions and plant needs play a key role in the efficient management of digestate, as highlighted Riding et al. (2015), Tampio, Salo and Rintala (2016).

2.2.3 The environmental benefits of digestate when applied to soil

Garcia-Sánchez et al. (2015) carried out studies on the application of digestate from anaerobic digestion in soils contaminated with heavy metals, observing a 26.8% increase in the total organic carbon content after 30 days of treatment. This increase was associated with the degradation of readily available organic compounds. The digestate also contributed to an increase in the water-soluble carbon content in the deeper layers of the soil, indicating an
increase in organic matter stocks. Water-soluble carbon and soil carbohydrates were related to microbial activity in the soil, and their presence was linked to the increase in the total organic carbon content in the soil.

Ibeto et al., (2020) evaluated the effects of the application of digerides from anaerobic digestion, both fully and in their liquid and solid fractions, in soils contaminated with phenanthrene. They observed that the digested ones affected the properties of the contaminated soil, especially the levels of nitrates (NO₃), which were higher in the uncontaminated soils. In contaminated soil, the presence of phenanthrene inhibited microbial growth and slowed the nitrification process. However, digestate improved microbial populations, soil fertility, and phenanthrene mineralization rate, resulting in a significant increase in total organic carbon content in the soil.

Slepetiene et al. (2020) and collaborators investigated the benefits of digested anaerobic digestion in degraded, contaminated and eroded soils. They found that the digestate increased the concentration of NH₄, P and K in the soils, making these nutrients more readily available to plants compared to undigested organic matter. The composition of the digestate depends on the raw material and the digestion technology used, which should be considered in the characterization of the digestate for recovery from degraded or contaminated areas. The liquid and solid fractions of the digestate have contributed to the increase of the humified organic matter in the soil, as well as providing essential nutrients for plants and promoting carbon sequestration, which helps reduce CO₂ emissions in the atmosphere. Figure 5.

**Figure 5** - Composition of the liquid and solid fractions of the digested ones and the contribution of these fractions in the amount of AH, AF and AH/AF ratio, where: L - liquid fraction of digested ones; S - solid fraction of digested ones; ASL - liquid fraction of digested ones in soil; ASS - solid fraction of digested ones in soil; TOC - total organic C; AF - Fulvic acid; AH - humic acid; AH/AF - humic acid and fulvic acid ratio and Co - control; applied in eroded soils.

**Source:** adapted from Slepetiene et al. (2020).
2.2.4 Benefits of integrating digestate into other waste treatment processes

We observe the importance as a conditioner and the environment of the application of digestate to the soil. Di Maria, Segoloni and Pezzolla, (2016) they analyzed the benefits of the integration of the solid fractions of digested from anaerobic digestion, and the composting found that after 90 days of application in the soil it increased from 10 to 14% of total organic carbon in relation to the undigested compound. Integration increased the levels not only of total organic carbon but also of humic acid, fulvic acid and N, which are stable and useful sources for plants (crops) and for the agricultural properties of the soil compared to undigested compost. The final concentration of humic acid and fulvic acid in the process of integration of digestate into composting is influenced by the initial concentration of the raw material (biomass), composition, proportion, more and less reactive components present, nature and intensity of the digestion process.

Monlau et al. (2016) studying the benefits of the integration of the solid fractions of the digestate from anaerobic digestion to pyrolysis, they found that the pyrolysate had 50% more total organic carbon than the unpyrolyzed one. The process of integration raises the levels of fixed carbon of the digested from 1% to 1.3% to 7.7% to 12.6% when pyrolyzed. Slow pyrolysis provides specifically larger areas of carbon fractions relative to rapid pyrolysis. The biochar classification of the pyrolyzed digerides according to the percentage of organic carbon was between class 1 and 2 according to the European classification criteria for biochar, the stability of carbon by the molar ratio of hydrogen/organic carbon and oxygen/organic carbon, and lower values relate to greater stability of carbon, the values found were 0.39 to 0.42 respectively for hydrogen/organic carbon and oxygen/organic carbon, thus ensuring a minimum half-life of one thousand years, indicating long-term stability of carbon from the pyrolysis of digerides, concluded that pyrolysis if digested cells contribute to carbon sequestration in the soil, showing that the material from the pyrolysis of digested cells increases the corrective capacity and stability of carbon in the soil Figure 6.

![Figure 6](image-url)

*Figure 6* - Analysis of two sources of digerides when pyrolyzed (PC) and non-pyrolyzed (DG) in relation to the increase of the mineral elements Ca, K, Mg and P and of ce - enrichment coefficient of these minerals.

*Source:* adapted from Monlau et al. (2016).

Already Miliotti et al. (2020) evaluating the effects of the integration of the solid fractions of the digestate with pyrolysis, they verified that the biomasses rich in lignin are preferable for the production of coal with a high level of fixed carbon and low level of ash. However for the anaerobic digestion process the ideal characteristics are contrary to the charring of the digerides. The integration increases the carbon content with reaction temperature and waiting time in the pyrolysis process of the digerides; the carbon content also varies with
the content of the digerides’ raw material. Integration increased the concentration of the minerals K, Si, Na, Ca and Mg significantly, tending to increase the concentration of these minerals with increased temperature and pyrolysis time. Integration is a heat treatment process that represents a stabilizing potential of the digested, turning them into high value products, capable of bringing nutrients back to the soil by means of retention in biochar before and after application in the soil, thus solving problems of leaching and nutrition. Studies on the effects of the application of biochar of digerides in plants (crops) are necessary for further clarification of their benefits.

