Anaerobic Digestate-Based Fertilizers in Agriculture: Benefits, Limitations, and Future Prospects - A Comprehensive Review

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Friday, 23 June 2023

ROOM 1

SESSION XXI

WASTE VALORIZATION IV

Chair: M. Koutinas, F. Patuzzi, S. Vakalis

15.45-16.00	G. Izydorczyk, K. Trzaska, K. Chojnacka From waste to table: assessing the biological efficacy of fertilizers derived from anaerobic digestate
16.00-16.15	M. Samoraj, K. Trzaska, D. Skrzypczak, K. Chojnacka Conversion technology of anaerobic digestates from biogas plants to fertilizer formulation

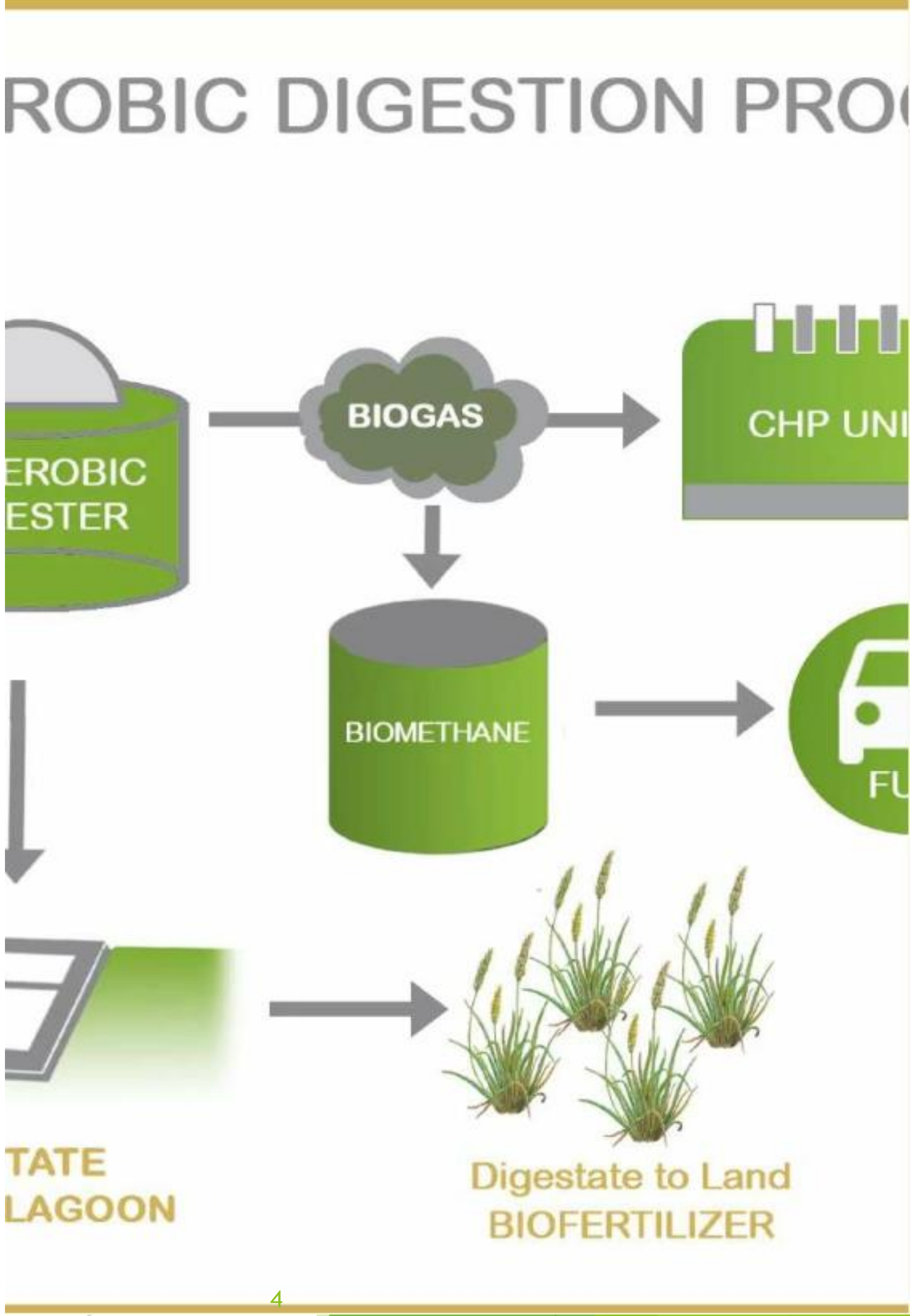
Circular Agriculture

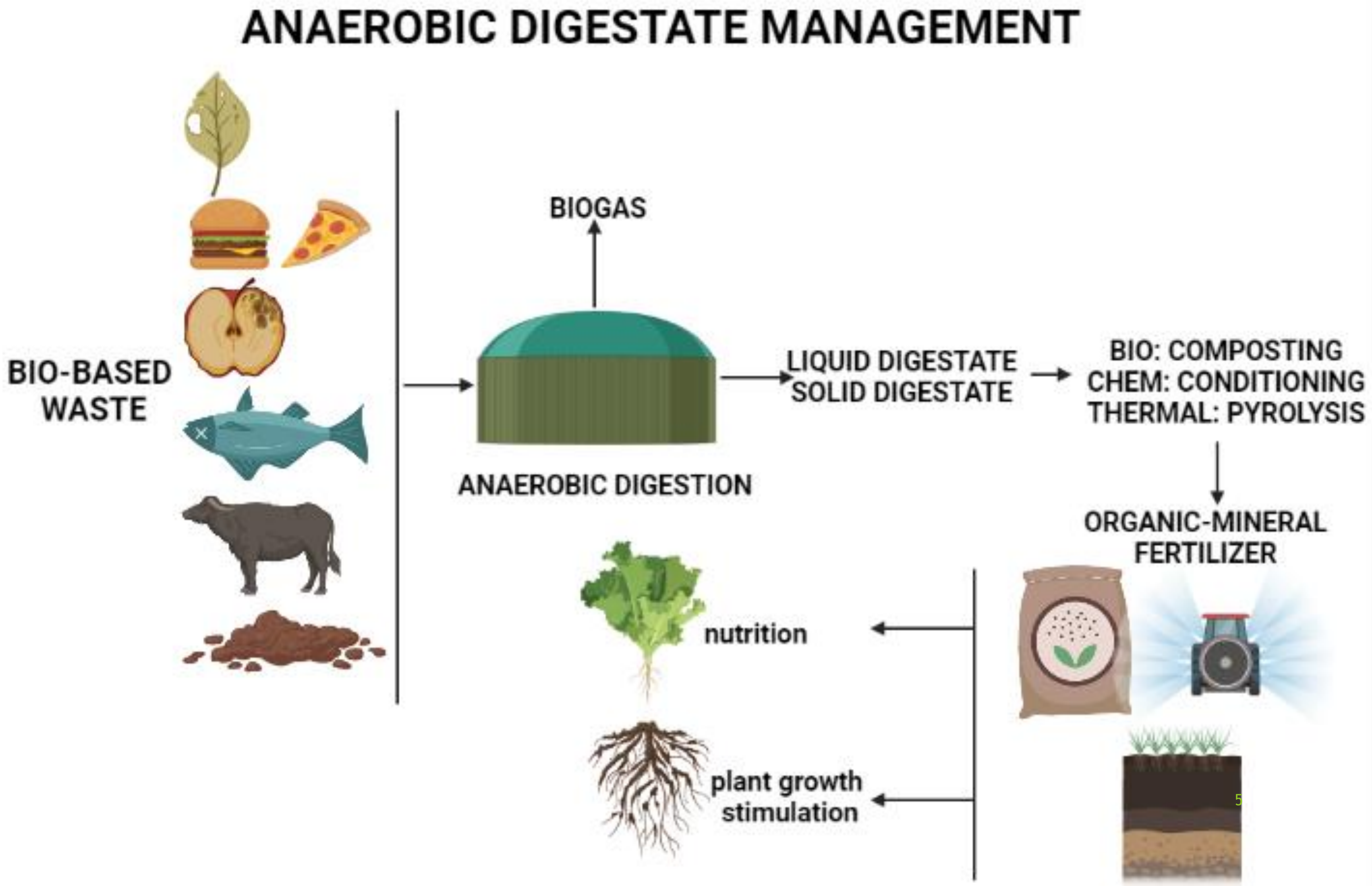
Minimizing Waste Streams

Maximizing Agriculture Biomass

- The amount of agricultural biomass produced worldwide is over ***4 billion tonnes***.
- ***29%*** of the land surface of the Earth is used for agricultural purposes.

- The use of **anaerobic digestion** as a sustainable method for processing **organic waste** has gained significant attention.
- Anaerobic digestate-based fertilizers have gained popularity as an **environmentally friendly alternative to synthetic fertilizers**.
- This presentation aims to explore their **benefits, limitations, and future prospects** in agriculture.




ANAEROBIC DIGESTATE MANAGEMENT
BIO-BASED WASTE
BIOGAS
ANAEROBIC DIGESTION
LIQUID DIGESTATE
SOLID DIGESTATE
BIO: COMPOSTING
CHEM: CONDITIONING
THERMAL: PYROLYSIS
ORGANIC-MINERAL FERTILIZER
nutrition
plant growth stimulation

- Anaerobic digestion is a **biological process** that **breaks down organic matter**.
- This process produces **biogas**, which can be used as a renewable energy source, and **digestate**, a nutrient-rich substance that can be used as a fertilizer.
