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Review

Harnessing Animal Waste Sustainably for The Production of Biofuels and Bio-Fertilizers

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Abstract

The sustainable valorization of animal waste for producing biofuels and biofertilizers presents a promising solution to waste management and renewable energy challenges. This comprehensive review delves into the various methodologies for converting livestock and poultry waste, which are abundant in organic nutrients, into a range of valuable biofuels including biogas, biodiesel, bioethanol, biochar, bio-oil, syngas, and bio-hydrogen. The processes examined include anaerobic digestion, fermentation, thermochemical, and electrochemical methods. Anaerobic digestion facilitates the biological decomposition of organic matter without oxygen, producing biogas and digestate, which can be used as a biofertilizer. Fermentation processes convert organic materials into bioethanol, while thermochemical processes such as pyrolysis and gasification transform solid waste into biochar, bio-oil, and syngas. Electrochemical methods, though less common, also offer potential for bio-hydrogen production. The byproducts or digestate from these processes are particularly valuable as biofertilizers, which improve soil fertility and health by enhancing nutrient availability, thus reducing the reliance on chemical fertilizers and promoting sustainable agricultural practices. The review emphasizes the environmental benefits of these technologies, including reducing greenhouse gas emissions, mitigating climate change, and supporting a circular economy. Furthermore, the review discusses the practical applications and technological advancements in these fields, highlighting the efficiency and scalability of different methods. By harnessing the potential of animal waste, these processes not only address waste management issues but also contribute significantly to renewable energy production and sustainable agriculture. The insights provided in this review underscore the pivotal role of animal waste in the global effort to achieve sustainable energy and agricultural practices, aligning with environmental conservation and economic development goals.

Keywords: Biochar, Biodiesel, Bioethanol, Biofertilizer, Biofuel, Biogas, Vermicompost.

Introduction

Global energy consumption has soared to 14 billion tonnes of oil equivalent, with fossil fuels accounting for 80% of this total. However, using fossil fuels as energy sources raises serious environmental issues, including causing global warming and climate change. To address these concerns, there's growing attention towards bio-ethanol, biodiesel, and biogas as alternative fuels, as they are viewed as promising carbon-neutral options (Jung *et al.*, 2021). Animal wastes represent valuable sources for biomass-based conversion processes, particularly in the production of bio-energy and bio-fertilizers (Balman *et al.*, 2019).

Animal waste from livestock and poultry comprises a blend of excrement (manure), bedding materials or litter (such as wood shavings or straw), leftover feed, deceased animals/birds, feathers, and cracked eggs (Parihar *et al.*, 2019). As per the 19th Livestock Census, India's livestock population stands at 512.05 million, generating 1095 million metric tons of dung annually (Prasad *et al.,* 2014). Historically, this significant quantity of manure was processed and marketed as fertilizer for agricultural use or directly applied to farmlands for disposal (Balman *et al.,* 2019).

The widespread practice of land application for utilizing animal wastes raises several concerns, including emissions of greenhouse gases, soil and water pollution, and the transmission of diseases (Akinbile *et al.*, 2016). Animal waste represents a noteworthy pathway for the transmission of zoonotic diseases. Pathogens found in animal waste can pollute food or water sources, or infiltrate the body through different avenues like inhalation, skin abrasions, and other susceptible entry points (Cavin *et al.*, 2016). The bacterial contamination of groundwater, often through leaching or seepage, and surface waters that receive runoff from lands where manure is applied, pose a significant health risk (Akinbile *et al.,* 2016).

Livestock manure is a substantial source of both nitrous oxide (N_2O) and methane (CH_4) emissions, with a majority of these emissions stemming from storage and handling practices (Cheng *et al.*, 2022). Manure-derived methane accounts for about 4% of all human-caused methane emissions (Tauseef *et al.*, 2013). Anaerobic digestion processes involve the breakdown of manure by microorganisms in the absence of oxygen, resulting in the production of a biogas mixture (primarily CH_4 and CO_2) and digestate. The biogas can be harnessed and used as renewable energy for producing heat or electricity. Moreover, this procedure indirectly reduces greenhouse gas (GHG) emissions by replacing emission-heavy fossil fuels and modifying the emission profile from the typical mix of N_2O and CH_4 to a blend of CO_2 and CH_4. In contrast to conventional manure treatment methods, anaerobic digestion can yield more than a 30% decrease in GHG emissions (Cheng *et al.,* 2022).

