Approaches for treating domestic wastewater with food waste and recovery of potential resources

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ABSTRACT
Continuous population growth associated with sanitation, food waste (FW), and domestic wastewater (DWW) is becoming critical globally. Crucial efforts and appropriate measures to utilize the FW and DWW for resources are needed. This paper reviews the conventional treatment techniques, challenges, and associated merits for treating FW and DWW. In the context of this review, DWW is often referred to as blackwater (BW)/feces. Due to the rationale for resource amplification, the review proposed that both mixtures (FW and DWW) be stored in a sub-surface storage tank for several months or years. They are further biodegraded in a bioprocess to generate energy with stabilized digestates. The effluent’s peculiar features are low organic acids with a low pH value, offering a stabilized and sanitized effluent. The second proposed route was to integrate anaerobic digestion, composting, and pyrolysis. Anaerobic digestion will offer bioenergy and digestates. Composting will cater to compost production and avert digestate drying and heating costs during pyrolysis. The pyrolysis of the digestates will generate biochar and bioenergy materials, while improved bioprocess performance is attained with the simultaneous biochar utilization in the bioprocess. The integrated technological routes can valorize DWW and FW for maximum resource recovery and sustainable development in a real-world context. The concept can be applied to an existing facility to create a cleaner and more efficient DWW with FW recycling. However, a comprehensive techno-economic analysis must be conducted.

Introduction
Household food waste (FW) and domestic wastewater (DWW) are inevitable daily products of domestic waste generation. In the context of this review, blackwater (BW)/feces is often referred to as DWW. Due to urbanization and population growth, the amount of DWW and FW generated has fundamentally expanded [1]. The generation of the DWW and FW per person, based on diet compositions, amounted to 350 g and 400 g, respectively [1,2]. The household FWs are mainly disposed of via composting and other biochemical techniques [3], while the DWW is flushed directly into a centralized sewer system [4]. Traditional wastewater treatment methods require additional energy input and are ineffective at dealing with climate change and resource recovery [5].

Mostly, the adopted treatment techniques for DWW are via aerobic digestion. The sludge generated is associated with negative environmental impacts such as greenhouse gas emissions and further limits the resource recovery from the sludge. Hence, consideration is given to treating DWW with FW to improve and harness the valuable resource materials with anaerobic digestion treatment. Another obvious challenge is that wastewater treatment plants’ energy requirements and discharge standards are capital-intensive; therefore, several plants in China are being upgraded and reconstructed [6]. An economical and sustainable waste management approach for collecting and treating these DWWs demands urgent attention. Adopting decentralization disposal techniques has been addressed as a future sustainable method for agriculture and energy [7,8].

Rather than adopting novel treatment techniques, avoiding associated rigors and financial costs is critical to improving resource recovery from these waste streams (DWW and FW). Combined treatment of the substrate in the house (decentralization option) via anaerobic digestion is a green and efficient waste disposal method. It also offers some alleviation of global climate warming and a reduction in fossil fuel utilization [8]. These waste streams’ source separation and...
treatment were conducted with about 400 inhabitants in a German housing estate called Flintenbreite [9]. The FW was first disposed of with a FW disposer; subsequently, the concentrated BW and FW were mixed and treated with an anaerobic digester to generate biogas and improve digestates. The co-digestion of this substrate would be an efficient technique to promote methane (CH₄) generation and balance the organic matter and nutrient ratio when mixed [1,10,11].

In China, by 2017, the anaerobic digestion capacity of FW treatment attained 16,000 t/d. The aims of the national urban waste disposal facilities in the outlined China’s 13th Five-Year Plan were to devise modern FW resources facilities and, in the same vein, amplify existing treatment plants to generate treatment capacity beyond 34,400 t/d by the year 2020 [12,13]. The foremost producer of biogas electricity generators was the European Union, with an estimated 17,400 biogas plants and an installed capacity of 10 GW [13,14]. In order to achieve the appropriate Sustainable Development Goals, one alternative may be to produce bioenergy and biofuels using anaerobic digestion methods. It is essential to comprehend feedstock pre-treatment and process modeling, optimization, and operation to make anaerobic digestion a successful management system that reaps substantial economic and environmental benefits [15].

Irrespective of the efficiency associated with the anaerobic digestion of organic waste [16], various accompanying challenges/limitations, such as inhibition from ammonia [17], bio-process instability, and volatile acid concentrations, are witnessed [18]. The anaerobic digestion process to produce stabilized digestate and high biogas is controlled by monitoring the process conditions. Simultaneously, the seasonal fluctuations in co-digestion feedstock need to be included in modeling and optimization [19]. The majority of scientific studies focus on monodigestion. Due to their high mixing operational pattern, single-stage bioprocesses such as the CSTR cannot support a significant number of methanogenic microbes [20]. Applying a serial reactor to the co-digestion of organic waste would improve biogas production [21–23]. Research has shown that serial digestion compared to conventional treatment of organic waste, such as sewage sludge, produced 11% more biogas [22], and FW from corn stover at HRT20 + 20d and HRT30 + 10d systems was 8.3%–12.2% and 13.8–14.6%, respectively [21].

The disposal of the organic waste stream with anaerobic digestion generates digestates with high moisture content, unsuitable for direct disposal with pyrolysis or other thermochemical processes due to the accrualment of additional costs for drying and heating. Therefore, composting is a valuable method that is also thought to be cost-effective for waste management. Due to the substitution of fossil fuel, anaerobic digestion is preferable to composting in terms of greenhouse gas emissions compared to the former. A study on the technical, economic, and environmental comparison of the two methods for disposing of organic waste found that compost and anaerobic digestion have comparable economics at 20 kt/ha if the excise charge on the CH₄-enriched biogas is eliminated [24]. The compost from composting is an organic material endowed with nutrients that can be utilized as a soil amendment for horticultural and agricultural purposes [25]. Significant factors influencing composting process performance include moisture, oxygen, nutrients, and temperature. Another way to convert the compost to sustainable resource recovery is to utilize pyrolysis. The moisture content of the compost will be lower at this stage without needing further heating and water drying before being pyrolyzed.

Pyrolysis encompasses waste decomposition without atmospheric air conditions at 300°C and possibly extending to 800°C. Pyrolysis produces solid (char), liquid (tar), and gaseous products (syngas), with the quality of the product yield determined by waste characteristics, heating rate, and pyrolyzed temperature [26]. The operation at a higher temperature is prone to yield more gaseous products than in lower temperature conditions. The pyrolysis device’s core merits are that it minimizes ecological and environmental pollution, such as greenhouse gases. It is cost-effective, though challenges with the emission of volatile organic compounds into the gas must be abated with control devices to promote further its circular technological application.