- The digestate can be processed further to produce organic-mineral fertilizers. These fertilizers contain organic matter, which improves **soil structure** and **water-holding capacity**, as well as **essential nutrients**, NPK, which are released slowly over time, reducing the risk of nutrient leaching and pollution.

The Benefits of Anaerobic Digestate- Based Fertilizers

Utilizes Organic Waste

Improves Soil Health

Sustainable

a reduced carbon footprint.

Fertilizing with Digestate

Biomass Recycling

Nutrient Recovery

Sustainable Agricultural Practices

Closed Economy

- Developing **guidelines** for the safe use of digestate-based fertilizers is crucial.
- The type of **feedstock** and method used to treat the digestate can affect agronomic properties.
- **Legal aspects** such as compliance, quality assurance, and standardized testing are complex, making the transition towards a circular bio-economy challenging.
- **The growing interest in biogas** production requires sustainable management of the accompanying by-product, digestate.

Item	Data as of 2020	Updated Data as of 2023
Number of biogas plants in Europe	~18,202	21,322 biomethane-producing facilities
Growth of biogas plants	N/A	299 new plants, ~30% increase from 2021
Quantity of produced anaerobic digestate	~85 million tonnes (estimation based on 2018 data)	N/A
Amount of waste biomass processed	~94.9 million tonnes (2018 data)	Total biomass supply approximately **1 billion tonnes** of dry matter (tdm), uses amount to 1.2 billion tdm

Waste Management for Biogas Production

AD Compared to Other Methods

Methods like landfilling, composting, incineration, and gasification

AD Waste Management Planning

The value of proper planning with local biogas plants and farms for minimizing transport costs

The Benefits of Biogas Production

The advantages of biogas production over other biowaste management alternatives and ts potential as a renewable energy source

Methods of AD Management

The advantages of AD with biogas production and the various methods for managing AD waste.

