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From Waste to Wealth with Sugarcane Bagasse Digestate in Crop Production

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Abstract: The escalating global demand for food and energy has intensified the production of agro-industrial wastes, necessitating sustainable strategies for their valorization. Sugarcane bagasse, a major by product of the sugar industry, is increasingly utilized in biogas production through anaerobic digestion, generating a nutrient-rich effluent known as anaerobic digestate. This review synthesizes current scientific evidence on the agronomic valuation of anaerobic digestate from sugarcane bagasse in field crop production. The results demonstrate that combined application of 100% recommended dose (RD) of chemical fertilizer with bagasse ash and digestate @20t/ha significantly improves crop yield and physiological parameters, achieving 27% taller shoots, 64% higher grain yield compared to control, and superior chlorophyll content (56.7 SPAD). Post-harvest soil analysis reveals significant improvements in soil organic matter (1.27%), available phosphorus (10.1 mg/kg), and potassium (211 mg/kg). The integrated use of 75% NPK with bagasse ash and digestate produced yields comparable to 100% NPK alone, indicating the potential to reduce mineral fertilizer use by 25% while maintaining productivity. Furthermore, the benefit-cost ratio was maximized with combined applications, demonstrating economic viability. This review highlights that recycling sugarcane bagasse digestate as a soil amendment not only improves soil fertility and crop productivity but also offers a sustainable solution for managing agro-industrial waste in alignment with circular bio-economy principles, particularly suitable for farmers near sugarcane processing facilities.

Keywords: Sugarcane bagasse, anaerobic digestate, field crops, nutrient recovery, integrated nutrient management, soil fertility, circular bio-economy.

1. Introduction

The sustainability of agricultural productivity is of utmost importance considering the global population, which is expected to plateau at approximately 9 billion people by 2050. Accordingly, the extensive use of chemical fertilizers is practiced to increase agricultural production and meet global food demands. However, low use efficiency of fertilizers is a big question and concern both for food production and environmental degradation. Moreover, prolonged excessive use of chemical fertilizers and intensive agricultural practices have led to the deterioration of soil fertility and also caused damage to the environment.

In recent times, energy consumption and economic pressure on industries need sustainability in the utilization of resources and to get optimum yield. Bio-based products (straw, husk, bagasse, animal wastes) utilized by agro-industries and through modern technologies produce energy and a huge quantity of residual wastes in the form of ash, biochar and digestate. So, there is a gravid need for more attention into the depth of these residual by-products of agro-industrial waste utilization and recycling methodology. Due to easy availability and being cheap, these organic materials can be effectively used in agriculture for soil enrichment and amendment. Recycling of these wastes on croplands will not only help in reducing pollution but also improve soil fertility when applied as soil amendment.

Sugarcane bagasse is a major agro-industrial byproduct generated in large quantities by sugar mills worldwide. Modern technologies have enabled the conversion of this lignocellulosic biomass into bioenergy through anaerobic digestion, producing biogas and a nutrient-rich effluent called anaerobic digestate. Anaerobic digestate is rich in organic matter and macro-micronutrients, including nitrogen, phosphorus, and potassium, which are essential for plant growth.

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Vietnam represents a particularly significant context for the agronomic valuation of sugarcane bagasse digestate. As a major agricultural producer in Southeast Asia, sugarcane ranks among the country's most important industrial crops, covering approximately 127,000 hectares of plantation area and producing around 7.5 million tons of cane annually. This production supports 25 sugar mills with a total milling capacity of 110,000 tons per day, concentrated primarily in the southern and central regions. The harvesting and processing of sugarcane annually generates about 5 million tons of bagasse and over 3.5 million tons of sugarcane trash, with a total energy potential of approximately 27 TWh, primarily available in the central regions of Vietnam.

The management of sugarcane bagasse presents a substantial environmental challenge for Vietnam. Traditional disposal methods such as open burning, landfilling, and low-efficiency composting lead to serious air pollution, land occupation, and high treatment costs. Vietnam's tropical climate and rapid agricultural industrialization have intensified the pressure on sugar enterprises to find sustainable solutions for this abundant biomass waste. The conversion of sugarcane bagasse into renewable energy through anaerobic digestion has emerged as a promising strategy, with biogas typically composed of 55-70% methane and 30-45% carbon dioxide serving as a potent renewable energy source for electricity generation, heat production, or upgrading to biomethane for vehicle fuel.