However, the FW and DWW valorization technologies are limited in their resource intensification. Hence, to close the gap, the review proposed innovative strategies to promote the DWW and FW exploitation routes via storage in a sub-surface tank for several months or years. The substrates are biodegraded in a bioprocess to generate energy with stabilized digestates. Additionally, it proposed the integrated application of pyrolysis, anaerobic digestion, and composting technology, notably with the addition of biochar in the bioprocess. It reviews individually generated DWW and FW characteristics, treatment processes, and combined routes, offering an understanding of associated challenges and merits. The proposed treatment offers sustainable FW and DWW valorization for resource recovery.

2. Assessment of single waste stream treatment

2.1. Concentrated black water/feces treatment

Separation of household wastewater into different streams emerged from high organic matter in the range of 50–75% and nutrients such as nitrogen (N)
(80%) and phosphorus (90%) in the toilet water [27]. BW contains high organic matter (>50%) and nutrient levels 80–95% [3,28]. Developing a sustainable wastewater treatment approach to improve ecological sanitation [29] and decentralized sanitation and reuse [1,9,30] has offered tremendous progress in the domestic household waste stream management. The solution that will provide global direction in utilizing the household concentrated BW/feces from a centralized approach and the ecological sanitation problem would need to consider the source separation of the accompanying waste streams as a way forward.

Due to the associated challenges of water shortages globally and the need to source alternative and recycle available water, the option of the water-saving toilet was implemented in some households. Household water-saving toilets use (0.5–1.2 L water/flush) [5] and (0.5–1 L water/flush) [3] compared to traditional household flush systems, which use (up to 9 L water/flush) [31], and (6–9 L water/flush) [3]. Specifically, the BW/feces disposal technique/management with the vacuum toilet received attention due to the potential for water conservation in the range of 0.5–1.2 L per flush [30,32–34]. BW generated from vacuum toilets contains pollutants such as sulfides, metal ions, high concentrations of ammonium-N greater than 1000 mg/L, and chemical oxygen demand (COD) concentrations above 10,000 mg/L [3,33,34].

In the bioprocess treatment of BW, the digestibility is often hindered due to the presence of the physicochemical properties that include high free ammonium and associated high pH value usually greater than 8.8 [35], and a community pit BW/feces pH value of 7.4 ± 0.1 [1]. Various treatments that include the usage of the vacuum toilet have been proposed for the resource recovery potential of the BW [31,34,36]. In addition, due to BW digestibility, anaerobic digestion has been proposed and severely applied for the treatment and energy recovery in the form of CH₄ or biogas [1,31,37]. Dry toilet BW produced an average value of 402.36 mL CH₄/g VS with an anaerobic digestion biomethane potential (BMP) process [38]. Source-separated BW collected from sealed septic tanks and treated with Auto-thermal aerobic digestion combined with the addition of 1% w/w urea offered the degradation of urea into ammonia (5.1 g N L⁻¹) after 14 days and a stabilized pH value of 9.2 after a week. The E. coli and Salmonella spp., were inactivated because they were sensitive to ammonia during the first few days of the study [39]. BW collected from a vacuum toilet (1 L of flushing water per flush) and treated with a USAB reactor at HRT 2.6 days and 4.1 kg COD/m³/day yielded an 84% ±5% removal efficiency rate for COD and 0.68 ± 0.08 m³/day for CH₄ production [5]. The microalgae, specifically Chlorella sorokiniana and Chlorococcum sp can remove N and P from AnBW at a rate of 28 to 62 mg L⁻¹·d⁻¹ and 2.3 to 5.4 mg L⁻¹·d⁻¹. Under low light conditions and for an extended period, it can remove NO₂—N concentrations above 400 mg L⁻¹.

Buller et al [40], claimed that biogas from sewage sludge anaerobic digestion can be transformed into electricity, and the excess electricity obtained from biogas combustion can be sold to the grid as part of the decentralized energy strategy for wastewater treatment plants with a hybrid system. Anaerobic digestion technology might reduce energy expenses by 77%. For medium-sized wastewater treatment facilities, the hybrid setup with biogas combustion can be an alternative, promoting both financial and environmental advantages. Additionally, the findings of this case study could be used in other facilities with a similar setup to improve and clean up the recycling of sewage sludge.

The biochar amended in the septic tank enhanced the robust microbiome at an OLR of 3 g COD/L·d. The daily CH₄ generation from reactors amended with biochar was ~ 4.3 times greater than the control (300 vs. 70 mL per day) [41]. At a stable state of operations for domestic wastewater treatment with the application of a Living System (LM) and the A²O system of a municipal wastewater treatment plant, the average removal rate of COD was 85% (#1), 82% (#2), and 83% (#3), while TN was 47% (#1), 44% (#2), and 40% (#3), respectively [42]. The TP reduction rate in the LM system was 7 mg/L (#1), 4 mg/L (#2), and 3 mg/L (#3) compared to the A²O system, indicating higher performance due to enhancement of the fermentative consortia.

The biological treatment in municipal wastewater treatment plants (MWWTP) alone is not ideal for the matrix of DWW treatment. Treatment can be expanded by integrating additional processing units, such as chemical oxidation, to reduce the content of COD [43] tremendously. In raw and mechanical pre-treated BW, the C: N ratio is disadvantageous for the second step of complete N elimination (denitrification). Thermochemical technology with pyrolysis in valorizing a mixture of human feces, urine, toilet paper, and wood chips was previously reported [44]. The feedstock was pyrolyzed at 500–650°C for 10 min to obtain a valuable product such as biochar. Feces were considered because of their inherent nutrient value in biochar for agriculture and soil amendment. Among several investigations, Table 1 shows the sources of BW and a few techniques/technologies used in BW/Feces treatments.