Landfill

Not a sustainable alternative to AD as it generates greenhouse gases and has a negative environmental impact

Incineration

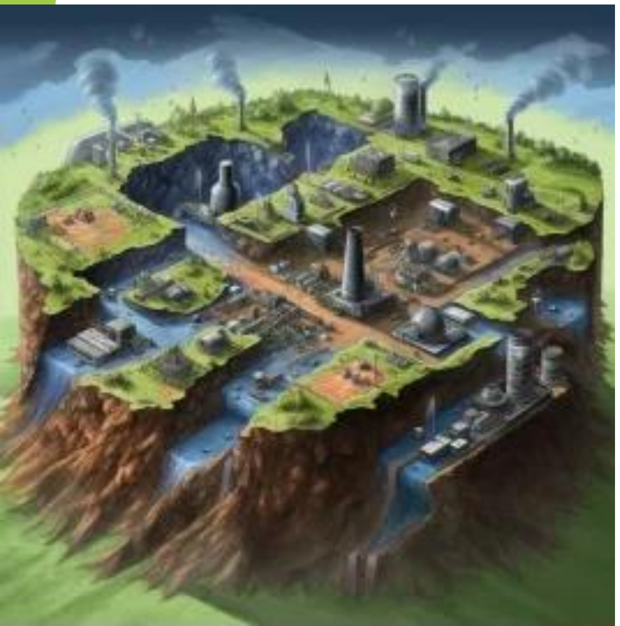
Produces greenhouse gases and toxic byproducts

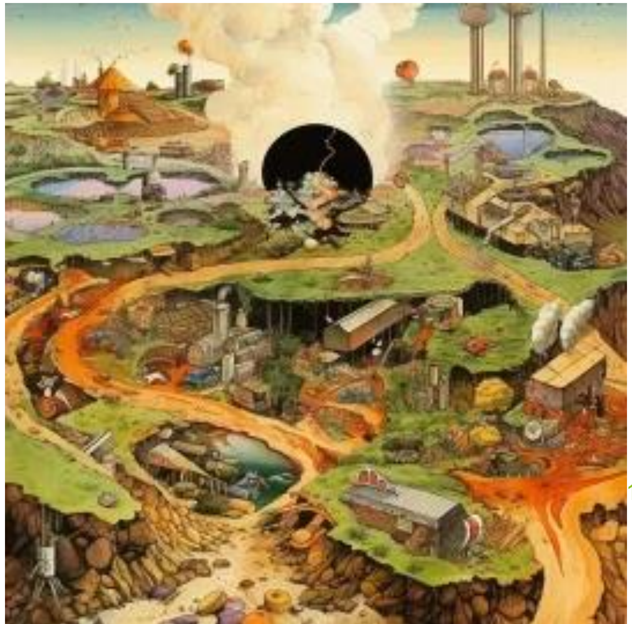
Gasification

Alternative to AD but more costly and complex

Composting

Doesn't produce a renewable energy source and is less sustainable than AD





The Limitations of Anaerobic Digestate - Based Fertilizers

Variable Nutrient Content

Potential for Pathogen Contamination

Transportation and Storage Issues

Table 1 The composition of digestate.

Parameter	(Al Seadi et al. 2013)	(Koszel and Lorencowicz 2015)	(Chuka-ogwude et al. 2020)	(Barampouti et al. 2020).	((Möller and Müller 2012)
As				29 mg/kg DM	-
C total g/kg FM			6.8-26.9	0.2-17.7 % DM	365-460 g/kg DM
C:N			1.5-6.1	1.3-29.8	4-20
Ca total	1.4-2.5 g/kg	0.25 g/L		0.0036-2.56 % DM	0.25 g/L
Cd		<0.43 mg/L		0.1-10	<1 mg/kg DM
Cr		<0.43 mg/L		6-188	2-103 mg/kg DM
Cu	2.7-12.8 mg/kg	0.43		1-681	61-270 mg/kg DM
DM	5.6-6.4 %			1.4-45.7 %	15-30 %
Fe		70.7			10800-47000 mg/kg DM
K total	2.9-4.1 g/kg	5.25 g/L		0.001-4 % DM	5.25 g/L
Mg total	0.5-0.8 g/kg	0.04 g/L		0.001-0.512 % DM	0.04 g/L
Mn		2.20		0-1100	133-780 mg/kg DM
N NH_3	3.1-3.4 g/kg		1.7-4.5 g/kg FM	0.05-2.75 %DM	1.7-4.5 g/kg FM
N total	4.6-5.2 g/kg			0.005-7.8 %DM	22-46 g/kg DM
Ni		<0.43 mg/L			20-57 mg/kg DM
P total	0.9-1.1 g/kg	0.09 g/L		0.002-2.4 % DM	0.09 g/L
Pb		<0.43 mg/L			<25 mg/kg DM
pH			7.6-8.3	5.6-9	7-8.5
TKN (g/kg FM)			2.2-8.7 g/kg FM		
Total solids (g/kg FM) (TS)			19.9-78.8		
Volatile Solids (g/kg FM) (VS)			12.3-63.7		
Zn		2.01			