Research in Vietnam has demonstrated that sugarcane by-products can significantly improve soil fertility and crop productivity. A study evaluating the effects of inorganic fertilizers combined with sugarcane filter cakes on rice yield in An Giang province found that the application of sugarcane filter cakes improved soil fertility by reducing soil acidity and electrical conductivity, while increasing organic matter, total nitrogen content, and exchangeable potassium. The treatment combining inorganic fertilizer with sugarcane filter cakes achieved the highest rice yield (8.82 tons/ha), with statistically significant differences compared to other organic fertilizer treatments. Similarly, research in ThanhHoa province demonstrated that organic fertilizer produced from sugarcane tops and leaves significantly impacted sugarcane growth, development, yield, and quality, with optimal economic fertilizer rates of 11.10 tons/ha under irrigated conditions and 11.54 tons/ha under non-irrigated conditions .

These findings align with the broader theme of integrated nutrient management, where the combined use of both organic and inorganic amendments should be adopted to achieve agricultural sustainability and for the restoration of soil fertility status and crop productivity. Introducing the use of bio-based fertilizer made up of nutrient-rich digestate and bagasse ash can enhance soil fertility of varying soil types and plant productivity of multiple agricultural crops.

This review synthesizes current scientific evidence on the agronomic valuation of anaerobic digestate from sugarcane bagasse in field crop production, examining its chemical composition, effects on crop growth and yield, impacts on soil fertility, and economic viability. The sustainability of agricultural productivity is of utmost importance considering the global population, which is expected to plateau at approximately 9 billion people by 2050. Accordingly, the extensive use of chemical fertilizers is practised to increase agricultural production and meet global food demands. However, low use efficiency of fertilizers is a big question and concern both for food production and environmental degradation. Moreover, prolonged excessive use of chemical fertilizers and intensive agricultural practices have led to the deterioration of soil fertility and also caused damage to the environment.

In recent times, energy consumption and economic pressure on industries need sustainability in the utilization of resources and to get optimum yield. Bio-based products (straw, husk, bagasse, animal wastes) utilized by agro-industries and through modern technologies produce energy and a huge quantity of residual wastes in the form of ash, biochar and digestate. So, there is a gravid need for more attention into the depth of these residual by-products of agro-industrial waste utilization and recycling methodology. Due to easy availability and being cheap, these organic materials can be effectively used in agriculture for soil enrichment and amendment. Recycling of these wastes on croplands will not only help in reducing pollution but also improve soil fertility when applied as soil amendment.

Sugarcane bagasse is a major agro-industrial byproduct generated in large quantities by sugar mills worldwide. Modern technologies have enabled the conversion of this lignocellulosic biomass into bioenergy through anaerobic digestion, producing biogas and a nutrient-rich effluent called anaerobic digestate. Anaerobic digestate is rich in organic matter and macro-micronutrients, including nitrogen, phosphorus, and potassium, which are essential for plant growth. The global biogas industry achieved a total

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energy output of 1.61 exajoule (EJ) in 2021, with the European Union alone producing an estimated 180 million tons of digestate. However, the direct application of digestate to croplands as fertilizer faces challenges including nutrient overload, heavy metal contamination, pathogens, and regulatory constraints.

Integrated nutrient management (INM) is a scheme that refers to the safest way to dispose of crop residues and produce high-quality crop by a balanced and integrated use of both sources of fertilizers (organic and inorganic) for maintaining soil fertility and providing plants with an optimum level of nutrients. The combined use of both organic and inorganic amendments should be adopted to achieve agricultural sustainability and for the restoration of soil fertility status and crop productivity. Introducing the use of bio-based fertilizer made up of nutrient-rich digestate and bagasse ash can enhance soil fertility of varying soil types and plant productivity of multiple agricultural crops.

This review synthesizes current scientific evidence on the agronomic valuation of anaerobic digestate from sugarcane bagasse in field crop production, examining its chemical composition, effects on crop growth and yield, impacts on soil fertility, and economic viability. By integrating evidence from research studies, this review aims to provide a comprehensive framework for the adoption and optimization of sugarcane bagasse digestate as a sustainable soil amendment.

2. Chemical Composition and Characterization of Sugarcane Bagasse Digestate

2.1 Nutrient Composition

Anaerobic digestion of sugarcane bagasse significantly alters its nutrient profile, enhancing the availability of essential plant nutrients. Research indicates that sugarcane bagasse digestate contains substantial amounts of nitrogen (N), phosphorus (P), and potassium (K), which are key macronutrients for crop production.