Categorization of Animal waste

A. Solid Waste: It includes dung, wasted feeding material and soiled bedding material, dead bird/animal, feathers
B. Liquid Waste: Urine and washed water
C. Gaseous Waste: Ammonia, Methane, Carbon dioxide and Nitrous oxide

Animal Waste-Derived Bio-Fuels Production Process

A. Biogas Production

Anaerobic digestion (AD) is a widely adopted approach for tapping into the potential of lignocellulosic biomass materials (Li *et al.,* 2011). This process facilitates the biological breakdown of complex blends of carbohydrates, lipids, and proteins into biogas (comprising CH_4 and CO_2) without necessitating their separation (Pilli *et al.*, 2016). Illustrated in Fig. 1, insoluble polymeric mixtures in water undergo a chemical transformation into monomeric sugars, amino acids, and fatty acids. Subsequently, in the acidogenesis stage, long-chain monomers undergo further decomposition into short-chain volatile fatty acids and alcohols through biological reactions. Minor products including hydrogen, carbon dioxide, ammonia, hydrogen sulfide, siloxanes, and other impurities are produced (Park *et al.,* 2011; Im *et al.,* 2003). In the third step, acetogenic microorganisms generate acetic acid, hydrogen, and carbon dioxide through the degradation of volatile fatty acids and alcohols. These compounds are subsequently transformed into methane and carbon dioxide, with hydrogen being consumed (Xu *et al.,* 2020).

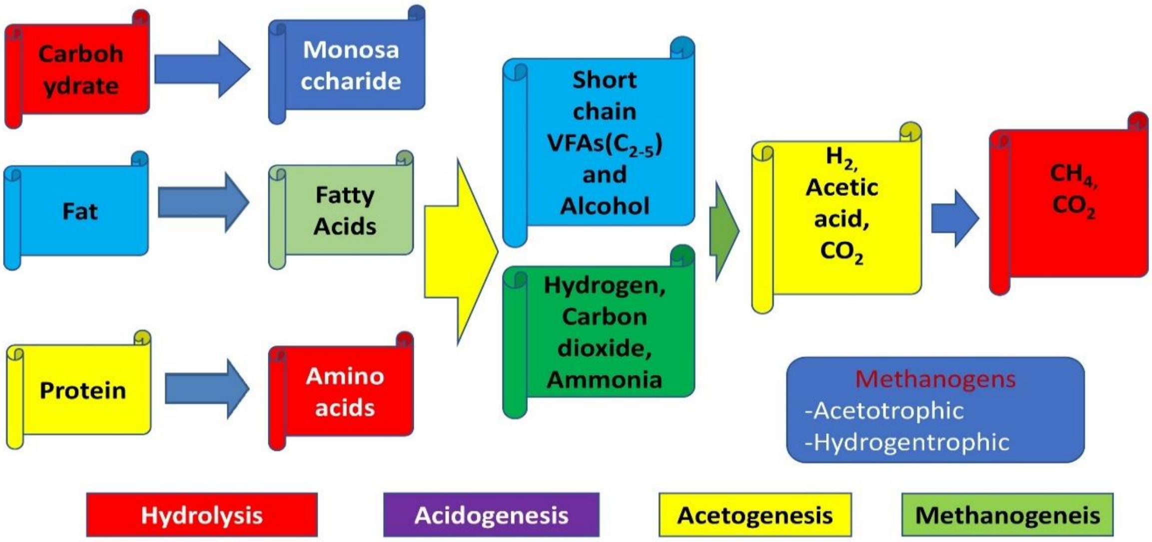

Figure 1: Biogas production process from lignocellulosic biomass

Ideal Conditions for Biogas Generation

Typically, the temperature range should fall between 35°C and 37°C. Both carbon and nitrogen are essential elements for the proliferation of microorganisms and the AD process for biogas formation. The ideal C:N ratio should range from 25:1 to 30:1. It's essential to uphold a pH level between 6.8 and 7.2. Biomass must be free from any toxic materials harmful to microorganisms. The organic loading rate should be within the range of 1.5 to 3.0 kg VS/m^3/day (Parihar *et al.*, 2019).

Anaerobic Digestion Technologies

Anaerobic digestion takes place within a closed tank or vessel commonly referred to as a digester, creating an oxygen-free environment. Various AD technologies exist, differing in aspects like feedstock moisture levels, feeding intervals, mixing methods, temperature, and other factors.

