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Digestate: The Coproduct of Biofuel Production in a Circular Economy, and New Results for Cassava Peeling Residue Digestate

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Abstract

Circular economic paradigm applies residue from one process as input material for another, fostering sustainable benefits for humanity. Anaerobic digestion (AD) is an attractive technology for biogas production in a circular economy. Digestate is the residual organic matter generated as coproduct of biogas. Because digestate is nutrient rich and largely stabilized, it has varied management options. Digestate is suitable for direct use as bio-fertilizer and is a good amendment material to improve soil physical properties. However, the quality, safety, and utility of digestate are dependent upon the characteristics of feedstock, digester process, pre- and post-digestion treatments. Digestates emanating from AD of animal manure, energy crops, food processing residues, and other feedstocks have been reported in published literature. On the other hand, there is dearth of reports on digestate emanating from AD process that utilized cassava peeling residue (CPR) as sole feedstock. This chapter presents relevant information on digestates including production, feedstock, quality and safety requirements, processing and treatment technologies, regulatory aspects, applications management options, cost implications, as well as challenges and opportunities. In addition, new results of nitrogen (N), phosphorus (P), and potassium (K) compositions of liquid fraction of CPR digestate are reported.

Keywords: anaerobic digestion, biofuel, biogas, cassava, cassava peeling residue, CPR, circular economy, digestate, management options, renewability, sustainability

1. Introduction

Linear economic model has been constructed on the premise of production, use, and disposal of used resources as wastes. However, there are serious limitations associated with the linear paradigm. These include nonrenewability, unsustainability, and environmental perturbations characterized by negative impacts on air, eco-diversity, soil, and water quality and safety. On the other hand, circular economic model maximizes the 3 (three)Rs of reduce, reuse, and recycle resources. In particular, circular economy applies residue from one process as input material for another process. This approach delivers sustainable benefits for humanity in terms of air, ecology, energy, environment, food, forest, housing,

sanitation, soil and water quality, safety and security; as well as improvements in animal and human health, economic, social, and industrial developments.

On the predicate of biorefinery platform, biotechnological upgrading of biomass via biological, chemical, physical or some combinations of these would create bio-based energy, chemicals, and other beneficial metabolites and products within the domain of circular economic model. In this context, anaerobic digestion (AD) is an attractive technology as it would utilize organic resources in waste streams to generate biogas and digestate. However, the quality of digestate is dependent upon variables such as characteristics of feedstock, digester process, and treatment options. Digestates emanating from AD of animal manure, energy crops, agricultural residues, organic fraction of municipal solid wastes (OFMSW), and other feedstocks have been reported in published literature [1–3]. On the other hand, there is dearth of reports on nutrient properties of digestate generated from AD processes that utilized cassava peeling residue (CPR) as sole feedstock. This chapter presents relevant information on digestates in general, and new results of a technical experiment conducted to secure overview assessment of nitrogen (N), phosphorus (P) and potassium (K) compositions of liquid fraction of CPR digestate.

2. Anaerobic digestion (AD)

AD is a biochemical process that decomposes organic matter to generate flammable biogas and residual digestate. The process is achieved with the assistance of a suite of microorganisms in a near oxygen free environment. Biogas is basically composed of methane and carbon dioxide in the respective range of 40–75% and 25–40%. Other constituents are hydrogen, nitrogen, oxygen, hydrogen sulfide and other trace components ranging from 0.1 to 3% [4]. Successful AD operations are carried out within digester or reactor systems designed to supply nutrients required for metabolic activities of the microbes, as well as prevent conditions or elements that may become stressors or present inhibitory effects. AD digester operations and systems may be classified according to the following [5–7]:

- Optimal temperature regimen: psychrophilic (<20°C), mesophilic (30–38°C), and thermophilic (48–57°C);
- Total solid (TS) content: wet digestion (TS < 12%), semi-dry digestion (TS 12–20%), and dry digestion (TS > 20%);
- Feeding mode: batch, fed-batch, semi-continuous, and continuous;
- Process stage or step: single-stage (where all AD processes—hydrolysis, fermentation, acetogenesis, and methanogenesis are executed in one reactor), and multi-stage (where the processes are separated into two or more reactors);
- Fluid-dynamic mode: plug flow, completely stirred or mixed, and hybrid; as well as
- Digester design: anaerobic baffled reactor (ABR), anaerobic filter (AF), anaerobic dynamic membrane reactor (AnDMBR), anaerobic mixed biofilm reactor (AMBR), completely or continuous stirred-tank reactor (CSTR), covered lagoon, expanded granular sludge bed (EGSB), fixed dome, flexible balloon or tube, floating cover or drum, sequential batch anaerobic composting

(SEBAC), stirred anaerobic sequencing batch reactor (SASBR), up-flow anaerobic sludge bed (UASB) or up-flow multistage anaerobic reactor (UMAR).

Today there are millions of anaerobic digesters (domestic, medium, and large-scale versions) operating in the world and generating tremendous amount of biogas. In 2016 for instance, about 60.8 billion m³ of biogas (1.31 EJ) was generated worldwide; most of it, 84%; in Europe (54%) and Asia (30%) [8]. The technical status of AD plants varies widely. Advanced state-of-the-art systems are prevalent in Europe and more low-tech installations in Africa, Asia and South America. However, irrespective of the level of sophistication, the two fundamental products of AD are biogas and digestate.

3. Digestate

Digestate is the residual organic matter generated as coproduct of biogas production. Digestate is suitable for direct use as bio-fertilizer, as raw material for production of bio-fertilizers, and as amendment material to improve soil physical

S/N	Feedstock	S/N	Feedstock
1	Agro-industrial residues	61	<i>Miscanthus sacchariflorus</i> (Maxim.) Hack silage
2	Animal manure	62	<i>Miscanthus sinensis giganteus</i> Silage
3	Barley straw	63	Molasses
4	Biodegradable plastics	64	Mozzarella Cheese Whey
5	Biodiesel wastewaters	65	Municipal solid waste
6	Biowastes	66	Municipal waste water
7	Blood industry residues	67	Oat silage
8	Buffalo farming wastewater	68	Olive oil mill wastewater
9	Buffalo manure	69	Olive Pomace, olive waste
10	Cacao	70	Orange peel waste
11	Cardboard	71	Organic fraction of municipal solid waste
12	Cattle/cow: manure/slurry	72	Paper
13	Cattle (beef) urine	73	Paper sludge
14	Cereal bran	74	Peach-juice pulp
15	Cereal-WPS	75	Peeled Cassava wash water
16	Cereals	76	Pharmaceutical industry sludge
17	Cheese Whey	77	<i>Phleum pratense</i> L. silage
18	Chicken manure	78	Pig urine
19	<i>Chroococcus</i> sp. (algal biomass)	79	Piggery wastewater
20	Coconut chips	80	Pig/swine effluent; manure; slurry
21	Coffee grounds	81	Plum stones
22	Corn	82	Potato chips production residues
23	Corn cob mix	83	Potato waste
24	Cornmeal	84	Potatoes