A comprehensive analysis of sugarcane bagasse digestate revealed the following nutrient composition: nitrogen content of 0.85% ± 0.04, phosphorus content of 0.58% ± 0.02, and potassium content of 0.88% ± 0.03. In comparison, sugarcane bagasse ash contains negligible nitrogen but provides 0.97% ± 0.14 phosphorus and 1.03% ± 0.09 potassium. The digestate also contains essential micronutrients and organic matter, which contribute to improved soil fertility.

The high potassium content in digestate is particularly noteworthy, as potassium plays a critical role in plant physiological processes including stomatal regulation, enzyme activation, and osmoregulation. Studies have confirmed that the anaerobic digestion process significantly enhances the nutrient content of organic matter, making it more readily available for plant uptake. This nutrient enhancement is attributed to the breakdown of complex organic compounds during digestion, which releases nutrients in plant-available forms.

2.2 Organic Matter Content

Beyond its mineral nutrient content, sugarcane bagasse digestate is rich in organic matter, which plays a crucial role in improving soil physical and biological properties. The digestate contains a sufficient amount of organic matter (20-30%) necessary for soils with lower organic matter contents. Soil spreading of organic bioenergy residue in the form of digestate resulted in a higher amount of organic-C compounds and N, which played an important role in improving soil organic matter content, thus improving crop yield.

The organic matter in digestate contributes to improved soil structure, enhanced water-holding capacity, increased cation exchange capacity, and provides a food source for beneficial soil microorganisms. This is particularly important for degraded soils that have lost organic matter through intensive cultivation.

2.3 Role in Enhancing Anaerobic Digestion Performance

Recent research has explored the use of sugarcane bagasse ash (SCBA) as an accelerant in anaerobic co-digestion to enhance

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both biogas yield and digestate fertility. A study investigating the anaerobic co-digestion of buffalo dung and vegetable residue found that the addition of 1.5 wt% SCBA resulted in the highest cumulative biogas yield (153.67 mL/g VS), COD removal rate (31.18%), and digestate fertility (5.08%). The SCBA acts as a source of trace elements, facilitating enhanced direct interspecies electron transfer (DIET) between acetogenic bacteria and methanogenicarchaea.

Carbon- and iron-based additives, including SCBA, have shown significant potential in enhancing AD performance by stimulating microbial activity and facilitating electron transfer. These additives influence downstream digestate management, improving dewaterability and enhancing soil structure and plant productivity. The combined use of biochar and SCBA increases the nutrient NPK content in digestates, improving their fertilizer quality.

This synergistic approach—using sugarcane bagasse ash to enhance the AD process and improve the fertilizer quality of the resulting digestate—represents a promising strategy for developing a rural circular bio-economy that integrates bioenergy production with sustainable agriculture.

3. Effects of Sugarcane Bagasse Digestate on Crop Growth and Yield

3.1 Physiological Parameters and Growth Enhancement

Field and pot experiments have consistently demonstrated that the application of sugarcane bagasse digestate, particularly in combination with bagasse ash and chemical fertilizers, significantly enhances the physiological parameters of field crops.

Table 1: Effect of Sugarcane Bagasse Digestate and Ash on Wheat Yield Components

Treatment	Grain Yield (g/pot)	Biomass Yield (g/pot)	Harvest Index (%)	Sustainable Yield Index	Field Grain Yield Increase (%)
Control	4.59	9.89	46.4	0.59	-
BA @20 t/ha	5.00	11.12	45.0	0.81	25%
DA @20 t/ha	5.13	11.37	45.1	0.82	36%
BA + DA (10+10 t/ha)	5.31	11.82	44.9	0.86	-
100% NPK	5.40	12.10	44.6	0.88	-
75% NPK + DA	5.49	12.38	44.3	0.89	-
100% NPK + BA + DA	5.72	12.90	44.3	0.91	49%

In a greenhouse pot experiment on wheat, the combined use of 100% recommended dose of NPK with digestate and bagasse ash (T8) produced the highest chlorophyll content (SPAD value of 56.7), compared to control (44.2). Similarly, relative water content in leaves was maximized at 68.1% under the same treatment, compared to 17.4% in the control. The maximum shoot length (27% taller than control) was also observed in the T8 treatment. These improvements were attributed to the sustained and prolonged supply of nutrients and improved fertilizer efficiency because of the integration of organic and inorganic amendments.