1. Wet Digester

Wet digester stands out as the predominant type, accommodating feedstock with a moisture content exceeding 85%. Mechanical stirring prevents the settling of solids, while substrates are typically fed continuously and removed after a designated Hydraulic Retention Time (HRT).

2. Dry Digester

Dry digesters, conversely, are tailored for feedstock with elevated solid content (>15%). Generally, these digesters entail layering feedstocks within a sealed tank, with hot water or slurry dispersed over them to uphold a designated digestion temperature. Solid animal manure, biosolids from municipal solid waste (MSW), food waste, yard trimmings, and energy crops are suitable contenders for the dry digestion process.

3. Batch Digester

In a batch digester, feedstocks are introduced at the beginning of the process and then sealed for a predetermined period. The digester is emptied before the next batch of feedstocks is added. Although operation and maintenance of a batch digester are uncomplicated, biogas production happens intermittently.

4. Continuous Digester

Continuous digesters entail the ongoing addition of feedstocks, while biogas and digestates are extracted at a consistent rate. This approach ensures a steady biogas production rate while minimizing digester downtime. In reality, many digesters operate as semi-batch or semi-continuous systems, enabling continuous operation while still necessitating periodic maintenance.

B. Bioethanol Production

Bioethanol production from animal waste involves utilizing the organic matter present in the waste, such as manure, to produce ethanol through fermentation processes. This typically includes collecting and preprocessing the waste to extract fermentable sugars, which are then fermented by microorganisms like yeast into ethanol. The process may involve various pretreatment steps to enhance the accessibility of sugars for fermentation and to minimize inhibitors (Zhao *et al.,* 2011).

The weight proportions of cellulose and hemicellulose, representing the carbohydrates available for conversion into fermentable sugars (C_5 and C_6), typically fall within the range of 30% to 50% (dry basis). Because of the biological breakdown occurring during digestion in livestock digestive systems, it is anticipated that the degree of polymerization of cellulose and hemicellulose in livestock manures is lower compared to other lignocellulosic waste materials. Generally, livestock manures contain not only monomeric and dimeric compounds but also oligomeric compounds like phenolic compounds, amino acids, and volatile fatty acids (Vardon *et al.*, 2011).

Pretreatment

Initial investigations into bioethanol production from livestock manures have primarily centered on the hydrolysis of dairy manures to generate fermentable sugars. Acid hydrolysis, typically employing sulfuric acid (H_2SO_4), serves as a conventional method for hydrolyzing and saccharifying lignocellulosic materials to convert them into monosaccharides. This process involves the use of concentrated acid to degrade and decrystallize the polymeric matrix of fibers (cellulose, hemicellulose, and lignin) in the lignocellulosic materials. Subsequently, diluted acid is employed for further hydrolysis of the decrystallized fibers into monomeric sugars (Choi *et al.*, 1996).

An alternative approach to derive fermentable sugars from dairy manures entails a two-step process that integrates chemical and biological hydrolysis: (Parihar *et al.*, 2019) acid hydrolysis for breaking down polymeric substrates and removing residual biopolymers, succeeded by (Prasad *et al.*, 2014) enzymatic hydrolysis to generate monosaccharides.

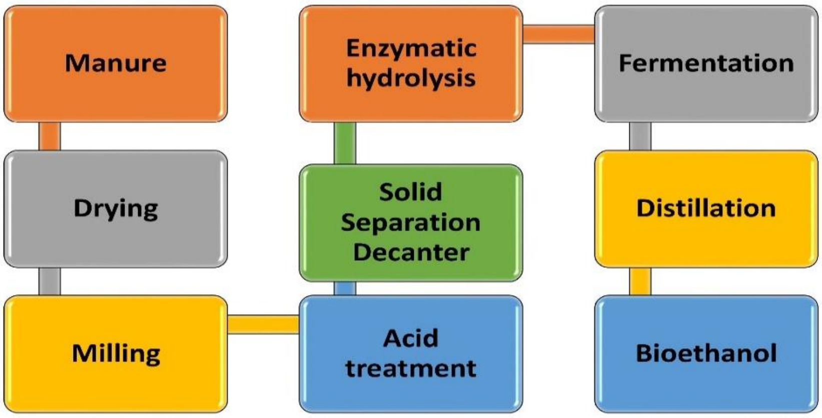

Figure 2: Bioethanol Production Process (Jung *et al.*, 2021)