S/N	Feedstock	S/N	Feedstock
25	Corn residue	85	Poultry litter/manure/waste
26	Cover crops	86	Primary sludge
27	Crushed cassava juice	87	Pumpkin waste
28	Dairy manure	88	Rabbit manure
29	Distiller's waste	89	Rape residue
30	Dried blood of slaughterhouse waste	90	Restaurant food waste
31	Duck slaughterhouse sludge	91	Rice residues
32	Edible oil	92	Rye
33	Energetic crops	93	Sewage sludge
34	Energy maize	94	<i>Sida Hermaphrodita</i> Rusby silage
35	Fennel waste	95	Slaughterhouse waste
36	Fish by-product	96	Sludge from Slaughterhouse wastewater treatment plant
37	Food industry residues	97	Solid farmyard manure
38	Food waste	98	Sorghum silage
39	Fruits and distillery by-products	99	Source-separated organic household waste
40	Fruit Marc	100	Source-separated municipal solid waste
41	Garden wastes	101	Starch processing wastewater
42	Glycerin	102	Straws (cereal, pea)
43	Grape seeds	103	Sugar beet pulp
44	Grass (clover, Sudan); grass silage	104	Sugar sorghum (<i>S. saccharatum</i> L. Moench.) silage
45	Green waste	105	Sunflower residue, sunflower silage
46	Hemp	106	Tea leaves
47	Household kitchen waste	107	<i>Tetraselmis</i> sp. (algal biomass)
48	Household waste	108	Thin stillage (bioethanol by-product)
49	Human excreta	109	Triticale
50	Human urine	110	Triticale silage
51	Industrial and commercial wastes	111	Turkey manure
52	Jute Caddis	112	Vegetable waste
53	Kitchen waste	113	Vinasse
54	Landscape waste	114	Waste-activated sludge
55	Ley silage	115	Waste potato starch
56	Livestock waste	116	Wastewater
57	Maize stover	117	Wastewater sludge
58	<i>Medicago sativa</i> L. silage	118	Wheat
59	Milk (serum, whey)	119	Yeast production wastewater
60	Millet	120	<i>Zea mays</i> L. (corn, maize) silage

Source: Assembled from scientific literatures in the public domain, most of them cited in this present work.

Table 1.
Feedstocks used in digestate production and studies.

properties such as bulk density, hydraulic conductivity, and moisture retention capacity. Digestate is also attributed with improved sustainability and veterinary safety; reductions in odors, weed seeds, plant pathogens, food chain contamination risks and greenhouse gas emissions. The three basic types of digestate are: whole digestate, liquor (liquid fraction) digestate, and fiber (solid fraction) digestate. Whole digestate is the digestate as obtained leaving the digester at the end of AD process. It contains less than 15% dry matter. This whole digestate could be separated into liquid and solid fractions using appropriate technology and method. The liquid fraction constitutes up to 90% of the digestate by volume, contains 2–6% dry matter, particles <1.2 mm in size, and most of the soluble nitrogen and potassium, while the solid fraction retains most of the digestate phosphorus, and contains dry matter content > 15% [9, 10].

However, the quality, safety, and utility of digestate are dependent upon variables such as feedstock characteristics (pH, chemical composition, carbon-nitrogen ratio (C/N), particle size), digester process (temperature, inoculum, microbial community, hydraulic retention time (HRT)), as well as pre- and post-digestion treatments. Feedstock should possess balanced nutrients, including optimal C/N to satisfy physiological needs of the microorganisms. High or low C/N would disrupt biogasification and lead to reduced biogas output due to low buffer capacity (high C/N) or ammonia inhibition (low C/N). Generally, for biogas production, C/N of 20–30 is considered optimal. For food wastes, C/N of around 15 could be appropriate. Digestates within C/N range of 15–20 are regarded as safe for application to agricultural land without further treatment [11]. When sole feedstock lacks sufficient nutrients for adequate C/N, feedstocks with complimentary nutrients profile are co-digested to offset the limitations. **Table 1** highlights some feedstocks that have been used in AD operations and digestate studies.

4. Regulations, quality, and safety requirements

Perhaps the most important variable affecting the quality and safety of digestate is feedstock. Starting with a high-quality feedstock would virtually guarantee a safe and quality digestate. Source separation can be used to achieve high purity feedstock. The biological, chemical, and physical properties of digestate may be governed by regulations and quality assurance systems. The European Union (EU) and many European national governments have hygienic, quality and safety standards for digestate certification that consider feedstock source and other aspects such as digester process, treatment options, handling and storage requirements. The essential quality and safety requirements for digestate destined as biofertilizer must be achieved regardless of the initial raw material. Essential quality and safety parameters include nutrients content, dry matter and organic dry matter contents, homogeneity, pH, purity (free of inorganic impurities such as glass, metal, plastic, and stones), sanitized and safe for soil organisms and the environment with regards to biological status (pathogenic organisms) and chemical status (organic and inorganic contaminants/pollutants). Furthermore, the digestate should be free of odor, phytotoxicity and weed seeds; and be satisfactorily stabilized.