### 2.2. Food waste treatment scenario

The amount of FW generation is disturbing. 1.3 million tons of food are wasted annually, representing 1/3 of the global yearly production [49], and is expected to increase by 53% in 2025 [50]. The composition of FW
Table 1. Studies on the various BW/feces sources and treatment techniques/technologies.

| Blackwater/feces Sources | Properties | Treatment techniques | References |
|--------------------------|------------|----------------------|------------|
| Community pit toilet black water | Total COD: 6,807 ± 505 mg/L, Dissolved COD: 2,298 ± 21 mg/L, Particulate COD: 4,509 ± 25 mg/L, NH₄+ – N: 980 ± 35 mg/L, Total N: 1,022 ± 81 mg/L, Total P: 70 ± 0.88 mg/L, TS: 4,510 ± 540 mg/L, Volatile solid(VS): 2,825 ± 315 mg/L, pH: 7.4 ± 0.2 | The serial semi-CSTR 35°C | [45] |
| Black water generated by flushing toilets | COD: 1,712 ± 225 mg/L, CODcol: 651 mg/L, CODt: 26.25 g/L, TN: 1.77 g/L, TAN: 10.9 g/N/L, and TP: 0.33 g/L, pH: 8.6 | Filter-based packaged system as an alternative of conventional septic tank System tank with biochar additives | [46] |
| Recipe of synthetic BW (C₇H₅O₃) in 13.70 g/L bovine serum albumin (BSA) 4 g/L, oleic acid (C₁₇H₃₃O₂) 0.7 g/L, sodium bi-carbonate (NaHCO₃) 5 g/L, trace elements-DSMZ 141 mL/L, ammonium chloride (NH₄Cl) 3.82 g/L, urea (CH₂N₂O) 0.28 g/L, hydrated disodium hydrogen phosphate (Na₂HPO₄·2H₂O) 2.85 g/L, po- tassium chloride (KCI) 0.02 g/L | LM systems at stable influent rate are COD: 723 ± 409 mg/L, Ammonium nitrogen(NH₄-N): 135 ± 43 mg/L, TN: 207 ± 81 mg/L, TP: 20 ± 19 mg/L, A²O system was COD: 137 mg/L, NH₄-N: 21 mg/L, TN: 30 mg/L, TP: 3 mg/L | LM system and the A²O system of a municipal wastewater treatment plant. | [42] |
| Septic tank of the dormitory building of Wenzhou University. | CO₂, COD: 1,712 mg/L, NH₄-N: 88.7 mg/L, TN: 117.5 mg/L, TP: 38 mg/L, VSS: 63 mg/L, TVSS: 61 mg/L, pH: 8.1, VFA: 47 mg/L | Filter-based packaged system | [47] |
| On-site treatment of source separated domestic wastewater (BW) | COD (523–5.737 mg L⁻¹) with COD average value (2.010 mgL⁻¹⁴), pH: 8.75, BOD: 402 mg/L, COD: 784 mg/L, TOC: 334 mg/L, TKN: 185 mg/L, NH₄-N: 43 mg/L, TN: 219 mg/L, TP: 21 mg/L | Biological treatment in municipal wastewater treatment plant (MWWT), Biological treatment in MWWT, Anaerobic digestion: BMP test. | [43] |
| BW from conventional flushing toilets and urinals. Mechanically pre-treated BW from the storage tank with 500 μm pore size filter bags. | COD: 21,900 mg/L, TN: 3673.3 mg/L, TN: 5050 mg/L, TN: 77.49 g/L, VS: 35.48 g/L | USAB reactor operated at 35°C with a heating blanket. Pilot Photobioreactor (PBR) inoculated with precultured Chlorella sorokiniana (Algae) Auto-thermal aerobic digestion combined with the addition of 1% w/w urea. | [38] |
| Dry Toilet Generated BW | COD: 21,900 mg/L, TN: 3673.3 mg/L, TN: 5050 mg/L, TN: 77.49 g/L, VS: 35.48 g/L | USAB reactor operated at 35°C with a heating blanket. Pilot Photobioreactor (PBR) inoculated with precultured Chlorella sorokiniana (Algae) Auto-thermal aerobic digestion combined with the addition of 1% w/w urea. | [38] |
| Mixture of human feces, urine, toilet paper and wood chips. | COD: 21,900 mg/L, TN: 3673.3 mg/L, TN: 5050 mg/L, TN: 77.49 g/L, VS: 35.48 g/L | USAB reactor operated at 35°C with a heating blanket. Pilot Photobioreactor (PBR) inoculated with precultured Chlorella sorokiniana (Algae) Auto-thermal aerobic digestion combined with the addition of 1% w/w urea. | [38] |
| BW collected from vacuum toilet (1 L flushing water per flush) | COD: 10,977 ± 903 mg/L, pH: 8.05 ± 0.24, NH₄-N: 51.17 ± 5.18 mg/L, TP: 114 ± 27 mg/L | USAB reactor operated at 35°C with a heating blanket. Pilot Photobioreactor (PBR) inoculated with precultured Chlorella sorokiniana (Algae) Auto-thermal aerobic digestion combined with the addition of 1% w/w urea. | [38] |
| Anaerobically digested BW (AnBW) | Anaerobically digested BW collected from USAB reactor fed with vacuum-collected BW at 35°C | Pilot Photobioreactor (PBR) inoculated with precultured Chlorella sorokiniana (Algae) Auto-thermal aerobic digestion combined with the addition of 1% w/w urea. | [38] |
| Source-separated BW collected from sealed septic tanks | pH: 7.8, Total solid (TS): 0.69%wb, VS: 82%, TN: 0.69 g L⁻¹, Salmonella spp. per 50 g wet weight: Positive, Enterococcus spp. log₁₀ cfu mL⁻¹: 3.9, E.coli log₂ cfu mL⁻¹: 2.6, Total COD: 6,749.00 ± 705.00 mg/L, Dissolved COD: 2,294.00 ± 23.00 mg/L, Particulate COD: 4,455.00 ± 27.00 mg/L, NH₄+ – N: 981.00 ± 48.00 mg/L, Total N: 1,025.00 ± 79.39 mg/L, Total P: 69.00 ± 0.90 mg/L, TS: 4,500.00 ± 550.00 mg/L, VS: 2,830 ± 310.0 mg/L, pH: 7.4 ± 0.1 | BMP reactor | [1] |