C. Biodiesel Production

During the initial phase of biodiesel manufacturing, lipids, predominantly triglycerides, are sourced from various oil-rich biomass materials like soybean, palm, rapeseed, sunflower, jatropha, chicken fat, and waste fish oil. Triglycerides are composed of three fatty acids bonded to a glycerol backbone, with the possibility of minor quantities of free fatty acids within the lipid composition. To produce biodiesel, these fatty acids must undergo a conversion process into either fatty acid methyl esters (FAMEs) or fatty acid ethyl esters (FAEEs) via (trans)esterification. This chemical process entails the addition of methanol or ethanol to the fatty acids, ultimately yielding the desired biodiesel derivatives.

Extracting lipids from raw biomass materials is an essential pretreatment step in biodiesel production. Various methods have been developed for this purpose, including solvent extraction using a Soxhlet apparatus, ultrasonic-assisted extraction, and supercritical CO_2 extraction. Among these, Soxhlet extraction with n-hexane is widely favored for its ability to efficiently recover lipids from oil-rich feedstocks under relatively mild conditions (typically 50–68°C for 4–20 hours).

To convert the extracted lipids into biodiesel, both esterification of free fatty acids and transesterification of triglycerides are necessary, typically utilizing an alcohol as a reactant. Methanol is commonly chosen for transesterification reactions, which occur in the presence of either alkaline or acidic catalysts.

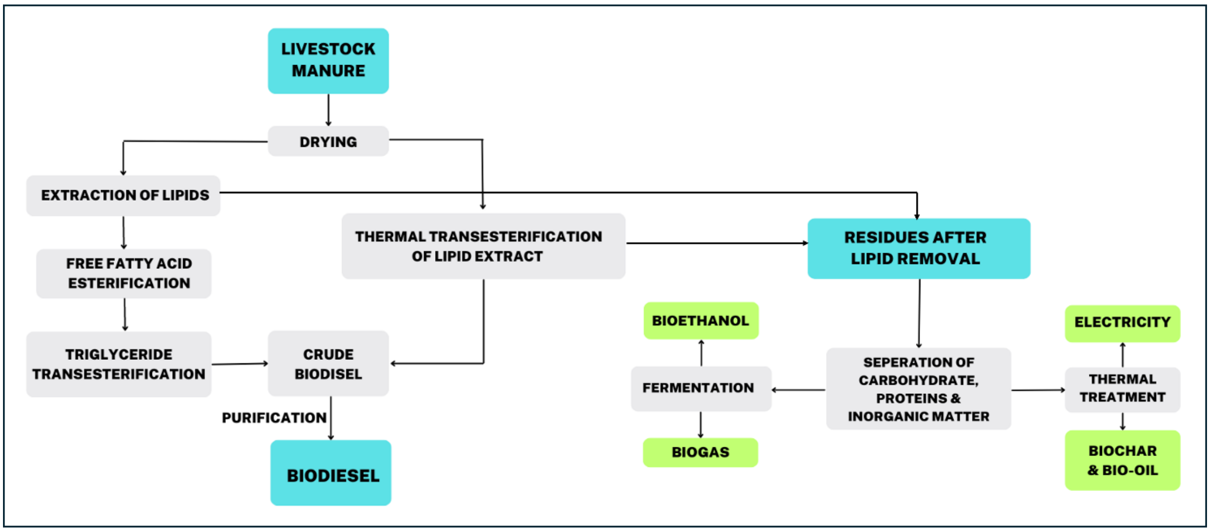

Figure 3: Biodiesel production and other gas production through various methods (Jung *et al.*, 2021)

D. Biochar, Bio-Oil, And Syngas Production from Thermo- Chemical Processes

Thermochemical processes transform solid organic feedstocks into three-phase pyrogenic products, including biochar, bio-oil, and syngas. In many cases, pretreatment is unnecessary except for drying manure, as the carbon, oxygen, and hydrogen elements in various lignocellulosic materials—such as cellulose, hemicellulose, lignin, lipid, and protein—can be thermally degraded and converted into syngas (a mixture of hydrogen and carbon monoxide). The quantity and makeup of pyrolytic products vary significantly based on the operational parameters of thermochemical processes (such as temperature, retention time, heating rate, and reactor type) and the characteristics of the feedstocks.