Quality assurance systems for digestate certification may comprise monitoring to ensure control; standardization to ensure repeatable performance; characterization label to identify product fitness; declaration to describe product constituents; application guidelines to ensure safe and proper use; and documentation to prove that the product received required treatments following approved protocols. **Table 2** presents established criteria and characteristics for the production and use of quality and safe digestates. In the EU, conformity with these criteria is enough to

Criteria	Process/parameter	Requirements
Hygiene	Pasteurization at 70°C	1 h
	Sterilization at 133°C	20 min
	Weed seeds and sprouting plant parts	≤2/L
	Odor	Free of annoying odors
Pathogens	<i>E. coli</i>	≤1000 CFU/g fresh matter
	<i>Salmonella</i> spp.	Absent in 25 g fresh matter
Heavy metals	Cadmium (Cd)	0.8–20 mg/kg DM
	Chromium (Cr)	75–1000 mg/kg DM
	Copper (Cu)	75–1000 mg/kg DM
	Lead (Pb)	80–900 mg/kg DM
	Mercury (Hg)	0.6–16 mg/kg DM
	Nickel (Ni)	30–300 mg/kg DM
	Zinc (Zn)	300–4000 mg/kg DM
Organic	Polycyclic aromatic hydrocarbons	3–6 mg/kg DM
Pollutants	Dioxins and furans	20 ng TE/kg
	Chlorinated pesticides	0.5 mg/kg Product
	Polychlorinated biphenyls	0.2 mg/kg DM
	Absorbable organic halogens	500 mg/kg DM
	Linear alkylbenzene sulphonates	1300 mg/kg DM
	Nonylphenol and nonylphenoethoxylates	10 mg/kg DM
	DEPH: Di (2-ethylhexyl) phthalate	50 mg/kg DM
Inorganic	Non-stone impurities >2 mm (glass, metal, plastic, etc.)	0.5% m/m dry matter
Pollutants	Stones > 5 mm	8% m/m dry matter
Stability	Volatile fatty acids	0.43 g COD/g VS
	Residual biogas potential	0.25 l/g VS
	Respiration rate	16 mg CO ₂ g VS ⁻¹ day ⁻¹
Declarations	Name of producer, type of product (whole, liquid, solid), mass of product, total nitrogen, ammonium nitrogen, total phosphorus, total potassium, soluble chloride, soluble sodium, dry matter, volatile solids, pH, bulk density, etc.	Relevant units where applicable (e.g., kg; kg/m ³ ; mg/(kg DM); mg/L; %;)
Additives and chemicals	Lime, iron chloride, iron oxide, bentonite, diatomaceous earth	
Feedstock sources	Agriculture (e.g., manure, harvesting by-products, silage, energy crops); animal by-products (e.g., manure, stomach intestine, raw milk); food industry (residues from food industry that contain food grade additives); food related shops (e.g., potatoes, dairy waste, bread, meat remnants, flowers, plants); forrest (e.g., bark, wood chips, sludge from the cellulosic industry); parks, gardens (e.g., leaves, grass); greenhouses (e.g., tops, peat products); households, kitchens, restaurants (e.g., fruit and vegetables residues, food, coffee and tea remainders, egg shells); etc.	

Source: [9, 12–16].

Table 2.
Quality and safety validation criteria for digestates.

ensure that digestate complies with European “End of Waste” criteria; and can be used without further waste management controls.

5. Treatment technology options

In the context of AD and digestate, we may distinguish between pre- and post-treatment processes. A pretreatment process refers to a processing operation applied upstream, before the digestate emerges from the digester. This could range from size reduction or thermochemical treatment of feedstock substrate; to process management (such as pH, temperature, and retention time control). On the other hand, a posttreatment process is that processing operation applied downstream of digestate harvest. This may also involve size reduction, other unit operations; composting, and end-product requirements that ensure the digestate sanitation. Post treatment may generate nutrient concentrates, liquid and solid fraction digestates conditioned to standardized biofertilizers, and final liquid effluent that could be discharged into a stream or sewage system. Benefits of posttreatment include enhanced marketability, reductions in handling, storage and transportation costs/requirements, and compliance with environmental regulations.

Depending on the starting feedstock and desired end product form of the digestate, similar technologies could be used for pre and post treatment processing. Applied technologies and methods may be classified as biological, chemical, or physical. The methods could also be used in combination. Biological treatment could be accomplished with the use of microorganisms and catalysts; chemical treatment with acids, alkalis and oxidants; and physical treatment by mechanical and thermal means. Physicochemical treatment combines physical and chemical techniques. Ammonia fiber explosion (AFEX), and supercritical CO₂ explosion are examples. The major classifications of treatment options and associated technologies are presented in **Table 3**.

Category/ method	Technology option	Example means/aids
Biological	Bacteria	<i>Clostridium</i> sp. strains LDC-8-c12, 5-8, CO6-72; <i>Rhodobacter sphaeroides</i> KD131; Thermosaccharolyticum strain M18
	Composting	Green waste, vine shoot pruning, wood chips
	Enzyme	<i>Carbohydrase</i> , <i>laccase</i> , <i>lignin peroxidase</i>
	Fungi	<i>Ceriporia lacerata</i> , <i>Ceriporiopsis subvermispota</i> (ATCC 96608), <i>Pleurotus ostreatus</i>
Chemical	Acids, organosolvs	Inorganic acids (hydrochloric, nitric, phosphoric, sulfuric); organic acids (fumaric, maleic). May be used in percolation, plug flow, shrinking-bed, batch, and countercurrent modes
	Alkalis	Ammonia, lime
	Ammonia recovery	Ion exchange; scrubbing, stripping, precipitation (struvite)
	Ionic liquids	1-Butyl-3-methylimidazolium hydrogen sulfate [bmim]HSO ₄ , 1-ethyl-3-methylimidazolium acetate (EMIM-OAc), 1-ethyl-3-methylimidazolium diethyl phosphate, 3-allyl-1-methyl-1H-imidazol3-ium chloride [Amim][Cl]
	Oxidants	Hydrogen peroxide, ozone

Category/ method	Technology option	Example means/aids
Physical	Mechanical	
	<i>Dewatering:</i>	Centrifuges, gravity tables, presses (belt, filter, rotary, screw)
	<i>Disintegration/maceration (chipping, grinding, milling, shredding):</i>	Ball mill, colloid mill, hammer mill, two-roll mill
	<i>Extrusion:</i>	Band, single screw, twin screw
	<i>Homogenization:</i>	High pressure homogenizers
	<i>Lysis:</i>	Lysis-centrifuges
	<i>Membrane separation:</i>	Electrodialysis, microfiltration, nanofiltration, pervaporation, reverse osmosis, ultrafiltration
	<i>Sonication:</i>	Ultrasound/sonoreactors (bath, flat plate, probe, tube)
	Irradiation	Electron beam, gamma ray
Physicochemical	Thermal	Drying/torrefaction, electric heating, evaporation, hot oil, hot water, hydrothermal, microwave, steam
	Expansion/explosion	Ammonia fiber expansion/explosion (AFEX), steam explosion, supercritical carbon dioxide (SC-CO ₂) explosion

Source: [10, 15, 17–36].