Consists of approximately 60% carbohydrates, 20% proteins, and 10% lipids [51]. In Giwa et al. [52], study on kitchen waste slurry characterization and treatment with a disposer device, the properties of kitchen waste indicated a wide variation in the concentration of the organic-matter parameters. This phenomenon may be due to the different fractions of vast amounts of solid matter in the samples during analysis. Since FW has varied compositions, Table 2 presents selected FW characteristics from different investigations. Approximately 97% of global FWs ended up in landfills [50] and are decomposed in landfill based on their chemical composition [59]. FW composting was recommended instead of landfills because landfills produce greenhouse gases in the atmosphere [60]. For example, FW quantity estimation is a complex task [61], and food...
| Parameters                  | Food waste (FAV) [53] | Food waste [54] | Food waste [58] | Wastewater + ground food [55] | Slurry food waste [56] | Restaurant food waste [45] | Kitchen waste [57] | Food waste [58] | Kitchen waste slurry [52] |
|-----------------------------|-----------------------|------------------|------------------|-------------------------------|-----------------------|--------------------------|-------------------|------------------|-------------------------|
| Total COD                   | -                     | 18,500 (mg/L)    | 154,126 (mg/L)   | 827 (mg/L)                    | 1500 ± 470 (mg/L)     | 145,050.50 ± 680 (mg/L) | 82,000 (mg/L)     | 1010 (gO₂ kgVS⁻¹) | 91,508 (mg/L)             |
| Dissolved COD               | -                     | -                | -                | -                             | 670 ± 150 (mg/L)      | 65,000 ± 591 (mg/L)    | 31,000 (mg/L)     | 905 (gO₂ kgVS⁻¹) | 68,099 (mg/L)             |
| Particulate COD             | -                     | -                | -                | -                             | 870 ± 410 (mg/L)      | 70,000 ± 321 (mg/L)    | 52,000 (mg/L)     | -                | 23,409 (mg/L)              |
| BOD                         | -                     | 8370 (mg/L)      | -                | -                             | 680 ± 180 (mg/L)      | -                        | -                | -                | 45,994 (mg/L)              |
| COD:TN:TP                   | -                     | -                | -                | -                             | -                     | -                        | -                | -                | 376.2:47:1                |
| NH₄-N                      | 0.60% (mg/L)          | 15.6 (mg/L)      | 1080 (mg/L)      | 49 (mg/L)                     | 0.6 ± 0.5 (mg/L)      | 690 ± 0.1 (mg/L)       | 144 ± 46 (mg/L)   | 0.4 (gN kgVS⁻¹) | 537 (mg/L)               |
| Total N                     | 3.28% (mg/L)          | 272 (mg/L)       | 8890 (mg/L)      | 69 (mg/L)                     | 24 ± 13 (mg/L)        | 12,509 (mg/L)          | 900 (mg/L)        | 18.1 (gN kgVS⁻¹) | 1,033 (mg/L)              |
| Total P                     | 0.67% (mg/L)          | 57.0 (mg/L)      | -                | 6.0                           | 16 ± 8 (mg/L)         | 190 (mg/L)             | -                | 0.5%             | 188 (mg/L)                |
| BOD:COD                     | -                     | 0.45 (mg/L)      | -                | -                             | 0.46 ± 0.06 (mg/L)    | -                        | -                | -                | 0.5 (mg/L)                |
| Moisture content            | -                     | -                | -                | -                             | 76.3% (wt%)           | 75.98 ± 0.2% (wt%)     | -                | -                | 75.98 ± 0.2% (wt%)        |
| TS                          | 13.87 (mg/L)          | 23 (mg/L)        | 168,851 (mg/L)   | -                             | -                     | 125,160.80 (mg/L)      | -                | 191 (gTS kgWW⁻¹) | 20 (mg/L)                |
| VS                          | 12.17 (mg/L)          | 10 (mg/L)        | 119,997 (mg/L)   | -                             | -                     | 101,700.50 (mg/L)      | -                | 191 (gTS kgWW⁻¹) | 18 (mg/L)                |
| pH                          | 5.69                  | -                | 5.3              | -                             | -                     | 5.7 ± 0.1              | -                | 5.1              | 5.7 ± 0.1                |

aFruit and Vegetable waste (FAV); Wet weight (WW)
loss occurs at various stages [62]. Moreover, 64% of households’ FW generation is avoidable [63].

In addition, FW could be treated by various processes such as anaerobic digestion, composting, incineration, landfill, and heat moisture reaction [49]. FW composting leads to improved soil physical properties and physicochemical parameter variations during the composting of FW [64,65]. Anaerobic digestion is an outstanding technology as it is environmentally friendly in contrast to the primary current FW management practices, i.e. landfilling, incineration, or composting, mainly when focusing on global warming potential [66,67]. During anaerobic digestion of FW, organic wastes and various biomass are converted into biogas (30%-40%) carbon dioxide, (60%-70%) CH4, and traces of other gases such as hydrogen and hydrogen sulfide). A nutrient-rich digestate can be used for land improvement [68]. Furthermore, FW can undergo pyrolysis to produce biochar and biofuel [69]. In China and some countries, FW can be utilized as a source of animal feed [70]. In Norway, FW is used as a source of plant nutrients and soil conditioners rather than pigs because of health risks and associated low quality [27]. Table 3 shows the different treatment routes and recycling of FW.

3. Assessment of Combined Waste Streams

Bioprocess technology, such as anaerobic digestion, has been widely implemented to attain viable treatment options for household concentrated BW/feces and FW treatment. Several co-digestion and pre-treatment methods for balancing energy requirements and biogas optimization have been adopted in anaerobic digestion [16]. The co-digestion process implies the concurrent anaerobic digestion of several waste organic materials in one digester [1,78]. Substrate compatibility must be considered to increase CH4 generation and avert the challenges of bioprocess failure and associated inhibitions. Co-digestion of the household waste streams (BW and FW) would offer an active method to balance the BW COD: N ratio with kitchen wastes and recover CH4 generation, such as vegetables and fruits waste co-digested with pig slurry [11].

3.1. Performance of black water and food waste co-digestion

The high pH of 8.8 and ammonia, expressed as free ammonia and ammonia-N greater than 200 mg/L, have hampered BW digestibility [3,5,35]. Difficulties are also associated with low COD to the ammonium-N ratio [33,34], thus offering a low value with the recommended COD bioprocess treatment COD/N = 100:2.5 [3,79]. Subsequently, household kitchen waste could offer high COD to the ammonium-N ratio in the value of 100:0.07–0.18 [3,10,34,80,81]. Considering the associated limitations and strengths of the individual substrate, the methodology to acquire high CH4 production is to co-digest household organic kitchen waste with BW via strategically balancing the COD to N ratio [3,10,11].