Pyrolysis occurs in an oxygen-free environment, where solid carbon in the feedstocks is redistributed into three main pyrolytic products through thermal degradation. Torrefaction, on the other hand, aims to produce biochar by heating biomass at relatively mild temperatures (around 200–300°C) for periods ranging from 20 minutes to several hours. Gasification, meanwhile, is a chemical process that converts solid organic materials into syngas in the presence of oxidants (like water, air, or carbon dioxide) at extremely high temperatures (ranging from 600 to 1200°C).

E. Bio-Hydrogen Production

Biohydrogen sourced from natural organic materials, or biomass, presents a promising alternative as a low-carbon fuel option. Hydrogen boasts a significantly higher energy yield compared to other fuels, with approximately 2.75 times the energy output per gram of biomass (122 kJ/g). Unlike fossil fuels or carbon-based combustion fuels, hydrogen combustion generates no toxic air pollutants or greenhouse gas emissions, only producing water as a by-product.

Hydrogen can be extracted from various sources, including fossil fuels like natural gas and coal, organic waste materials such as plant and animal matter, fruit and vegetable waste, agricultural residues, and industrial wastewaters from sectors like sugar, palm oil, and beverage production. This extraction is achieved through diverse biological technologies, encompassing bio-photolysis, microbial electrolysis, and fermentation techniques such as dark, dry, and photo-fermentation.

Among these methods, dark fermentation stands out for its lower energy requirements, higher yield, and faster production rate. Dark fermentation for hydrogen production can employ either a single or pure culture of fermentative bacteria, or a mixed culture/consortium.

Microbial hydrogen producers (MHPs) are categorized based on their oxygen resistance levels into obligate anaerobes, aerobes, and facultative anaerobes. Additionally, they are classified according to their preferred temperature ranges as psychrophilic, thermophilic, and mesophilic bacteria.

Various physical factors influence hydrogen (H_2) production during fermentation, including pH levels, partial pressure, temperature, nutrient composition in the feedstock, hydraulic retention time, feed rate, presence of inhibitory fatty acids, and operational mode. pH is particularly crucial, as it can inhibit the growth and activity of MHPs during fermentation. Both low and extreme pH levels can hinder H_2 production by impacting microbial growth and the activity of hydrogenase enzymes. Optimal H_2 production is typically achieved at pH 5 under standard temperature and pressure conditions.

The substrate used for hydrogen production must provide adequate nutrients to support microbial growth and activity. The carbon-to-nitrogen (C/N) ratio is a critical parameter influencing microbial growth during fermentation, as nitrogen is essential for DNA, RNA, protein, and enzyme synthesis. A lower C/N ratio can lead to reduced microbial growth due to insufficient carbon levels, resulting in ammonia formation. Moreover, a lower C/N ratio promotes nitrate accumulation in the reactor vessel, which can be detrimental to microorganisms.

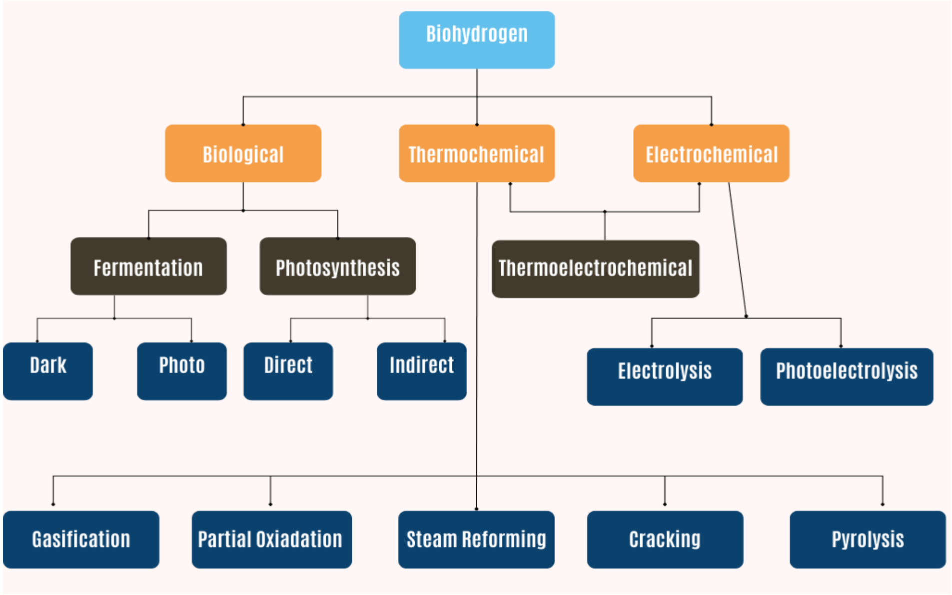

Figure 4: Biohydrogen production methods (Singh *et al.*, 2015)