Table 3.

Major categories of treatment and technology options for AD and digestate processing.

6. Applications management options for digestate

In the service of circular economy, there are many applications management options for digestate. These may include algae cultivation, energy production, bio-adsorbent production, building materials production, nutrients recovery/production, soil creation and other value-added commodities. Perhaps the two most widely recognized utilities of digestate are as land application for soil amendment and as biofertilizer.

6.1 Biofertilizer and soil amendment

Technological aids used in modern agriculture such as inorganic fertilizers and antibiotics have negative impacts on soil, water, and air quality and safety, and therefore pose health risks to humans and the ecosystem. Inorganic fertilizers for instance have caused environmental and soil quality degradation, eutrophication and heavy metals pollution. Similarly, field-spreading agricultural land with raw/untreated manures derived from medicated livestock contributes to dissemination of veterinary antibiotic residues and antibiotic-resistant pathogens. Lincomycin, monensin, and sulfamethazine antibiotics were reported to affect soil microbial community composition and respiration, denitrification and nitrogen transformations [37]. Applications of digestate for biofertilizer and soil amendment purposes could ameliorate some of these adverse effects.

Amendment propensity relates to capability to maintain soil fertility and humus balance. Dairy slurry digestate was found richer in humic substances than raw dairy

slurry [38]. Researchers concluded that digestate enhanced soil biological stability, microbial biomass and enzymatic activities [39].

On the other hand, fertilizer properties relate to provision of nutrients necessary for good crop performance. Leaves of alfalfa plant fertilized with digestate had higher contents of N, P, and K in comparison to alfalfa fertilized with mineral fertilizers [40]. Digestate also produced higher yields of dent corn than the application of chemical fertilizers [38]; higher yield of potato (*Solanum tuberosum*) over the application of compost [41]; and 30% increase in yield over farm yard manure [42].

6.2 Nutrients recovery

Digestate is applied in recovery of nutrients, production of fertilizers and volatile fatty acids (VFAs). Livestock manure contains about 49 g N/kg TS and 6 g P/kg TS; energy crops, 17 g N/kg TS and 2.5 g P/kg TS; and agro-wastes, 27 g N/kg TS and 3 g P/kg TS [43]. Much of these nutrients remain in digestate after AD operation. For example, total N, P, and K values for digestates obtained from wet AD of agricultural wastes were reported respectively in the ranges 44–120, 8–42, and 28–95 g/kg DM [44]. These nutrients could be recovered/harvested with the technologies outlined in **Table 3**.

VFAs are important input organic acids used extensively in the bioenergy, food, chemical, cosmetic, pharmaceutical, textile, and other industries. Acetic acid (E 260), propionic acid (E 280) and butyric acid are examples; and are GRAS (generally regarded as safe) rated by the FDA. Acetic acid is used to defend against *Campylobacter*, *Escherichia coli*, *Listeria*, *Salmonella*, and other pathogens in beef, chicken, pork, turkey, carcasses, skin and hides [45]. Butyric acid is used in the textile industry to enhance heat and sunlight resistance of fibers. In the food industry, it is used as additive for flavor formulation and modification [46]. Similarly, propionic acid (E 280) is used as antibacterial and antifungal agent to decontaminate packaging films and coatings, and to protect meat and meat products such as sausages, bologna and ham. VFAs have been harvested from digestates generated from short-term dry AD of swine manure, generated from AD of food waste, and used in recovery of biological nitrogen and phosphorus from sewage sludge [47–49].

6.3 Energy production

Digestate can be deployed for energy generation. Recirculating digestate into the digester maximizes biogas production, at the same time minimizing methane emissions during digestate storage, transport, and use. Digestate was pyrolyzed (via the use of Pyroformer, quartz rotary kiln reactor, and thermo-catalytic reforming reactor) to produce biofuels: pyrolysis oil (biooil) and pyrolysis gas (syngas). The biooil generated by thermo-catalytic reforming process at 750°C had a higher heating value of 33.9 MJ/kg, and a total acid number of 4.9 mgKOH/g [50].

Algae have widespread applications and potentials in: biofuels, cosmetics, biofertilizer, infant formulas, nutritional supplements, livestock feeds, chemical and allied industries, and biodegradable packaging. Perhaps more importantly, digestate could be used for the cultivation and production of microalgae. In the context of biorefinery platform and circular economy, various compounds produced by microalgae and their applications have been reported [51, 52].

6.4 Other applications

Digestates have other utilities and management options. These include applications in aquaculture, gardening and horticulture, and the production of building materials and biochar.

6.4.1 Biochar

Biochar (charcoal) is the byproduct of thermal pyrolysis of carbonaceous biomass; and has carbon sink properties. Dairy waste and whole sugar beet digestate biochar were effective in eliminating heavy metals (Pb^{2+} , Cu^{2+} , Ni^{2+} , and Cd^{2+}) from aqueous solutions [53].

6.4.2 Gardening and horticulture

Due to its organic origin and physicochemical characteristics, digestate is useful in gardening and horticulture. It could be applied in soil creation or remediation, and has found applications in green houses, plant nurseries, and home gardening [54].

6.4.3 Building materials

A 50% substitution of wood with cattle manure digestate produced particleboard panels that met ANSI performance requirements [55]. USDA reported that medium-density fiberboard and wood/plastic composite engineered materials could be created using digestate solids without compromising mechanical or aesthetic values [56].

6.4.4 Aquaculture

Digestate is better than raw manure in fertilizing fish ponds. Firstly, digestate is hygienic because most of the bacteria, parasites and their eggs are destroyed in the AD process. Thus, pond sanitation is improved; minimizing fish diseases and the cost of veterinary services. Secondly, the digestate is largely stabilized and therefore does not consume and compete with fish for dissolved oxygen. Tilapia, Silver carp, Bighead carp, Silver barb and Mrigal fish species raised in pond fertilized with digestate matured faster and achieved higher net weight gain than counterparts raised in pond fertilized with chemical fertilizer or raw manure. By comparison, while chemical fertilizer increased net yield over raw manure by 27%, digestate increased net yield by 55% [57].