The CSTR is one prominent and efficient reactor being applied to treat BW and FW, as well as high solid organic wet waste, and achieves an unceasing drift of reactant streams and yield [20]. These bioprocesses are the fixed-film bioreactor, UASB, CSTR, and the anaerobic sequencing batch reactor, tubular bior- eactors [1,82]. Please see Table 4 for the output and technologies adopted to treat BW/feces and household FW co-digested. In the investigation of BW from pit toilets and household FW; the kitchen waste equal mix ratio of 50% w/w with the BW co-digested offered the highest BMP of 295.13 mL CH4/g VS compared to 70:30, and 30:70 mix ratios, the CODt removal efficiency was ~90% [1]. Another study elucidated that with VS ratios of 1:2 and 1:3, the BMP of co-digested BW and kitchen waste was 0.85 ± 0.07 and 0.83 ± 0.06, respectively, while the BMP of BW alone was 0.34 ± 0.01 [3]. When BW and kitchen waste were co-digested, the hydrolysis efficiency increased from 57 ± 8% in the anaerobic digestion of BW alone to 87% at BW/kitchen waste VS ratios of 1:2 and 1:3, the CH4 production yield increased from 449 ± 32 NmL CH4 /gVS for solely BW to 680 ± 58 and 630 ± 52 NmL CH4 /gVS. Under a BW/kitchen waste VS ratio of 1:2, hydrogenotrophic methanogens dominated the methano- gen community. This study concluded that the findings imply that co-digesting BW and kitchen waste can enhance BW energy recovery.

The feasibility of two accumulation-systems (AC) for anaerobic digestion and storage of concentrated BW with (AC1) or without (AC2) urine kitchen organic-wastes was investigated [36]. The AC2’s influent-total COD (53,000 mg/L) was four times higher than the AC1. In both systems, suspended COD accounted for the vast majority (71–73%) of total COD. The batch-experiment results revealed that the waste(water) has a high anaerobic biodegradability (.85%). NH4 had no inhibitory effect, and the VFA concentration decreased over time. Both systems removed 58% of COD after 105 days at 20°C. Furthermore, if only the supernatant from AC1 is removed and the settled sludge is retained for future runs, only 20% of the influent total COD will be in the supernatant. Precipitation removed 74% of the influent ortho-P in AC2. As a result, the AC2 settled sludge had a high total-P concentration of 1,300 mg/L. The C:N:P ratios of the supernatant and sludge in AC1 were 26:13:1 and 35:4.5:1, respectively, and 28:14:1 and 32:2:4:1 in AC2. This study reported that the AC systems performed well in valorizing BW and kitchen waste co-digested for sustainable resource recovery.
### Table 3. Selected treatment and recycling techniques for food waste.

| Food waste type          | Treatment techniques          | Operational conditions                                                                 | Output                                                                 | References |
|--------------------------|------------------------------|----------------------------------------------------------------------------------------|----------------------------------------------------------------------|------------|
| FW mixture with sludge   | Anaerobic digestion          | TAcOD hydrolyzed FW and sludge; TAcOD 1 served as a methanogenic reactor; TAcOD 2, the modified reactor with only FW to produce hydrolyzed supernatant and solid further co-digested in TAcOD 1 | CH₄ gas and stabilized digested were produced.                     | [71]       |
| Fruit and vegetable FW   | Composting                   | The reactors are shaped like a truncated cone, made of poly-ethylene. Three treatments varying in the ratio of rice husk: raw fruit and vegetable leftovers (70:30, 50:50, 30:70; v:v) were used. | Higher percentage of FW (30:70) provided microbial growth with properties of mature composts within less time | [72]       |
| FW                       | Pyrolysis                    | 800–1300°C, heating rate between 10-200°C short time span between 1 and 10s. At 400-500°C, with a heating rate of 0.1–1°C/s at 5 and 30 min. | Biofuel liquid was obtained Higher biochar yield, liquid fuel and gas products in small amount CH₄ content was 63%, COD removal was 93.67% at OLR of 12.5 g-COD/L·d and 4d HRT. | [69]       |
| FW waste                 | UASBR technology             | Single stage UASB bioreactor, operated for 72 days; HRT 4 – 10 days                   | The biogas yield 578 (L/kg VS) and CH₄ yield 520 (mL/kg VS) The highest CH₄ production was 0.27 ± 0.71 m³ kg⁻¹ VS at 1.7 FW sludge ratio | [73]       |
| Kitchen waste FW         | Two stage bioreactors        | Two stage bioreactors, operated at 200 days; HRT 1–27 days                            | CSMEC performance was 1.5 times higher for biogas and CH₄ production compared to CSTR. | [74]       |
| FW mixed with sludge     | CSTR treatment               | Mixed FW: sludge at ratios of 1:3, 1:5 and 1:7. The frequency was 6.7 Hz and incubated at 35°C for 20 days. | The highest CH₄ production was 0.27 ± 0.71 m³ kg⁻¹ VS at 1.7 FW sludge ratio | [75]       |
| Garbage landfill FW      | Continuous stirred microbial electrolysis cell (CSMEC) treatment. | A CSTR integrated with microbial electrolysis cell to become a CSMEC technology | Methane production increased from 30.82% to 70.25% from the FW treatment, whereas Methanobacterium decreased from 66.14% to 14.49%. | [76]       |
| Grain, vegetables, fruits, meat, and grease FW | EGSB treatment | The EGSB reactor was operated at ambient temperature (about 20–25°C) at HRT of 24 h and a FW flowrate of 0.1 L/h. | Methane production increased from 30.82% to 70.25% from the FW treatment, whereas Methanobacterium decreased from 66.14% to 14.49%. | [77]       |

aTwo-phase anaerobic co-digestion (TAcOD)
Table 4. Different technologies, properties and performance output during black water/feces and food waste treatment.