Celletti et al. (2021) they also studied the integration of the solid fractions of the digerides of the anaerobic digestion with pyrolysis and concluded that the content of total organic carbon in the pyrolyzed digerides was from 39.4 to 43.3%, higher than the values in the non-pyrolyzed digerides that showed values of 36.6%. The carbon content in bovine manure pyrolysates is lower than in plant biomass pyrolysates obtained under similar conditions (lignin-rich biomass). Pyrolysis increased the carbon content significantly with increasing reaction temperature, along with P concentration in reducing pyrolysis time which was 26 to 46% in 1h from 19% to 38% in 3h. The residence time and temperature during the pyrolysis process affected pH and electrical conductivity. In this case, a longer residence time reduces the pH and the increase in temperature increases the electrical conductivity. The characteristics of the pyrolysates depended on the characteristics of the raw material (biomass) of the anaerobic digestion and the variations of the pyrolysis process temperature and residence time, the pyrolysis operating temperature of the digested has a greater effect on the concentration of minerals than the residence time. The pyrolysate proved valuable in the production of nutrient-rich and carbon-rich substrates, and detailed studies of its application in plants (crops) are still lacking.

Wang and Lee (2021) they emphasized that it is necessary to separate the liquid and solid phases of the digested from the anaerobic digestion to increase the efficiency of the use of the digested in the pyrolysis, thereby reducing the need for sensitive heat to reach the reaction temperature. The anaerobic digestion process takes an average of 50% of the carbon present in the raw material during the production of biogas, with the digested carbon rich recalcitrant after digestion left over from the initial raw material (biomass). The benefits of integrating pyrolysis with digestion by adding biochar at the entrance of the digestion process along with the raw material (biomass), accelerate the decomposition of the raw material during the digestion process. And integration at the process entry increases the concentration of recalcitrant carbon in the digestate, favoring the fixation of carbon in the soil in more stable fractions. Further studies are necessary to verify the response of the application of the pyrolysates of the digested plants to the soil (crops).

Antoniou et al. (2019) by researching the integration of the solid fraction of digerides from anaerobic digestion with gasification, they ensured that the pH increased to 11.4 and 50% of total organic carbon when compared with the non-carbonated digerides, leaving the carbonated digerides within the European biochar classification. In the carbonate increased the concentration of P, K, Ca and Mg and enrichment of the micronutrients Fe, Cu, Mn, Ni, Zn, making coal from the gasification of the digested potential fertilizers, gasification coal should be analyzed before application to the soil since heavy metal compounds in high quantities may be present. Gasification coal has recalcitrance of 0.34 while non-gasified digerides of 0.48, the lower the value the more recalcitrant is coal. It is true that the carbonated material sequesters more carbon, carbon in the soil than the non-carbonated digested material. The coal from gasification presented nutrient-rich carbonaceous material and recalcitrant carbon, which contributes to carbon sequestration in the soil. More studies with plant growth tests (crops) with the purpose of evaluating the agronomic benefits of the application of gasification charcoal from digerides in the soil are still necessary, verifying their effects. The integration proves to
be efficient in the production of energy and in the production of carbonaceous material for the application of plants (crops).

3 FINAL CONSIDERATIONS

Anaerobic digestion, in spite of being an old technology, is proving to be highly effective and of a simple process. It produces energy from the burning of biogas and generates digerides rich in nutrients and carbon. This process converts the complex organic matter of the raw material (biomass) into simple organic matter, resulting in the reduction or elimination of odors, pathogen degradation and decomposition of readily degradable carbon. The digestate concentrates readily available nutrients and produces more stable carbon, allowing carbon sequestration in the soil, as well as promoting microbial activities in the soil. The application of digestate is effective in mobilizing heavy metals, restoring degraded areas and improving soil quality.

The application of digestate in the soil increases microbial activities and organic matter, becoming a soil conditioner. However, it can result in initial release of CO$_2$ due to stimulation in microbial activities, and extensive application should be planned with care. The composition of digerides depends on the raw material and technology used, and the application of digerides can increase the ratio of humic acids to fulvic acids, contributing to the increase of soil organic matter.

The integration of digerides with other processes, such as pyrolysis, gasification and composting, as well as the separation of solid and liquid fractions, increases the efficiency, stability and carbon storage capacity in the soil. This also contributes to the reduction of problems related to nutrient leaching and environmental pollution. However, more studies are needed to evaluate the agronomic potential of digested food from different raw materials and the fractions resulting from integration with other processes in diverse production systems.

REFERENCES


Lilian, S., Silva, D. L., Cristine, T., Lucas, R., Kleber, S., Carlos, A., & Araújo, B. De. (2023). *OPTIMIZATION OF DOMESTIC AND INDUSTRIAL BIODIGESTORS BASED ON MACHINE LEARNING TECHNIQUES* Marcos Sousa Leite 1 1 INTRODUCTION The generation of waste stands out as one of the primary impacts of human activities on nature , especially the generation of bio. 1–18.