6.4.5 Bio-adsorbents and bedding

Digestates have been applied as bio-adsorbents to scavenge heavy metals from contaminated soils and water [58], and as chicken litter [54], and other livestock bedding. [56, 59].

7. Cost implications

The big picture cost elements relevant to AD systems include land acquisition, site preparation/development, plant and machinery (including digester/reactor, pre and post treatment technologies), personnel, feedstock, environmental impact,

other operating costs (electricity, logistics, regulations), and revenue from products (biogas and digestate). In the case of digestate, feedstock, treatment processes, and the logistics of storage, transport, handling and field application bear crucial concerns. Cost-effective digestate production process is presaged by efficient feedstock collection and sorting operations. A cost benefit analysis of municipal solid waste management system in Yangon, Myanmar, identified weak organizational structure and ineffective collection methods in the existing system that operated with just 32% waste collection efficiency. An alternative system with increased waste collection efficiency was then proposed. The new system required labor and vehicular productivity; using vehicles with container-hoist handling mechanism. The new system reduced operating and other costs associated with the old system by up to 42% [60]. It is noteworthy that consumer and public environmental behavior and cooperation on waste management could be modified by pecuniary and nonpecuniary information. In Surabaya city, Indonesia, researchers found that in the reference case in which the no information treatment was applied, mean WTP (willingness to pay) for marginal improvements in a waste collection and disposal program was estimated to be US\$ 14.65. The researchers reported that pecuniary information increased WTP by 20.5%, whereas non-pecuniary information had a negative but statistically insignificant effect on WTP [61].

A situation where 50% of whole unprocessed digestate was applied on agricultural land near the generating biogas plant and the other 50% transported to a location 20 km away was studied. Cost for digestate utilization near the biogas plant was € 3.34 (US\$ 3.73)/t, and that at a location 20 km away was € 5.47 (US\$ 6.10)/t [62]. This study highlights the impact that location or site of digestate utilization could have on cost. Such distance related cost also applies to feedstock substrate. Generally, the farther the distance, the higher the cost.

Researchers performed specific cost analysis for six scenarios that involved direct land application of digestate as reference, and various treatment technology options that included screw press and decanter centrifuge separation, belt drying, evaporation concentration, purification by ultrafiltration and reverse osmosis, and nutrients recovery by ammonia stripping and precipitation. Result indicated that net specific costs ranged from € 1.94 (US\$ 2.16)/m³ of digestate for the reference scenario, to € 5.45 (US\$ 6.08)/m³ for stripping, to € 6.80 (US\$ 7.58)/m³ for belt dryer [62]. Similarly, the costs of AD were found to vary up to € 109 (US\$ 122)/t of digestate from € 35 (US\$ 39)/t for basic storage of digestate for aerobic conditioning, to € 70 (US\$ 78)/t for digestate ready for direct land application, to € 79 (US\$ 88)/t for on farm co-digestion [63].

Case studies were conducted for separation systems in three regions (Aachen, Borken, and Siegen) of Germany. The researchers determined that investment and variable costs were respectively € 23,000 (US\$ 25,536) and € 0.47 (US\$ 0.52)/m³ for screw press; € 27,000 (US\$ 29,977) and € 0.48 (US\$ 0.53)/m³ for screening drum press; and € 163,000 (US\$ 180,970) and € 1.46 (US\$ 1.62)/m³ for decanter centrifuge. Further analysis revealed the unit cost of digestate disposal for screening drum press varied from € 4.1 (US\$ 4.6)/m³ in Aachen to € 4.8 (US\$ 5.3)/m³ in Borken, and Siegen [64].

The following were reported about AD in the UK. Least cost post treatment technology for digestate derived from a 10% solids content food waste was biological oxidation at €13.18 (US\$ 16.97)/t of feedstock. At 20% solids content, least cost option was direct application of whole digestate to agricultural land at €8.76 (US\$ 11.28)/t. The cost of treating 4000 t of slurry with a mechanical screen separator was €0.44 (US\$ 0.57)/t per year, and treatment with decanting centrifuge cost €2.21 (US\$ 2.85)/t per year. Furthermore, about €3.5M (US\$ 4.5 M) would be required to construct a 1 (one) MWe AD plant utilizing farm wastes as feedstock [65–67].

In the continent of Africa, cost of establishing a 4 m³ anaerobic digester was found to range from US\$ 555 in Uganda to US\$ 698 in Cameroun to US\$ 979 in Rwanda [68]; while that of founding a family size floating drum plant was estimated at US\$ 1667 [69].

Techno-economic analyses were performed for post treatment technologies used to recover nutrients from the digestates of five full scale farm AD systems. Results showed membrane technology had specific cost of € 6.97 (US\$ 7.72)/m³ of treated digestate. Drying was estimated at € 5.81 (US\$ 6.44)/m³, while stripping operated at € 5.44 (US\$ 6.03)/m³ [70]. In addition, the process economics of membrane-based nutrients extraction and fractionation from dairy manure digestate indicated cost of solid-liquid separation unit to be US\$ 11,000; the microfiltration extraction unit cost US\$ 30,000; the nanofiltration fractionation unit was priced at US\$ 60,000; and the daily cost of operation (chemicals, energy and water) was approximately US\$ 24 [71].

Finally, digestates are used as quilt for cattle bedding and poultry litter due to significant cost offsets to livestock farms. The cost of solid digestate as animal bedding (US\$ 55 per dry ton) is cheaper than the cost of alternative wood-based replacement materials such as wood chips at US\$ 65 per dry ton or sawdust and shavings at US\$ 124 to US\$ 248 per tonne [55, 59].

8. Challenges and opportunities

Digestates have good fertilizer qualities: nutrients, safety and other properties required for soil amendment and plants production. However, relative to mineral fertilizers, digestates are not well known in many countries. Therefore, their potential as mineral fertilizer alternative/substitute is limited. Perhaps, standardized quality assurance and control protocols, regulations, certifications, legal and other institutional management systems organized internationally could help demonstrate digestates' benefits, quality and safety, and thereby engender confidence in their utilization as sustainable fertilizer and soil amendment products. Reconciling and bringing such issues and their benefits to existence present challenges and opportunities. Presented in **Table 4** are some of these challenges and opportunities of the waste, AD and digestate system.