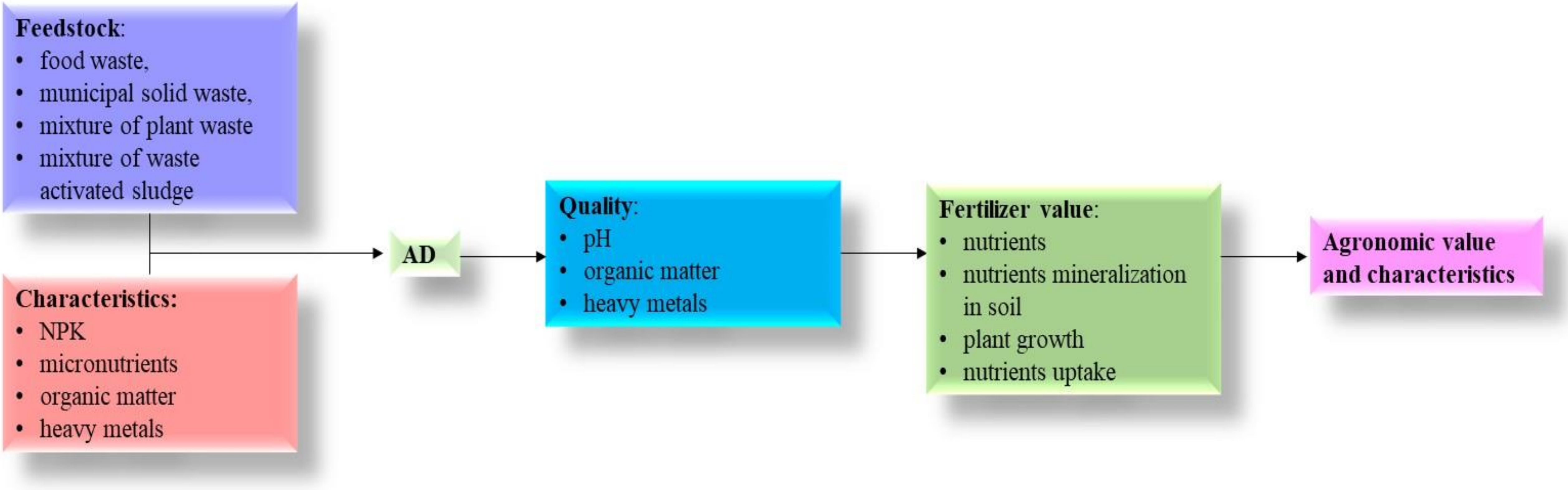


Fig. 2 Characteristics of the value of feedstock and fertilizers in the context of agronomic value and characteristics.

Anaerobic Digestion and Digestate Management

The AD Process

The four stages of AD (hydrolysis, acidogenesis, acetogenesis, and methanogenesis)

The Process Affects Digestate Properties

Factors like feedstock and fermentation time affect digestate properties

Dangers of Direct Application of Digestate

Potential risks like residual methane, ammonia, and hydrogen sulfide emissions, odorous gases, and phytotoxic effects

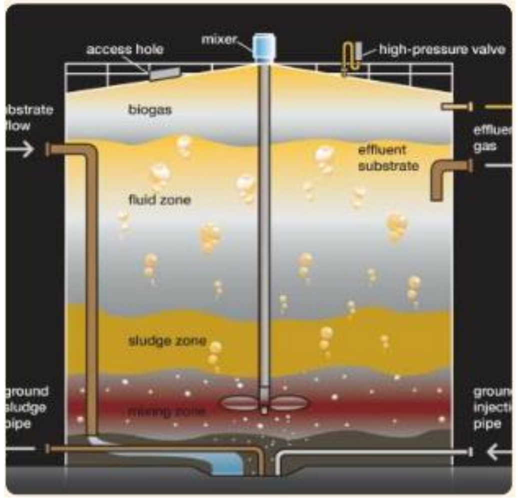
The Importance of Understanding Mechanisms

Understanding the AD mechanism can reduce the formation of phytotoxic compounds

AD Process: Bioreactor Design

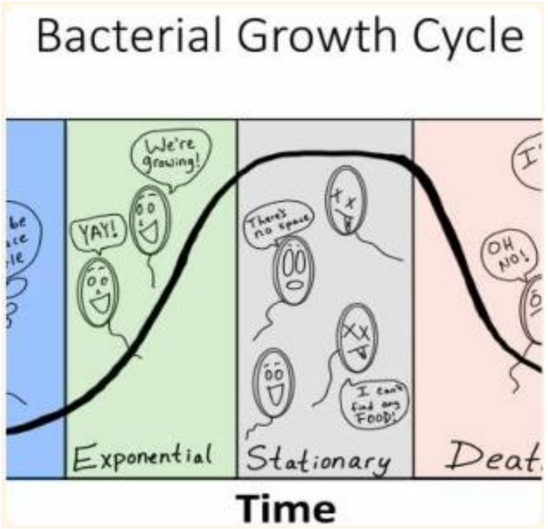
Process Optimization

Optimize the process through appropriate single or multi-stage reactors.



AD Reactor Design

The appropriate choice of the reactor can give significant advantages specific to the feedstock and the optimum performance of the process in terms of methane yield, effluent quality, and stability.



Bioreactor Microbes

Bioreactor microbial ecology is governed by cycles and dialectic processes of fermentative, syntrophic, and methanogenic bacteria.

Table Key microorganisms involved in biogas production and their functions (Demirel and Scherer 2008) (Wu et al. 2020) (Aigle et al. 2021) (Wu et al. 2020) (Mani et al. 2016) (Strazzera et al. 2018)

Stage	Microbial group	Examples of genera	Role	Strain	Examples
Hydrolysis	Bacteria, fungi	*Bacillus, Pseudomonas, Aminobacterium, Aspergillus*	Break down biopolymers into monomers	Hydrolytic bacteria, cellulolytic fungi	*Bacillus subtilis, Pseudomonas putida, Aspergillus niger*
Acidogenesis	Bacteria	*Clostridium, Bacteroides, Enterobacter*	Convert monomers into short-chain organic acids	Acidogenic bacteria	*Clostridium acetobutylicum, Bacteroides fragilis, Enterobacter aerogenes*
Acetogenesis	Bacteria	*Acetobacterium, Syntrophomonas, Moorella*	Convert short-chain organic acids into acetic acid, hydrogen, and carbon dioxide	Homoacetogenic bacteria, Acetogenic microbiota	*Butyribacterium methylotrophicum, Acetobacterium woodii, Syntrophomonas wolfei*
Methanogenesis	Archaea	*Methanobacterium, Methanosarcina, Methanococcus*	Convert acetic acid, hydrogen, and carbon dioxide into methane and carbon dioxide	Methanogens, Hydrogenotrophic methanogens, Acetotrophic methanogens	*Methanobrevibacter smithii, Methanosarcina barkeri, Methanobacterium bryantii, Methanogenum thermautotrophicus, Methanosarcina mazei, Methanosarcina thermophila*
Sulfate-reducing bacteria	Bacteria	*Desulfovibrio, Desulfobacter*	Produce CO_2 and H_2S	-	*Desulfovibrio vulgaris, Desulfobacter postgatei*