| Blackwater digested with Food waste sources | Properties | Treatment techniques | Operational conditions | Effluent | Biogas/CH₄ | References |
|---------------------------------------------|------------|----------------------|-----------------------|----------|-----------|------------|
| BW from pit toilets and household FW.      | VFA: 438 mg/L, CODt: 120,666.50 ± 680 mg/L, NH₄-N: 1,112.50 ± 0.025 mg/L, TP: 105 ± 0.03 mg/L, TS: 100,116 ± 0.28 mg/L, VS: 80,100 ± 0.500 mg/L, pH: 7.24 ± 0.1 | Single phase Anaerobic digestion: BMP reactor - AMPTS II | BMP reactor- AMPTS II operated at hydraulic retention time of 30 days 50:50 (% v/v). | VFA: 1,309 mg/L, CODt: 13,963.40 mg/L, NH₄-N: 1,010 ± 0.3 mg/L, TP: 97.62 ± 0.1 mg/L, TS: 285, 678.65 mg/L, VS: 10, 922.81 mg/L, pH: 7.01 ± 0.1 | BMP of 295.13 mL CH₄/10 g VS | [1] |
| BW and kitchen organic waste                | COD: 18.668 mg/L, NH₄-N: 586 mg/L, TP: 111 mg/L, Kj-N: 1,290 mg/L, pH: 8.1, COD溶解物: 26 g/L, VFA-COD: 2.0 g/L, TS: 11.3 g/L, VS: 10.0 g/L | BMP tests with a lab scale CSTR of 500 mL ID: D X H11mm X187 mm. | CSTR was maintained at 35 °C, mixing speed of 120 rpm. | BW/KW VS ratios(1:3) COD: 3.2 g/L, COD溶解物: 1.2 g/L, VFA-COD: 0.4 g/L, TS: 2.4 g/L, VS: 1.4 g/L | CH₄ production yield 630 (NmL CH₄/g VS). | [3] |
| BW with low urine concentrations and kitchen organic wastes. | CODt: 18.668 mg/L, NH₄-N: 586 mg/L, TP: 111 mg/L, Kj-N: 1,290 mg/L, pH: 8.1, COD溶解物: 26 g/L, VFA-COD: 2.0 g/L, TS: 11.3 g/L, VS: 10.0 g/L | Accumulation reactors (AC1) (AC2) | Each AC system was a closed tank made of polyethylene with height, diameter and maximum volume of 1.6 m, 0.984 m and 122 m³. Operated for 150 days at 20 °C. | COD: 3,500 mg/L, NH₄-N: 1,310 mg/L, TP: 578 mg/L, Kj-N: 2,630 mg/L, pH: NIL, COD溶解物: 1.2 g/L, VFA-COD: 0.4 g/L, TS: 2.4 g/L, VS: 1.4 g/L | NIL | [36] |
| BW with high urine concentrations and kitchen organic wastes. | CODt: 18.668 mg/L, NH₄-N: 586 mg/L, TP: 111 mg/L, Kj-N: 1,290 mg/L, pH: 8.1, COD溶解物: 26 g/L, VFA-COD: 2.0 g/L, TS: 11.3 g/L, VS: 10.0 g/L | Accumulation reactors (AC1) (AC2) | Each AC system was a closed tank made of polyethylene with height, diameter and maximum volume of 1.6 m, 0.984 m and 122 m³. Operated for 150 days at 20 °C. | COD: 3,500 mg/L, NH₄-N: 1,310 mg/L, TP: 578 mg/L, Kj-N: 2,630 mg/L, pH: NIL, COD溶解物: 1.2 g/L, VFA-COD: 0.4 g/L, TS: 2.4 g/L, VS: 1.4 g/L | NIL | [36] |
| Vacuum toilet BW and raw FW.               | pH: 8.0 ± 0.2, COD: 254 (±1.2) g/L, TN: 2.7 g/L, COD/TN: 9.41 mg/L, PO₄³⁻: P 341 (±8.5) mg/L, TS: 206 (±0.9) mg/L, VS: 17.5 (±0.6)mg/L | UASB reactor | A 3.5-L (3.3-L working volume) UASB reactor was operated at 35°C for 130 days, and at HRT 2.6 days, and at the organic loading rate of 10.0 (±0.5) kg (COD)/m³/day, and BW/FW VS mixing ratio of 1:1 | pH: 7.6 (±0.2), COD: 4.2 (±0.8) g/L, TN: 1.2 (±0.0) g/L, COD/TN: 9.41 mg/L, PO₄³⁻: P 212 (±6.4) mg/L, TS: 5.9 (±0.3) g/L, VS: 2.9 (±0.3) g/L | CH₄ production rate of 2.42 (±0.15) L/day was obtained | [84] |
| BW from community pit toilets and household FW. | pH: 7.2 ± 0.1, COD: 128,670 ± 550 mg/L, TS: 101,219 ± 2.0 mg/L, VS, 80,100 ± 21 mg/L, TN: 1134 ± 0.1 mg/L, Acetate: 511 ± 0.1 mg/L, Propionate: 130 ± 0.2 mg/L, Butyrate: 20 ± 0.1 mg/L, COD/N: 113 ± 0.2 mg/L | Two-stage semi-CSTR | The reactor has a 1000 mL total volume and a working capacity of 800 mL (600 and 200 mL, respectively) with a headspace of 200 mL operated at 35 °C, BW-FW 1:1 proportion at the organic loading rate of 2.7 gVSL/d at 30 HRT and mixing speed of 150 rpm. | pH: 7.9 ± 0.3, COD: 7912 ± 102 mg/L, TS: 24,750 ± 101 mg/L, VS: 10,601 ± 56 mg/L, TN: 257 ± 0.5 mg/L, Acetate: 1400 ± 2.0 mg/L, Propionate: 335 ± 10 mg/L, Butyrate: 59 ± 0.3 mg/L, PO₄³⁻: P 80 ± 0.2 mg/L, pH: 7.45 ± 0.2 mg/L, COD/N: 29 ± 0.4mg/L | The highest biogas volume was 400 ± 0.6 mL/d | [45] |
| BW from office building with FW.           | COD: 20,072 mg/L, Influent N (mg/L) = 417, Influent P (mg/L) = 43 | Membrane bioreactor (MBR) operated as a sequential batch reactor. | The pilot plant consists of a 600 L pre-fermenter and a 600 L membrane bioreactor. Operated at 260 days, HRT = 2 days, Temperature = 54 ± 3°C | Effluent N (mg/L) = 38 mg/L, Effluent NH₄-N (mg/L) = 38 mg/L | NIL | [87] |
Vacuum toilet BW (utilizing 1 L flushing water per flush) and raw FW that is composed of grains (e.g. rice, noodles, bread), vegetable residuals (e.g. broccoli, carrot, onion), fruit residuals (e.g. banana and orange peels, apple cores), and beverage residuals (e.g. tea, coffee) were conducted at a mix ratio of 1:1 proportion [83]. In this study, the optimal biogas production ratio of the BW:FW V5 mixing ratio of 1:1 was achieved. The high performance is due to the solid substrate hydrolysis efficiency (85.9%) and high microbial activities (sludge hydrogenotrophic methanogenic activities) that were 2.4 times higher than that of the BW alone [84]. The BW from vacuum toilets containing urine, feces, toilet paper, flushing water and kitchen refuse offered about four times the biogas production compared to the BW alone. The anaerobic digestion of BW combined with kitchen refuse is a promising technique for wastewater treatment facilities and waste management [83].