Issues	Challenges and opportunities
8.1. Concept of waste	<p>Challenge: the conventional or customary status of looking at waste as a problem presents significant challenge.</p> <p>Opportunity: seeing waste as potential resource would help change perception and attitude, possibly stimulating salient management options. Opportunities may emerge in the areas of prevention, recovery, collection, sorting, reducing, reusing, and recycling. For developing countries these have implications for environmental hygiene and sanitation.</p>
8.2. Biowaste	<p>Challenge: because biodegradable waste could be a source of heavy metals and polluting organic compounds, it presents challenges to life generally, and to the environment.</p> <p>Opportunity: these challenges create opportunities to develop management options (e.g., biological treatments) to protect life, environment, and to benefit agriculture and ecosystem. Biowaste is reported to have potential to tackle climate change in the areas of nitrous oxide (NO₂) emissions mitigation, and sequestration capacity of agricultural soils [72].</p>

Issues	Challenges and opportunities
8.3. E-waste	<p>Challenge: problems and dangers of e-waste, heavy industry products and components; including electrical and electronic equipment, waste batteries, engine blocks, paint, etc.</p> <p>Opportunity: guidance/support for the informal (non or loosely regulated) establishments, to call attention to dangers and health risks that may be associated with used or discarded electronic devices/items (acids, other chemicals, radioactive materials, etc.).</p>
8.4. Mineral waste	<p>Challenge: mining of solid minerals do present health and environmental challenges.</p> <p>Opportunity: chances to implement safeguards for hazardous minerals and to divert safe wastes to beneficial applications. Examples are uses as substitute for backfill material in open pit mining, landfill, or as grit in construction materials. Production of concrete and brick for structural work (bridges, dams, launch pads, highways) are possibilities.</p>
8.5. Source of feedstock	<p>Challenge: the source of digestate feedstock and its treatment could present barriers. PAS 110 in the UK does not approve certification for digestate generated from mechanically biologically treated waste. Such digestates require proof of biodegradability test to be considered suitable for recycling; like land spreading. There is also the issue of digestate originating from co-digestion of industrial waste and household waste. In the Netherlands, the desire in AD electricity regime to maximize biogas production by mixing manure with other organic material conflicts with AD biofertilizer rules for spreading digestate from co-digested manure on farm land.</p> <p>Opportunity: some of these challenges are consumer-induced barriers and lack quantitative elements. Opportunities might lie in the sociocultural realm, such as modifying social and cultural attitudes and behaviors towards waste and its inherent heterogeneity.</p>
8.6. Unrecovered organic matter	<p>Challenge: AD is more adapted to easily putrescible carbohydrates (starch, sugar). Recalcitrant lignocellulosic components (lignin, etc.) remain undigested. Efficiency of organic matter conversion was quite low as >97% of lignin in maize stover was found undigested [73]. AD could thus lead to unrecovered organic matter still present in digestate</p> <p>Opportunity: prospects for advanced and innovative pretreatment technologies to fractionate, recover, purify and convert lignin or other recalcitrant organics to more digestible biopolymers. Alkaline treatment, gamma irradiation, membrane technologies, organosolv, steam explosion, wet oxidation, etc. may come to the rescue (Table 3).</p>
8.7. Informal and low status	<p>Challenge: AD and digestate are perceived to be in domain of informal waste management system and service; and therefore, relegated as only appropriate for the rural populace.</p> <p>Opportunity: integration of formal and informal systems. Training to abate misconceptions, lack of awareness, and raise public profile of digestate. These may purge image of biogas and digestate as products that are derived from wastes, and hence belong to poor/rural settings.</p>
8.8. Legal barriers	<p>Challenge: lack of binding global (and for developing countries, own country) coherent rules, laws, directives, regulations and policy frameworks.</p> <p>Opportunity: the formulation of these guidelines and laws on waste governance system. Implementing appropriate technologies and business models for waste management.</p>

Issues	Challenges and opportunities
8.9. Data and waste reporting system	<p>Challenge: lack of reliable data on waste management systems, design features, standard operating procedures (SOPs), etc. could limit exchange of ideas and retard progress.</p> <p>Opportunity: waste management value chain information is vital. Quantity, type, economic sector, source, and composition data could guide prioritization of strategies and enable trends forecast that deliver better outcomes. Global exchange of briefs would catalyze spread of best practices.</p>
8.10. Standardization	<p>Challenge: although digestate products have similar characteristics as commercial chemical fertilizers, they are not classified in any way, are poorly developed in most countries, and there is no overall guidance [20, 62, 70]. These barriers restrict utilization and trade.</p> <p>Opportunity: these challenges create opportunities to establish frameworks that enable digestate utilization through standardization, fair comparison, commerce development, and international trade.</p>
8.11. Marketing	<p>Challenge: regional nutrient availability, agricultural structure, season, feedstock and degree of upgrading have been reported to challenge and impact digestate prices and marketing [54].</p> <p>Opportunity: upgraded products offer increased marketability due to their denser nutrients. Marketing to nutrient deficient regions, non-agricultural sectors and purposes represent prospects. Manufacturers of organic soils, particle- and fiber-boards, landscapers, and private customers all represent credible market outlets.</p>
8.12. Cost barrier	<p>Challenge: initial investment fund is a major issue. Cost of establishing a 4 m³ AD digester in the continent of Africa ranges from US\$ 555 to US\$ 979 [68]; and the price for a family size floating drum reactor was reported at US\$ 1667 [69]. In Sri Lanka, a family unit digester generating 6–10 m³ of biogas per day cost Rs. 17,000 (US\$ 5459); and described as difficult proposition for low-income families [74]. In the UK, a 1 MWe AD plant utilizing farm wastes as feedstock cost about €3.5M (US\$ 4.5 M) to construct [67]. Also, costs associated with animal breeding and maintenance (veterinary care, feed, water, etc.) escalate operating costs, and constrain availability of manure for feedstock.</p> <p>Opportunity: easing cost barriers would require support with appropriate and necessary interventions (policies, credit facilities, subsidy schemes, preventive maintenance that promote solutions, prolong facilities productive lifespan, and minimize operating costs). Furthermore, transparency on proposals and bidding for new plants and projects could build confidence in the process.</p>
8.13. Urban and rural dichotomy	<p>Challenge: differences between metropolitan, urban, sub-urban, and rural areas can compromise AD projects. Segregation by infrastructure and income for example could affect waste collection and limit access to feedstock.</p> <p>Opportunity: prospects for rural development with public utilities, services, and infrastructure (roads, power, water, etc.) These would facilitate logistics for waste collection, AD processes, and digestate handling/evacuation.</p>
8.14. Contamination of agricultural land	<p>Challenge: most of the digestate produced in AD is used for soil amendment and as biofertilizer. There are risks of spreading animal pathogens, heavy metals, and other pollutants on soils due to the presence of these hazards in animal by-products used in AD. Sulfadiazine and oxytetracycline are antibiotics found in</p>