Agronomic Properties & Characteristics	Potential Drawbacks
Rich in Nutrients (NPK): AD is a rich source of essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K), making it beneficial for plant growth and soil fertility (Serrano et al., 2020; Kataki et al., 2017).	**Variability in Nutrient Content:** The nutrient content of AD can vary depending on the feedstock and the conditions of the digestion process, making it challenging to apply at precise rates (Jin et al., 2022).
Organic Matter Content: AD contributes to the organic matter content in the soil, improving soil structure, water-holding capacity, and microbial activity (Serrano et al., 2020).	**Potential Contaminants:** AD may contain potentially harmful substances such as heavy metals or pathogens, depending on the nature of the feedstock (Kataki et al., 2017).
Improves Soil Structure: AD can enhance soil structure, leading to better aeration and water retention, and ultimately, improved crop growth (Kataki et al., 2017).	**Odor and Storage Issues:** AD may have a strong odor and can pose storage challenges, which could be problematic for some users (Jin et al., 2022).
pH Stabilizer: AD has a low pH, which can help to neutralize alkaline soils (Serrano et al., 2020).	**Potential Nitrogen Loss:** If not properly managed, the high nitrogen content in AD could lead to nitrogen loss through volatilization or leaching, potentially causing environmental pollution (Jin et al., 2022).
Soil Microbial Activity: The application of AD can stimulate soil microbial activity, contributing to improved soil health and nutrient cycling (Kataki et al., 2017).	**Potential Phytotoxicity:** In some cases, if applied in high amounts, AD could induce phytotoxic effects on plants, negatively affecting their growth (Serrano et al., 2020).

Environmental Impact of Unprocessed Anaerobic Digestate

Water Pollution

Air Pollution

Reduced Biodiversity

Ecological Impacts of Digestate Application

Phytotoxicity

Ecotoxicological Effects

Agronomic Compliance




Sustainable Valorization Methods for Anaerobic Digestate

Biological Processes
aerobic composting and vermicomposting

Chemical Processes
precipitation and ion exchange

Thermal Processes
pyrolysis and gasification

Mechanical Processes
centrifugation and filtration

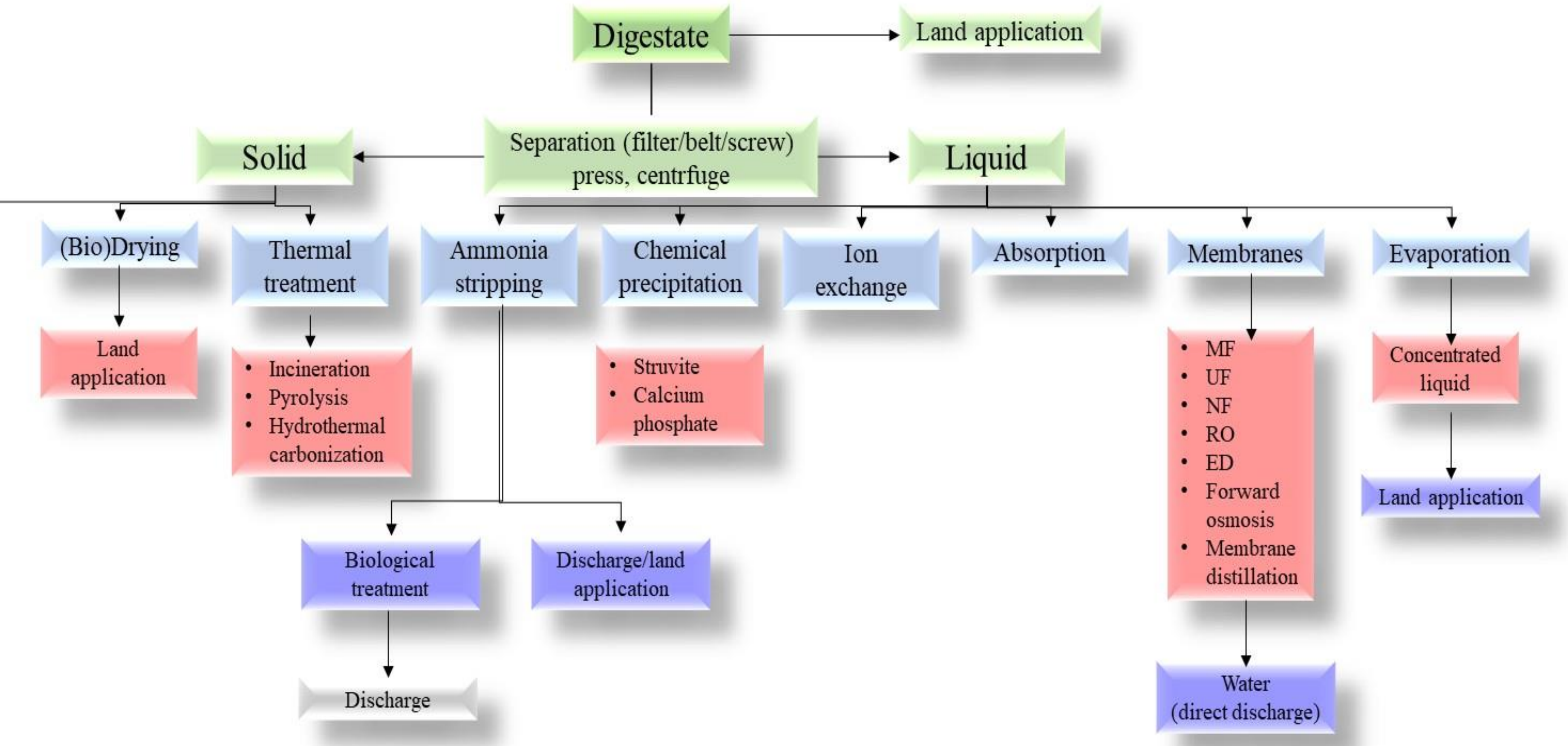


Fig. 1 Digestate processing: recovery of nutrients from anaerobic digestate (Barampouti et al. 2020) (Al Seadi et al. 2013).