F. Bio-Fertilizers Production

i. Composting

Composting involves the accelerated bio-oxidation of organic matter, undergoing a thermophilic stage typically between 45 to 65°C. During this phase, microorganisms, predominantly bacteria, fungi, and actinomycetes, generate heat, carbon dioxide, and water. Through turning or aeration, the heterogeneous organic material transforms into a homogeneous and stabilized humus-like product. This process constitutes aerobic degradation of biodegradable organic waste and is relatively rapid, typically taking 4–6 weeks to yield a stabilized material. The resulting composted material is characterized by its lack of odor, fine texture, low moisture content, and suitability for use as an organic fertilizer. When composting biological waste with poultry manure, it can effectively retain nitrogen within the manure. This not only enhances the fertilizer's value but also mitigates the potential for ammonia (NH_3) to contribute to environmental pollution (Mahimairaja *et al.*, 1994).

There are several methods of composting, each with its process and specifications:

a. Farm Trench Method

Farm composting involves placing farm wastes in trenches of specific dimensions (approximately 4.5 m to 5.0 m long, 1.5 m to 2.0 m wide, and 1.0 m to 2.0 m deep). The waste is layered within the trenches and filled up to 0.5 m above the ground. The compost matures within five to six months and is ready for application.

b. Coimbatore Method

Composting occurs in pits of different sizes depending on the amount of waste material available. Layers of waste are interspersed with a mixture of 5-10 kg of cow dung in 2.5 to 5.0 liters of water, and 0.5 to 1.0 kg of fine bone meal is evenly distributed over each layer. This layering process continues until the material reaches a height of 0.75 m above ground level. Subsequently, the pit is sealed with wet mud and left untouched for a period of 8 to 10 weeks.

c. Indore Method

Organic waste is distributed within cattle sheds for bedding purposes. Daily, the mixture of urine-soaked material and dung is gathered and arranged into layers approximately 15 cm thick at appropriate locations. Throughout the day, urine-soaked earth from cattle sheds is blended with water and applied to the waste layer two or three times.

d. Bangalore Method

Dry waste material, approximately 25 cm in thickness, is evenly distributed in a pit. Following this, a dense suspension of cow dung in water is sprinkled over the waste to provide moisture. A thin layer of dry waste is then placed atop the moistened layer. Subsequently, the pit is turned, sealed with wet mud, and allowed to sit undisturbed for approximately 5 months or until required.

ii. Vermicomposting

Vermicomposting involves earthworms consuming organic matter and producing small pellet-like material known as "Vermicompost." This process facilitates the release and conversion of essential plant nutrients such as nitrogen (N), phosphorus (P), potassium (K), and calcium (Ca) from the organic waste into more soluble forms that are readily available to plants. Additionally, vermicompost contains biologically active substances like plant growth regulators. Furthermore, the worms themselves serve as a protein source for animal feed. Vermicomposting boosts the N, P, and K content by 3 to 4 times, significantly reducing composting time to just 60-75 days.

Various species of earthworms exist, including *Eisenia foetida* (commonly known as Red earthworms), *Eudrilus eugeniae* (referred to as the nightcrawler), and *Perionyx excavatus*, among others. Among these, the Red earthworm is often preferred due to its rapid multiplication rate, facilitating the conversion of organic matter into vermicompost within approximately 45-50 days. As a surface feeder, it primarily processes organic materials from the top layer, contributing to its efficient vermicomposting capabilities. The conversion rate of Red earthworms typically amounts to 2 quintals per 1500 worms over two months.

Vermicomposting is carried out through different methods, with the bed and pit methods being the most commonly used.

a. Bed Method

Composting occurs on a solid or earthen floor by constructing a bed of organic mixture typically measuring 6x2x2 feet in size. This method is favored for its simplicity in maintenance and execution.

b. Pit Method

Composting takes place within cemented pits, usually sized at 5x5x3 feet. The unit is covered with thatch grass or other locally available materials. However, this method is less preferred due to challenges such as inadequate aeration, waterlogging at the bottom, and higher production costs.