Issues	Challenges and opportunities
	<p>manure of medicated animals that affect soil quality. Twenty five percent of 70 digestate and compost samples assessed in Switzerland contained polycyclic aromatic hydrocarbons (PAHs) concentrations beyond the regulated threshold value of 4000 µg/kg_{dw} [75].</p> <p>Opportunity: digestate is a sustainable fertilizer and soil improver; thus, necessary to assure its safety. The potential to contaminate soils with pollutants from digestate application beacons vigilance and chances to develop technical and monitoring strategies that sequester and purge the digestates of polluting hazards before their use.</p>
8.15. Air pollution	<p>Challenge: digestate has potential to emit substances and gasses that contaminate the air and influence global warming [11]. Challenges also exist due to lack of practical tools to monitor primary air pollutants [76].</p> <p>Opportunity: advanced methods of digestate management and reutilization to minimize emissions of air pollutants (ammonia: NH₃, nitrous oxide: NO₂) and greenhouse gases (methane: CH₄, nitrogen dioxide: N₂O). Strategies may include processing (composting, curing, dewatering); alternative applications (in construction, aquaculture, regeneration activities); and storage. Development of software tools that enable quantitative monitoring of emissions from digestate soil applications on a routine basis is another prospect area.</p>
8.16. Bad odors	<p>Challenge: compared to raw manure slurry, digestate has fewer bad odors. However, this may not be true when compared to chemical fertilizer. There have been complaints of nuisance odors associated with land-spreading of digestate [77], and at landfills and composting plants [78].</p> <p>Opportunity: this problem could be due to spreading practice and/or the spreading of unstable digestates. Application of good timing and spreading techniques (trailing-shoes, injection), and use of stabilized digestates (sufficient HRT, aerobic composting) would minimize odor issues.</p>
8.17. Bad legacies	<p>Challenge: there are challenges associated with bad reputation of AD systems and biogas plants around the world. A study in 2006 found that 60% of 600–700 domestic biogas plants in Ethiopia was not functioning [79]. During the 7 years period from 2009, more than 3600 biogas plants were installed in the Tigray region of Ethiopia; and a 2017 study reported that 58.1% of the installations was not operational [80]. The 21 biogas plants installed by Pakistan council for appropriate technology (PCAT) in the 1970s were reported to have failed to perform [81]. In 1986, a survey of the status of 25 biogas plants in Kenya found 36% to be alive, functional and maintained. Another 36% was described as dead, not functional, and not maintained. Unfinished projects accounted for 8%; while remaining plants were reported in disrepair, with varied patterns of being alive, dead, not functional, and not maintained [82]. The regional bioenergy program of the Latin American energy organization (OLADE), catalogs biogas technology projects in Latin American countries. Experience began in 1953 and by 1986 at least 22 countries including Bolivia, Colombia, Costa Rica, Dominican Republic, Ecuador, Grenada, Guatemala, Guyana, Haiti, Honduras, Nicaragua, Jamaica, and Peru had projects at varying levels of implementation. Out of the 3950 biodigesters inventoried, 60% was found operable and 40% was either shut down or functioning irregularly or completely abandoned [83]. Though China rebounded and emerged as a major reference on</p>

Issues	Challenges and opportunities
	<p>household digesters, about 50% of biogas tanks installed from 1958 into the 1970s were abandoned in the 1980s. By 1988 the seven million rural digesters existing in 1980 dropped to 4.7 million [84]. In 1986, a survey of biogas plants in Sri Lanka indicated that 61% was functional. By 1996 only 28.5% of completely surveyed 365 biogas systems was reported functional. At this point 16 units had been abandoned and the success rate for biogas systems implementation was reported as 32.9% [74]. In the Netherlands, for a period of over 30 years beginning in the 1970s, many AD projects using biomass were considerably delayed, suspended, abandoned and out rightly never realized. [85, 86]. These failures and circumstances taken together portrayed negative images and bad legacies for biogas plants. Opportunity: reasons adduced for failures included economic, social, technical, and policy components such as high investment and maintenance costs, urbanization and socio-cultural constraints, poor dissemination strategy, complicated permit regulations, shortage of feedstocks, lack of or inadequate training, poor digester design, etc. These reasons provide opportunities to create circumstances, provisions and tools that would promote and sustain biogas systems. Some examples are mobilization of local and external funds, more business-friendly policies and rules, appropriate and sustainable technologies, technical training, warranties for plant performance. Also, public dissemination of information and follow-up on successful programs could help.</p>
8.18. Low diffusion rate	<p>Challenge: in Latin America, the number of rural biogas plants installed yearly from mid-1985 to 1992 was less than 15% of that installed from 1982 to mid-1985. Challenges included technology adoption, technical manpower and materials of construction. However, non-technical reasons for biogas adoption failures accounted for up to 69%, 50% and 25%, respectively, in Cote d'Ivoire (Ivory Coast), Costa Rica and Tanzania [84]. Unstable institutional environment, lack of network and lobby activities, lack of initiatives between academia, research institutes, private sector entrepreneurs and stakeholders were cited nontechnical reasons. For the Netherlands, apart from technological problems; limited economic feasibility, fragmented support from the government, decreases in energy prices, and lack of financial support which made return on investment uncertain contributed to inadequate AD diffusion. Opportunity: cooperation between academia, government, industry and other stakeholders (farmers, energy sector, municipalities). Cooperative efforts that landed mutually beneficial outcomes should be highlighted, applauded and replicated. Well planned long-term, clear and supportive arrangements would facilitate continuity. Government policy that guide search for solutions, market formation and resources mobilization. Ease of technology adoption would also require reliable and sustainable infrastructure (technical assistance, manpower, cohesive farming approach with biogas and digestate, integration and dissemination of societal and cultural values and norms).</p>
8.19. Inhibition of microalgae	<p>Challenge: it has been shown that the green alga (<i>Raphidocelis subcapitata</i>) is sensitive to digestate, with ecotoxicity index; EC₅₀ of 0.77% [87]. Similarly, <i>Scenedesmus bijuga</i>; and oil-rich <i>Chlorella</i> sp., including <i>C. minutissima</i> and <i>C. sorokiniana</i> were found sensitive to digestate. Also, the dark color of liquid digestate of algal biomass inhibited the growth of <i>Chroococcus</i> sp. Therefore, cultivation of algae for value added products recovery could be</p>