Legal and Legislative Considerations

Legal Provisions

Actualizing closed-economy rules requires the development of comprehensive regulatory frameworks aimed at a sustainable approach to fertilizer production. This will facilitate the wider use of digestate-based fertilizers.

Compliance with Organic Regulations

The use of digestate-based fertilizers as organic fertilizers under organic farming standards may require adaptation of current regulations.

Feedstock Specifications

Clear definitions of feedstock suitable for producing digestate-based fertilizers must be established to avoid market issues.

Economic Feasibility

Legislative facilitations can make the commercialization of organic-mineral fertilizers based on AD more economically feasible in future.

The European Union's Green Deal

Reducing Greenhouse Gas Emissions

Strategies for reducing greenhouse gas emissions and achieving carbon neutrality

Promoting Circular Economy

Methods for promoting circular economy and increasing resource efficiency

Renewable Energy

Plans of transition to renewable energy sources

Organic-Mineral Fertilizers from Anaerobic Digestate

Producing organic-mineral fertilizers from AD can help to reduce dependence on synthetic fertilizers, which negatively impact the environment. Methods for producing organic-mineral fertilizers:

Nutrient Recovery

Recovering nitrogen, phosphorus, and potassium can produce a wide variety of fertilizers

Process Summary

Applicable processes like pretreatment, separation, stabilization, and conditioning

Fertilizer Quality Standards

The importance of meeting fertilizer quality standards

Agronomic Digestate Management

Consideration must be given to maximizing the beneficial uses of digestate for efficient nutrient recovery of agricultural products and minimum waste production:

Maximizing Nutrient Recovery

- Matching nutrient demands of crops with nutrient supplies
- Recirculating digestate onto farmland
- Segregating feedstocks prior to processing
- Assuming the initial digestate has a low dry matter content

Minimizing Environmental Impact

- Increasing the nutrient supply productivity of the agricultural system
- Reducing losses of nutrients: N, P, and K
- Ensuring the optimal nutrient potential of nutrient-rich agricultural byproducts
- Reducing runoff into waterways.

Quality Indicators for Digestate-Based Fertilizers

Agronomic Effectiveness

Crop yield, nutrient balances, and extractable nutrients when evaluating the quality of digestate-based fertilizers.

Feedstock and Processing Methods

Animal and food waste can affect digestate properties. Different processing methods introduce changes to the digestate's properties as well.

Regulatory Compliance

The Fertilizing Products Regulation aims to establish a uniformed standard across Europe regarding nutrient content, labeling, and quality assurance for fertilizing products, including those made from digestate.

Customer Perception

Market research indicates negative perceptions of the feedstock for the fertilizer. Farmers as the end-users must be educated to trust in the effective use of digestate-based fertilizers.

- **Quality Indicators and Regulatory Compliance for Digestate-Based Fertilizers**
- **The Role of Fertilizing Products Regulation (FPR)**
  - Establishes *uniform standards* for fertilizing products across Europe
  - Includes digestate-based fertilizers
  - Ensures *safety*, *effectiveness*, and environmental *sustainability*
- **Key Quality Indicators for Digestate-Based Fertilizers**
  - **Nutrient Content**: Ensures effectiveness in promoting plant growth
  - **Heavy Metal Content**: Prevents soil and crop contamination, protecting human health and the environment
  - **Pathogen Levels**: Reduces the risk of disease spread to plants, animals, and humans
  - **Physical Properties (Moisture Content & Particle Size)**: Affects usability and nutrient availability to plants

Table Standardization parameters for organic-mineral fertilizers and anaerobic digestate (AD) management (Chuka-ogwude et al. 2020) (REGULATION (EU) 2019/1009 OF 2019) (Lavergne et al. 2018) (Reuland et al. 2021) (Nardi et al. 2004)

Parameter	Method	Acceptable range/limits	Importance for fertilizer management	Sources of organic and mineral components
Total Nitrogen (N)	Kjeldahl method	1-5%	Determines the fertilizer's NPK ratio	Livestock manure, crop residues, rock phosphate, etc.
Phosphorus (P)	Colorimetric method	0.1-3%	Promotes root growth and seedling development	Rock phosphate, bone meal, manure, etc.
Potassium (K)	Flame photometry	0.5-3%	Improves plant resistance and quality	Wood ash, compost, manure, etc.
pH	pH meter	6.0-7.5	Affects *nutrient availability* and plant uptake	Lime, dolomite, gypsum, etc.
Electrical conductivity (E)	Conductivity meter	0.2-2.5 mS/cm	Indicates the presence of excess *salts* in the soil	Rock dust, kelp meal, manure, etc.
Carbon/Nitrogen ratio (C/N)	Calculation using total organic carbon and total nitrogen	10-20	Affects decomposition rate and nutrient availability	Straw, sawdust, leaves, manure, etc.
Heavy metals (e.g., Pb, Cd, Hg)	Atomic absorption spectroscopy	Pb: <100 mg/kg, Cd: <3 mg/kg, Hg: <1 mg/kg (based on EU standards)	Ensures safety for plants and the environment	Compost, manure, etc.
Soluble nutrients (Ntot, Ptot, Ktot)	Standard SFS-EN 13652	1:5 water extraction, g/kg FM	Ensure nutrient availability to plants	Organic and mineral fertilizers
P availability	Sequential extraction	H_2O, 0.5 $NaHCO_3$, 0.1 M NaOH, 1 M HCl	Determines the portion of total P available to plants	Organic and mineral fertilizers
Volatile Fatty Acids	Gas chromatography	Acetic, propionic, n-butyric, iso-butyric, caproic, iso-valeric	Ensure the proper digestion of organic matter and methane production	Organic waste and manure
N-P-K Ratio (e.g., 2-2-2%)	ICP-OES, CN elemental analyzer	As specified by regulatory bodies	Ensures balanced fertilization of crops and improves soil fertility	Organic and mineral fertilizers
Moisture content	Gravimetric analysis	40-60%	Affects the stability and storage of the organic-mineral fertilizer	Organic and mineral fertilizers
Total solids	Gravimetric analysis	40-60%	Determines the organic and mineral matter content	Organic and mineral fertilizers
Chemical oxygen demand (COD)	Standard analysis	As specified by regulatory bodies	Determines the amount of organic matter in the fertilizer	Organic and mineral fertilizers
Biochemical oxygen demand (BOD)	Standard analysis	As specified by regulatory bodies	Measures the amount of oxygen consumed by microorganisms	Organic and mineral fertilizers
Ammonia (NH3)	Colorimetric analysis	As specified by regulatory bodies	Determines the amount of ammonia in the fertilizer	Organic and mineral fertilizers