Challenges associated with a single CSTR include the inability to sustain a high amount of the fermentative organism due to the fast-mixing nature of the reactor; thus, the application of a serial CSTR reactor can mitigate the effect [21]. The serial CSTR in sewage wastewater treatment offered 11% higher biogas production than a single-phase [22]. Furthermore, improved biotransformation of organic feedstocks with serial digestion is feasible [21,23]. The first step reactors of the serial-CSTR function as the core biodegradation reactors. The additional reactor serves as the reclamation step to enhance the biodegradation of the extra-produced effluent. During the co-digestion of BW with household FW, Giwa et al. [45] reported a 25% higher biogas generation from the serial CSTR-35 °C compared to the single CSTR-55 °C and a 38% increase in the single CSTR-35 °C. Steady and enhanced biogas generation via connecting bioprocesses in series offered suitable techniques that averted single CSTR limitations and improved the bioconversion rate. In the post-treatment of digestate dewatering, the low-cost implication was associated with utilizing a serial phase reactor that improved net biogas production compared to a conventional one-stage bioprocess [85,86]. During the treatment of BW co-digested with household kitchen waste at a mix ratio of (1:1.6 to 4.4), a 58–78% COD removal efficiency rate was reported as a result of the mixing ratios techniques implemented [3,34], and 83% COD [45]. Relative to the serial-CSTR digester, the co-digested culture methanogenic process was conducted in the main reactor. The second reactor was adopted for digestate polishing in the methanogenic chamber; 93% CODt and 90% CODs were achieved [45].

4. Development of Future Conceptual Route

4.1. Substrate storage and bioprocess application

This route does not apply to a comprehensive network pipeline system and sewerage work. It is an independent approach important for rural and sub-rural cities. It operates close to the source of the FW and concentrated BW/feces generation for agronomy and energy enhancement. A FW disposer can also be adapted to shred the FW as source segregation to overcome the challenges in FW collection and promote municipal solid waste management systems [88]. The alternative use of household FW disposal from landfills via a FW disposer is an excellent disposal-management option [52,56]. However, this review will highlight the direct household FW collection from the source. The concept focuses on rural and sub-rural communities devoid of sewage and long pipeline systems, not the smart cities with FW disposers.

Concentrated BW/feces generated from a vacuum or the dry toilet will be preferred to conveniently adopt this technique because of their water-saving competence and peculiar characteristics. The adoption of vacuum or dry pit toilets is encouraged for water-saving sanitation in light of the global population, with over 2.4 billion people without simple sanitation facilities [89]. In western counties, the predominant use of conventional toilets results in 20–40% per capita water use, creating pressure on the continuous demand for scarce freshwater resources [44]. Water-saving sanitation appliances could give rise to fecal sludge, often called partial or raw digestates, slurry emanating from storage, collection, or treatment with mixed excreta, BW, or either with or without grey water [44,90]. Domestic organic waste from households contains a high COD level [1]. The codigestion of these substrates would offer a valuable resource for nutrient and energy production [3,91]. Different investigations have reported the treatment and reduction of COD due to BW and KW from ‘source separation’ [8,34,45], along with the consequences of substrate (BW and FW) ratio, which reveals the bio-treatment efficiency [1,3,11].

The source separation and treatment of these two waste streams (FW and concentrated BW/feces) would alleviate the waste transportation challenges and offer economic operating conditions [27]. The FW and concentrated BW/feces can be stored in a sub-surface storage tank for one or two years. Treatment via the anaerobic or aerobic thermophilic reactor can be applied for substrate sanitization. The digestates and biogas products can be utilized in agricultural and biogas production. Figure 1 presents the route description. Storing FW in a closed sub-surface tank generates acids with a low pH 4 value, conserving the waste.

A minimum amount of volatile organic acids and emissions (hydrogen sulfide, CH₄, carbon dioxide, etc.) are also generated [1,27].
The digestates from the anaerobic digester would offer stabilized products with the feasibility of agronomic value due to organic matter and nutrient content. Digestates have a variety of uses that are advantageous to the soil, plants, and crops. First and foremost, because digestate contains essential nutrients for plant growth, it is well known to have fertilizing properties that boost plant production. Second, their importance to soil health cannot be overstated because they play essential roles in nutrient cycling, carbon transformation, and soil structure maintenance, all of which improve soil efficiency. Nitrogen is crucial for plant growth and soil microbial activity as the most abundant nutrient absorbed by plants and the most frequent growth-limiting factor. A significant justification for its use is the digestate’s contribution to nitrogen availability in the soil. NH₄-N, which plants quickly absorb, is particularly abundant in the digestate. Digestate fertilization of agricultural soil over a long period is most advantageous to crop productivity since it does not impair crop quality, quantity (yield), or environmental factors in any manner [92]. Consequently, research is being done on various alternatives to digestate valorization aside from land application. These alternatives include using digestate liquor to replace freshwater and nutrients in algae cultivation. Using solid digestate for energy production through biological (such as anaerobic digestion, bioethanol) or thermal (such as combustion, hydrothermal carbonization, and pyrolysis) processes and turning solid digestate into added-value products (char or activated carbons) through a pyrolysis process [93].

The sanitized substrate could be spread across land farms in farming operations to support crop growth. Direct compost of the FW and the anaerobic digestate is feasible for agricultural utilization. Composting is well-known for its simple processing, procedures, and low-cost implications; simultaneously, the heat-moisture reaction efficiently eliminates odor and bacteria [49].

Further, anaerobic digestion has been widely adopted to treat organic waste to generate biogas [45,94]; this proposed route would harness nutrient values from the substrate (FW and concentrated BW/feces) to include energy potential. The treatment, stabilization, and sanitization of concentrated BW/feces and FW are necessary at a thermophilic temperature of 50–55 °C. It will avert associated health risks and improve the agronomic value of plants and soil conditions [27]. Anaerobic digestion is typically carried out in single-stage systems under mesophilic conditions, as this temperature regime is thought to be more stable than thermophilic. However, thermophilic conditions are superior to mesophilic conditions in terms of CH₄ production and digestate hygienization (immobilization of coliforms, Escherichia coli, and Clostridium perfringens, among others) [95]. The anaerobic digestion process, which was most likely adopted at 50–55°C, increased CH₄ production rates linearly with temperature. As a result, the microbial community’s overall activity and alpha diversity may be reliable predictors of fermentation performance, particularly CH₄ production in anaerobic digestion systems [96].