Process of Vermicomposting

Following are the steps involved in preparing vermicompost: -

1. Choose a cool, moist, and shady site for the vermicomposting unit.
2. Mix cow dung and chopped dried leafy materials in a ratio of 3:1 and allow them to sit for 15-20 days.
3. Create a bedding layer at the bottom of the bed with 15-20 cm of chopped dried leaves/grasses.
4. Construct beds of partially decomposed material, each measuring 6x2x2 feet.
5. Place 1.5-2 quintals of raw material on each bed, adjusting the number of beds based on raw material availability and requirements.
6. Release 1500-2000 Red earthworms onto the upper layer of the bed.
7. Sprinkle water daily and cover the beds with gunny bags.
8. Turn the beds once after 30 days to maintain proper aeration for decomposition.
9. The compost should be ready in 45-50 days.
10. The finished product typically amounts to 3/4th of the raw materials used.

iii. Bio-fertilizer for Natural farming

a. Beejamrit

Beejamrit is an age-old sustainable agricultural technique used for treating seeds, seedlings, or any planting material, effectively safeguarding young roots from fungal infections. It is a fermented microbial solution rich in plant-beneficial microbes, applied as a seed treatment to enhance plant growth.

Inputs needed

- 5 kg cow dung
- 5 liters of cow urine
- 50 grams lime
- 1 kg bund soil
- 20 liters water (for treating 100 kg of seeds)

Preparation of Beejamrit

- Take 5 kg of cow dung wrapped in cloth and secure it with tape. Hang the cloth bundle in 20 liters of water for up to 12 hours.
- Simultaneously, in another container, mix one liter of water with 50 grams of lime and let it sit overnight.
- The next morning, squeeze the cow dung bundle in the water thrice to extract its essence thoroughly.
- Add approximately 1 kg of bund soil to the water solution and stir well.
- Incorporate 5 liters of desi cow urine and the lime-water mixture into the solution, stirring thoroughly.

Application as a seed treatment

- Add Beejamrit to the seeds of any fodder crop, coating them by hand.
- Dry the seeds well before sowing.
- For leguminous seeds with thin coats, quickly dip them in Beejamrit and allow them to dry. (Anonymous 2014)

b. Jivamrit

Jivamrit serves as a biostimulant, fostering the activity of soil microorganisms and foliar microorganisms when sprayed on foliage. It acts as a catalyst for microbial activity and also enhances the population of native earthworms.

Inputs needed

- 10 kg fresh cow dung
- 5-10 liters cow urine
- 50 grams lime
- 2 kg jaggery
- 2 kg pulses’ flour
- 1 kg uncontaminated soil
- 200 liters water

Preparation of Jivamrit

- Mix all the materials in 200 liters of water and stir thoroughly.
- Allow the mixture to ferment for 48 hours in the shade.
- Stir the mixture twice daily, once in the morning and once in the evening, using a wooden stick.
- Continue this process for 5-7 days until the solution is ready.

Application of Jivamrit

- Apply the mixture every fortnight.
- It can be sprayed directly on the crops or mixed with irrigation water.
- For fruit plants, apply it directly to individual plants.
- The mixture can be stored for up to 15 days. (Anonymous 2014).

Conclusion

In conclusion, the valorization of untreated animal wastes presents a compelling solution for environmental sustainability. These wastes, which often pose environmental challenges if left untreated, can be transformed into valuable resources for both energy and agricultural purposes. As conventional energy sources continue to threaten the environment, the utilization of animal wastes as a new carbon-neutral energy alternative holds significant promise. By harnessing the energy potential inherent in these wastes, we can reduce our reliance on fossil fuels and mitigate the detrimental effects of climate change. Moreover, the emergence of organic agriculture and natural farming practices underscores the importance of bio-fertilizers, derived largely from animal wastes, in reversing the adversities of conventional agricultural practices. These bio-fertilizers, rich in essential nutrients and beneficial microorganisms, contribute to soil health, crop productivity, and overall ecosystem resilience. By recognizing the value inherent in animal wastes and investing in innovative technologies for biofuel and bio-fertilizer production, we can pave the way for a more sustainable and environmentally conscious future in agriculture and energy production alike.

Contribution by Authors

Equal contribution. All authors declared that 'written informed' consent was obtained from the approved parties for the publication of this article and accompanying images.

Conflict of Interests

There is no conflict of interest.

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