Issues	Challenges and opportunities
	<p>minimized in the presence of digestate.</p> <p>Opportunity: because algae are exploited for biofuels, and various other useful biotechnological metabolites production by valorization of digestate, the inhibitory effect of digestate on algae cultivation is of practical interest. Therefore, digestate pretreatment or at least its dilution before use [88], would aid good algal productivity.</p>
<p>8.20. Nomadic and free-range culture</p>	<p>Challenge: many developing nations have nomadic animal husbandry architecture and free-range culture. These make the gathering of animal manure as feedstock for digesters a major challenge. In Pakistan, for example, livestock farmers from time to time relocate to weather conditions more benign to their livestock. However, current digester designs used by rural populations such as the fixed dome and floating drum are sedentary and cannot be readily moved by the farmers with their livestock.</p> <p>Opportunity: perhaps this challenge creates opportunity for a mobile biogas system such as the portable biogas plant reported in the year 2016 [81].</p>
<p>8.21. Disparity between developed and developing countries</p>	<p>Challenge: the economic, political and technological mismatches and divides between industrialized and industrially developing countries are challenging local, regional and international waste management systems. Environmental and health dangers do not know or respect boundaries (local, regional, or international) by land, sea, air or space. Planet earth is perhaps at the cusp of the axiomatic global village and economy. Sooner than later, pollution and instability at one corner of the earth would reverberate and affect other parts (Plastics in the oceans? Heavy metals in food, aquatic and terrestrial biota? Ebola in America? Flood events in Zimbabwe, Mozambique, Puerto Rico and U.S. Virgin Islands? Wildfires in Australia, Brazil, Portugal and USA? Coronavirus (COVID-19) in Japan, Singapore, and USA?).</p> <p>Opportunity: cooperation and support are needed to enable developing nations to leapfrog and shorten the learning curve and development timescales. Developing nations need guidance and assistance to cope with technological demands and challenges, and eschew reinventing the wheel. Waste management offers an opportunity for cooperation among nations for the betterment of humanity and planet earth.</p>

Table 4.
Challenges and opportunities of the waste, AD and digestate system.

9. Cassava peeling residue (CPR) digestate

N, P, and K are critical macro nutrients for crops production. N is considered the limiting nutrient in growth and yield [89]. P is required for energy transfer, signal transduction, photosynthesis, and macromolecular respiration [90]. K is responsible for metabolism of cell division, enzymatic reactions of amide formation, and amino acid activation during proteins biosynthesis and substrate phosphorylation [91]. To be a credible mineral fertilizer substitute, digestate must have the capacity to deliver the necessities and requirements of N, P, and K.

Table 1 presented a broad gamut of materials used in biogas and digestate creation. The table covered energy crops, agricultural byproducts, food processing residues, livestock effluents, organic fraction of municipal solid wastes, and pharmaceutical industry sludge. However, cassava peeling residue (CPR) was not

S/N	Nutrient	Value [mg/L]
1	Ammonia nitrogen	561
2	Ortho-phosphorus	20
3	Potassium	1066
4	Total Kjeldahl nitrogen	573
5	Total phosphorus	31

Table 5.

Nutrients values of liquid fraction of cassava peeling residue (CPR) digestate.

represented in the table. There is a published report on ammonium, potassium, total nitrogen, and total phosphorus contents of digestate generated from co-digestion of human urine, cow dung, and cassava effluent (a mixture of peeled cassava wash water and crushed cassava juice) [92]. CPR is a solid substrate abundantly generated during production of cassava root-based food systems such as gari and starch [93]. The present author is not aware of any report on nutrients value of digestate generated from the AD of CPR as sole feedstock. Therefore, a technical experiment was conducted to secure an overview assessment of N, P, and K compositions of liquid fraction of CPR digestate.

Some results of the research work on CPR as sole substrate for AD were reported earlier. These included proximate properties (e.g., moisture content, total solids, volatile solids), digester performance characteristics (methane content of biogas, pH, discharge effluent COD), feedstock materials, sampling procedures, analyses [94]. Presented in **Table 5** are results of nutrient values of liquid fraction of CPR digestate. **Table 5** results appear to be within the range of some published nutrients values for liquid digestates derived from other feedstocks such as algal biomass (*Chroococcus* sp.) [88], starch processing wastewater [95], source separated household waste [96], as well as liquid and solid manure slurries [97].

10. Conclusions

Cassava (*Manihot esculenta* Crantz) is perhaps third largest source of food energy for humans. Cassava supports the nutrition and subsistence of up to one billion persons in over 100 countries. Also, cassava is gluten free and could thus assuage medical complications for individuals with celiac disease. Cassava root processing byproduct such as CPR has organic matter content with applications in biogas and digestate production. This is a welcome development in views of biorefinery platform and the emergent circular economy. CPR digestate may be applied directly for agronomic uses or treated to generate products with varied applications and utilities. Treatment technologies may be biological, chemical, physical, or some combinations. Global benefits would include carbon sequestration, energy recovery, resource sustainability and recycling, waste reduction, profitability of AD process, biogas facilities, and agricultural systems in general. End effects of climate change mitigation, enhanced energy and food security, environmental and ecological protection, and sustainable development are good news for humanity and planet earth. These outcomes should motivate and provide consumers, farmers, regulators, managers, and other stakeholders in the emergent circular economy with insights to integrate and apply quality, safety, marketing, handling, storage, transportation, compliance with environmental regulations, and cost considerations and requirements strategies for digestate; into a renewable and sustainable energy production and waste management system.

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Conflict of interest

There is no conflict of interest (private or public) associated with this work.

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