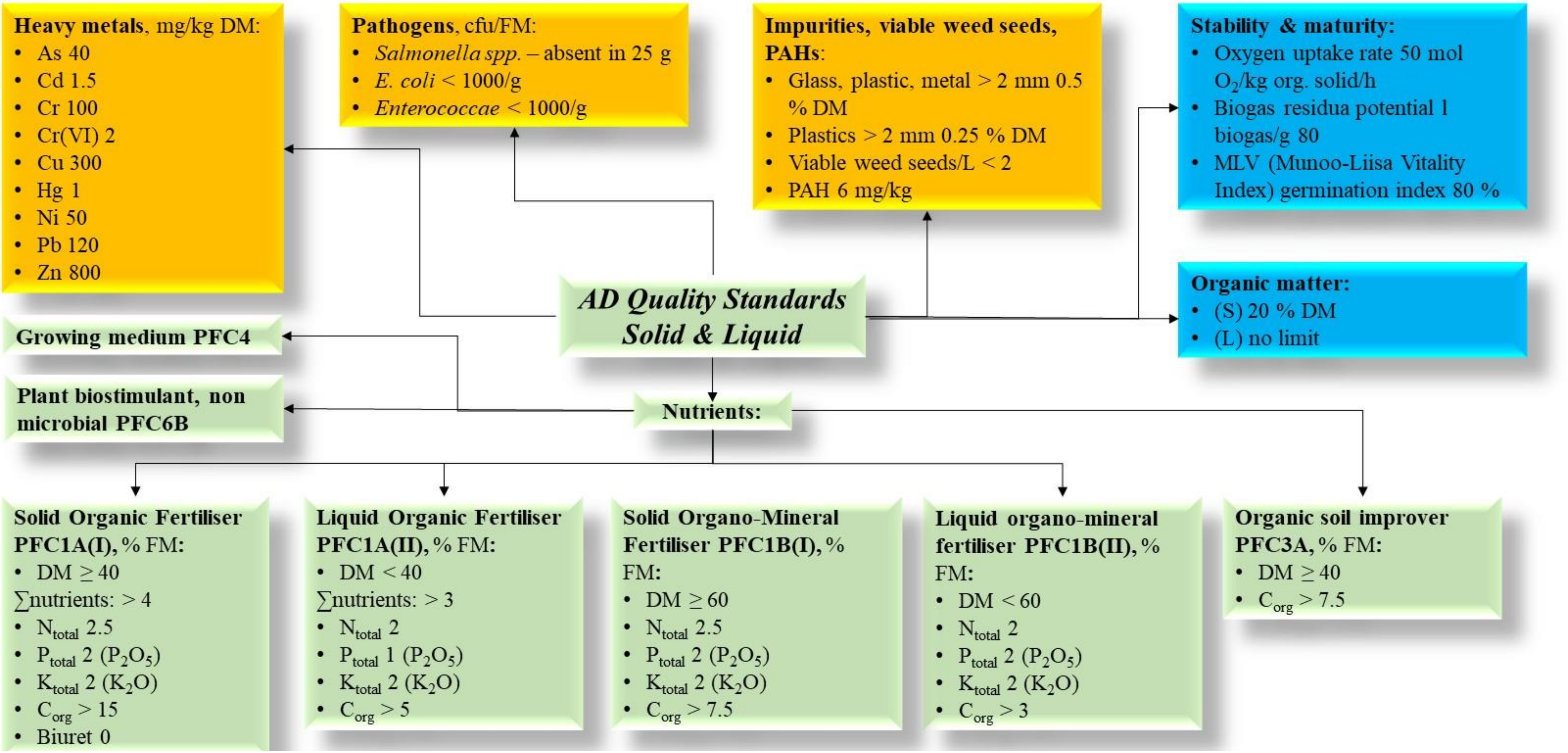


Fig. 3 Quality standards for solid and liquid fertilizers based on anaerobic digestate (REGULATION (EU) 2019/1009 OF 2019) (Saveyn and Eder 2014) (Government of Ireland 2020) (Guilayn et al. 2019) (Stürmer et al. 2020).

Applying directly to soil without any processing can pose several risks due to the presence of phytotoxic components and other undesirable substances. Phytotoxicity refers to the potential of a substance to inhibit plant growth.

Phytotoxic components in AD:

- **Ammonia**: High concentrations of ammonia can be toxic to plants. In anaerobic digestion, organic nitrogen in the feedstock is converted into ammonia. If the digestate is applied directly to soil, the high ammonia levels can cause leaf burn and stunt plant growth.
- **Organic Acids**: Anaerobic digestion can produce various organic acids, such as acetic, propionic, and butyric acids. These acids can lower the pH of the soil, making it too acidic for certain plants. They can also inhibit seed germination and root growth.
- **Heavy Metals**: Depending on the feedstock used in anaerobic digestion, the digestate may contain heavy metals such as lead, cadmium, and mercury. While some heavy metals are essential micronutrients for plants, high concentrations can be toxic and can also accumulate in the food chain, posing risks to human health.
- **Pathogens**: If the anaerobic digestion process is not properly managed, the digestate may contain pathogens such as bacteria, viruses, and parasites. These can pose risks to plant, animal, and human health.
- **Pharmaceutical Residues**: If the feedstock includes manure from animals that have been treated with pharmaceuticals, residues of these drugs can end up in the digestate. These can have negative effects on soil microbes and can also enter the food chain.