Field experiments confirmed these findings, with the 100% RD NPK+DA treatment producing 12.9% higher chlorophyll content, 14.5% higher photosynthetic rate, 19.6% higher stomatal conductance, 13.9% higher transpiration rate, and 8.9% higher photosynthetic water use efficiency compared to digestate and bagasse ash alone. The high chlorophyll content is a desirable characteristic because it indicates a low degree of photoinhibition of the photosynthetic apparatus.

The maximum values of agronomic and physiological parameters were found where digestate and bagasse ash (DA @20t/ha) were used in combination with 100% NPK, as the efficiency to release nutrients gets enhanced when applied together. Nitrogen supply from digestate and inorganic fertilizers promoted active photosynthetic pigments through increased stomatal conductance and thylakoid proteins in leaves.

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3.2 Yield Components and Productivity

The application of sugarcane bagasse digestate, especially in integrated nutrient management systems, significantly improves crop yield components and overall productivity.

In greenhouse studies, maximum grain yield (5.72 g/pot) was noted in pots receiving the full dose of chemical fertilizers plus digestate and bagasse ash (T8), while minimum (4.59 g/pot) was in control. The yield obtained through 75% NPK + DA (5.49 g/pot) was statistically similar to yield obtained through the application of 100% NPK fertilizer alone, indicating the potential to reduce mineral fertilizer use by 25%. Similarly, the highest biomass yield (12.9 g/pot) was obtained in the T8 treatment, while the lowest (9.89 g/pot) was found in the control. The harvest index (47.6%) and sustainable yield index (0.91) were also highest in the T8 treatment.

Field experiments demonstrated that around 49%, 25%, and 36% higher grain yields were recorded in plants treated with 100% RD of NPK+DA compared with the grain yield in control, bagasse ash, and digestate alone, respectively. The increased level of NPK fertilizer with a recommended dose of anaerobic digestate and sugarcane bagasse ash significantly increased spike length (16%), grains per spike (20%), and grain weight (26%) over control. Higher grain and straw yield, as well as nutrient content due to integrated use of chemical fertilizers and bioenergy residues as soil amendments, was due to the supply of essential nutrients in plant-available form.

3.3 Nutrient Uptake and Quality Enhancement

The integrated application of digestate and bagasse ash with chemical fertilizers significantly improves nutrient uptake by crops. The highest N contents (5.03% in shoot and 3.91% in grain) were observed in the full dose of chemical fertilizers plus digestate and bagasse ash. The improved nutrient uptake is attributed to the timely supply of nutrients with integrated nutrient management.

Figure 1: Sugarcane

Figure 2: Sugarcane Bagasse

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Figure 3: Sugarcane bagasse ash

The integrated use of organic (digestate) and inorganic fertilizers improved nutrients uptake, growth, and fertilizer use efficiency, which might lead to increased biomass and grain yield. The delivery of nutrients (P, K, NH_4^+) in soluble form was found maximum in digestate and bagasse ash treatment applied @20t/ha, and when applied in combination with mineral fertilizer, the prompt uptake of nutrients by the plant is the reason for improved yield and nutrient contents.

4. Residual Effects on Soil Fertility and Economic Viability

4.1 Soil Fertility Enhancement

The application of sugarcane bagasse digestate and bagasse ash, particularly in combination with chemical fertilizers, has significant positive residual effects on soil fertility and physical properties.

The post-harvest analysis of soil samples after wheat harvesting indicated that application of bioenergy residues along with inorganic fertilizers significantly improved soil fertility and caused a decrease in bulk density and improved porosity, water holding capacity, and chemical parameters. The combined application of both chemical fertilizers and bioenergy residues resulted in maximum improvement in soil organic matter (1.27%), available phosphorus (10.1 mg/kg), and potassium (211 mg/kg).

Table 2: Chemical Composition of Sugarcane Bagasse Ash

Chemical compounds	Percentage by weight (%)
SiO_2	60-65
Al_2O_3	4-5
Fe_2O_3	6-8
CaO	10-12
MgO	2-3
SO_3	1-2
K_2O	2-4
LOI	4-6

The significant positive change in soil organic matter, P, and K contents is due to the timely supply of nutrients with integrated nutrient management during the study period. The total porosity of soil increased with bagasse ash with decreased bulk density, that affected ECe and pH with minute increased that led to improved yield and yield components of wheat. The decrease in bulk density and improvement in porosity positively affected water retention and moisture availability in the root zone, which ultimately results in root proliferation due to better availability of plant roots as bagasse ash along with digestate was involved in the supply of Ca, Mg, K, and micronutrients to soil. Incorporation of digestate as organic amendments to soil increased soil organic matter with a major component as organic carbon, which leads to improving soil physical properties due to reduced bulk density. The treatment effect on soil pH was found non-significant, consistent with findings that organic fertilizer supplementation does not significantly change soil pH due to the high buffering capacity of the soil.