Methods for producing organic-mineral fertilizers from AD:

- **Composting**: mixing the digestate with a bulking agent, such as wood chips or straw, and allowing it to decompose aerobically.
- **Pelletizing**: The digestate can be dried and then processed into pellets, which are easy to handle and apply. The pellets can be used directly as a fertilizer or mixed with mineral nutrients to produce organic-mineral fertilizers.
- **Liquid Fertilizer Production**: can be used as a foliar spray or soil drench, providing plants with a quick boost of nutrients.
- **Biochar Integration**: Digestate can be mixed with biochar, a type of charcoal produced from biomass. The biochar can adsorb nutrients from the digestate, creating a slow-release fertilizer that can improve soil fertility and carbon sequestration.
- **Nutrient Recovery**: Advanced technologies can be used to recover specific nutrients from the digestate, such as phosphorus or nitrogen. These nutrients can then be used to formulate customized organic-mineral fertilizers.

The risks associated with the direct application of unprocessed AD to soil can be mitigated to reduce the levels of phytotoxic components:

- **Pasteurization**
- **Solid-Liquid Separation**: The anaerobic digestate can be separated into solid and liquid fractions. The **solid** fraction, which contains most of the **organic matter and phosphorus**, can be composted or further processed to produce a soil conditioner or organic fertilizer. The **liquid fraction**, which contains **most of the nitrogen and potassium**, can be treated to remove contaminants and then used as a liquid fertilizer or irrigation water.
- **Advanced Treatment Technologies**: **struvite precipitation** for phosphorus recovery, **biochar amendment** for heavy metal immobilization, and **advanced oxidation** processes for the degradation of organic contaminants.

High-Quality Co- composting

Co-Composting for High Quality

Monitoring of Key Parameter

Performance Enhancement

Maximizing the Value of Anaerobic Digestate

Digestate Pretreatment

Algae Cultivation: incorporate digestate as a nutrient-rich medium component for cultivating algae, introducing a new approach to resource recovery.

Sustainable Nutrient Source

Enhancing Digestate Combustion

Process - Drying & Pelletizing

Optimization - Key Parameters

Safety - Emissions Monitoring

Agronomic AD management

- **Digestate Storage**: Proper storage of the digestate is crucial to prevent nutrient losses, odour issues, and water pollution. The digestate should be stored in a covered, impermeable structure to prevent exposure to rain and evaporation. The storage area should also have a system for collecting and treating any runoff.

- **Digestate Transportation**: The transportation of the digestate from the anaerobic digestion facility to the field should be planned and managed to minimize costs and environmental impacts.

- **Digestate Application**

Application of Anaerobic Digestate- Based Fertilizers in Agriculture

Fertigation

mixed with irrigation water and applied to the soil through drip systems.

Broadcasting

Spreading the fertilizer over the soil surface.

Foliar Application

An alternative application method is spraying the fertilizer onto the leaves of plants.

Effect of Anaerobic Digestate-Based Fertilizers on Crop Yield and Quality

Improved Crop Yields

Studies have shown that the use of anaerobic digestate-based fertilizers can increase crop yields by as much as 20% compared to synthetic fertilizers.

Better Nutrient Content

Additionally, these fertilizers can improve the nutrient content of crops, leading to better overall nutritional value.

Reduced Pest Damage

Some research indicates that the use of anaerobic digestate-based fertilizers can reduce pest damage in crops thanks to enhanced plant immunity.

The Sustainability of Anaerobic Digestate in Agriculture

Reduction in Greenhouse Gas Emissions

Sustainable Agriculture

Economic Benefits

The Benefits of Anaerobic Digestate-Based Fertilizers

Essential Nutrients

Contains nitrogen, phosphorus, potassium, and micronutrients, ideal for crops and plants.

Organic Matter

Improves soil structure, promotes better root growth, availability of nutrients, and water- holding capacity.

The Limitations
of AD-Based Fertilizers

Feedstock and Storage

Variation in Nutrient Content

Cost Barriers

Future Research Directions

Optimizarion

Emission Control: Implementing an ammonia scrubber has shown to effectively reduce ammonia concentrations by 94%, promoting environmental safety and compliance.

Nutrient Preservation: The drying process is carefully controlled to ensure nutrient preservation, which is crucial for producing a high-quality fertilizer product from the anaerobic digestate.

Sustainable Management of Digestate

Optimizing Soil Application

Quality Indicators

Future Prospects of Anaerobic Digestate-Based Fertilizers in Agriculture

Advanced Fertilizer Production Methods

Increased Adoption

New Partnerships and Research academia and industry

Future Research

Value Economics

Empirical Evidence of Agronomic Properties

Expanding Feedstocks

The Promising Future of Anaerobic Digestate-Based Fertilizers

Advanced Monitoring Techniques

Improved monitoring and reporting can optimize efficiency, better manage feedstock, and increase profitability

Policy Support

Public initiatives, and investment in sustainable development can help promote the adoption of anaerobic digestion technology and the implementation of sustainable practices in agriculture.

Conclusion

- The use of anaerobic digestate-based fertilizers is a promising path towards sustainable agriculture.
- While challenges exist, ongoing innovation and development are paving the way for improved productivity and an eco-friendly future.

Conclusion

- ***Environmentally Friendly Alternative***

Anaerobic digestate-based fertilizers are a sustainable alternative to synthetic fertilizers for improving soil health, increasing crop yields, and reducing the environmental impact of agriculture.

- ***Challenges Remain***

However, challenges remain in the form of inconsistent nutrient content, transportation and storage issues, and potential environmental impact. Further research is needed to address these limitations.

The Future Looks Bright

The future of anaerobic digestate-based fertilizers in agriculture is promising, and advancements in production methods and research partnerships will continue to improve the sustainability and benefits of these fertilizers.