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4.2 Economic Considerations and Cost-Benefit Analysis

The economic viability of sugarcane bagasse digestate application is a critical factor for adoption, particularly among smallholder farmers in developing regions. The economic analysis depicted that the maximum cost-benefit ratio was obtained with the combined application of 100% chemical fertilizer + digestate and bagasse ash (each @10t/ha), followed by the integration of 75% chemical + digestate and bagasse ash (each @10t/ha), while the minimum was in the case of sole application of either organic amendments and inorganic fertilizer application.

The treatments containing digestate and bagasse combination showed 4.2% and 3.6% more biomass yield over bagasse ash or digestate application alone, indicating the synergistic effects of combined application. The results showed non-significant effects on yield and nutrient contents with 100%, 75%, and 50% NPK along with bagasse ash and digestate @10t/ha each, therefore, it can be concluded that utilization of these wastes/residues can also reduce the use of mineral fertilizers with controlled environmental pollution.

The current approach will be more feasible and cost-effective for farmers who have bioenergy plants at their farm or have lands in the close vicinity of sugarcane industries. The economic benefits extend beyond immediate crop returns to include improved soil fertility, reduced input costs, and environmental benefits from waste recycling.

4.3 Challenges and Regulatory Considerations

Despite its agronomic benefits, the utilization of sugarcane bagasse digestate as fertilizer faces several challenges. These include nutrient overload, heavy metal contamination, pathogens, and the presence of emerging contaminants such as antibiotics and microplastics. The direct spread of digestate on croplands as fertilizer may exceed the receiver capacity of the croplands in many regions, leading to overspreading and serious environmental concerns including eutrophication by nutrients leaching and runoff, ground and surface water pollution.

Current regulations governing digestate utilization vary by country. In the EU, limits for digestate application are set at 170 kg N/ha/year, with higher allowances in the UK (up to 250 kg N/ha/year). Heavy metals and pathogens are satisfactorily regulated in the policies of major biogas-producing countries, but no specific limits exist for antibiotics and microplastics. Comprehensive and harmonized policies are essential to ensure the safe and effective utilization of digestate as fertilizer. Sustainability should be considered through a holistic, interdisciplinary approach, aligning with the principles of a circular bio-economy.

5. Conclusion

This review has examined the agronomic valuation of anaerobic digestate from sugarcane bagasse in field crop production, synthesizing evidence on its chemical composition, effects on crop growth and yield, impacts on soil fertility, and economic viability. Anaerobic digestate from sugarcane bagasse is rich in macro and micronutrients, with nitrogen (0.85%), phosphorus (0.58%), potassium (0.88%), and organic matter (20-30%), making it a valuable soil amendment. The integrated application of sugarcane bagasse digestate and ash with chemical fertilizers significantly enhances physiological parameters in wheat, with the 100% recommended dose of NPK + digestate and bagasse ash @20t/ha achieving the highest chlorophyll content (56.7 SPAD), photosynthetic rate (35.4 µmol CO_2 m^{-2} s^{-1}), and relative water content (68%), directly contributing to improved yield. Field experiments confirm that combined application produces 49% higher grain yield compared to control, 25% over bagasse ash alone, and 36% over digestate alone, while the 75% NPK + DA treatment yields comparable to 100% NPK, indicating potential for 25% reduction in mineral fertilizer use. Post-harvest soil analysis demonstrates significant improvements in soil organic matter (1.27%), available phosphorus (10.1 mg/kg), and potassium (211 mg/kg), with reduced bulk density and improved porosity contributing to better water retention and root proliferation. Economic analysis confirms that the maximum cost-benefit ratio is achieved with combined applications, particularly for farmers in proximity to sugarcane industries where these residues are readily available. The utilization of sugarcane bagasse digestate aligns with circular bio-economy principles, converting waste into a valuable resource while reducing dependence on synthetic fertilizers. However, challenges including regulatory constraints, heavy metal contamination, and pathogens require careful management. Future research should focus on optimizing application rates for specific crops and soil types,

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evaluating long-term effects on soil health, developing standardized quality control protocols, and exploring emerging technologies such as additive recycling to enhance digestate quality and economic viability.

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