4.2. Integration of anaerobic digestion, composting, and pyrolysis technology

The conceptual approach is proposed to improve the utilization of concentrated BW/feces and FW using anaerobic digestion, composting, and pyrolysis. Several benefits, comprising the generation of
renewable energy routes, projections on recycling nutrients; extensive minimization of waste quantity, and environmental mitigation, are linked with anaerobic digestion and composting [1,97,98] and pyrolysis technology application [16,99,100]. In Europe, electricity or natural gas alternatives are generated from the anaerobic digestion of organic waste biogas upgraded to about 97% CH₄ [13,101]. A high focus is on China’s energy and carbon intensity targets, notably with adopting anaerobic digestion [6]. The composting techniques occur under aerobic conditions, producing a final yield that refers to the compost as an organic soil conditioner. Applying the digestate compost as a soil amendment will fulfill the nutrient requirements for soil and maximize absorptivity. The FW and concentrate BW/feces composting will offer suitable substrates for pyrolysis enhancement to produce biochar and biofuel as energy materials [45].

On the other hand, pyrolysis is a thermochemical process that offers an ecologically advantageous and sustainable transformation of waste materials into high-value-added products such as biochar, gas, and bio-oil [13,102–104]. Biochar, one of the vital products of pyrolysis, can be applied as a soil amendment due to its carbon composition [105], improved bioprocess performance [16], and wastewater (water) treatment [106,107]. The other products can be applied as valuable chemicals or bioenergy, such as pyrolysis oil [108]. The syngas could be used for gas turbines and as industrial power boilers or improved to CH₄ with a chemical agent such as a catalyst [13,109].

Therefore, the review proposed conceptual anaerobic digestion of the waste streams (concentrated BW/feces from the vacuum toilet or the dry toilet) with the FW. The use of dry toilets for fecal sludge collection illustrates precious resources for organic matter and nutrient utilization in agronomy [44]. The amount of BW produced is enormous, and the efficiency with which resources are used is low. The high degree of decentralization in rural regions, in particular, makes treating BW challenging. BW is a valuable substrate for the anaerobic digestion of bioenergy because it has a high organic nutrient content. However, ammonia suppression and low biogas production efficiency may arise when BW is treated via anaerobic monodigestion. Due to the high total ammonia-N concentration in urine, which can enhance the buffer’s efficiency and provide trace elements to aid in the anaerobic digestion process, it may be employed a good input material for codigestion with KW [110]. Therefore, co-digestions are crucial for effectively treating BW, the primary liquid waste stream from households. It is anticipated that co-digestion of the two substrates (BW/Feces and FW) will improve digester performance, biogas output, and the balance of nutrients. A suitable substrate must offer beneficial interactions to achieve nutrition, moisture balance, and microbial synergisms. Choosing an appropriate substrate is crucial for co-digestion. Co-digestion will speed digestion, support high-rate CH₄ generation, and neutralize inhibitory effects like ammonia [75].

The waste streams (mixed FW/feces and BW) can be anaerobically digested [1,3,45]. If digested simultaneously, these household waste streams (BW and FW) constitute an important source of nutrients and energy. Anaerobic co-digestion of FW with BW would provide an affordable and environmentally friendly disposal method and decrease fossil fuel consumption and prevent global warming [45]. Therefore, coupling anaerobic digestion, composting, and pyrolysis to treat FW and concentrated BW/feces could offer significant advantages compared to the individual technological processes. It can recover bioenergy, alleviate greenhouse gas effects, recycle, reduce digestate management

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**Figure 2.** The simple description route for black water and food waste treatment via integration technology (Anaerobic digestion-composting-pyrolysis).
costs, and reutilize digestate for agronomy. Please see Figure 2 for the integration route description. The anaerobic digestion of both waste stream mixtures can be simultaneously treated by consortia of bacteria and archaean communities at the downstream section. The pyrolysis route could be applied upstream to valorize the digestate after composting. Composting in the middle of the integration process will convert the digestate of anaerobic digestion to substrates of low moisture content, averting extra costs for heating and drying during pyrolysis.

Upstream pyrolysis of the digestate and other recalcitrant matters such as wood, plastics, and some papers from the FW could offer high calorific products.

Additionally, it will reduce high moisture content and promote sporadic flammability. Several studies have previously reported individual pyrolysis of FW streams [16,25,111,112] and feces [44,113]. Pyrolysis application of the composted digestate obtained via composting and other waste streams such as plastics, wood, and paper segregated from FW is presently underexplored. The quality of biochar generated needs to be quantified and further investigated.

As a byproduct of pyrolysis, biochar is the most emphasized product among other yields. Before further enumeration of the biochar production and properties, the source of the substrate via composting will be highlighted. The biochar generated from FW and concentrated BW/feces can improve the bioprocess performance to yield high biogas production and enhance the soil quality for farmers as a bio-fertilizer. Further environmental merits of biochar could be found in purification, wastewater treatment, and bioenergy process enhancement. Numerous studies have presented biochar properties as a porous structure with surface area, alkaline, high ion-exchange capability, and the ability to reduce organic contaminants and different metals (loid) [114,115]. With the addition of the mixed waste stream (feces/concentrated BW and FW) with biochar, the possibility of increased biogas yield could be attained. Biochar performance under such a scenario could be attributed to favoring the reduction of a high quantity of hydrophobic and toxic furans and mitigation of inhibition from ammonia in the bioprocess. Adding biochar from corn stalks during the bioprocess of organic waste yielded an increased CH₄ content of about 60% [116]. The biochar from pyrolyzed sewage and difficult-to-degrade organic residues yielded an increased CH₄ content during the anaerobic digestion of FW [16,69]. Both waste streams are organic substrates; the stable performance and enhancement of biogas from organic materials such as FW with biochar additives and stabilized digestates for agronomy have been previously reported [106,117]. Previous research on energy balance found that combining thermochemical and biochemical treatments can improve energy recovery [108,118,119]. However, in this review, the potential energy requirements for integrating the three technologies for treating the substrates (FW and feces/concentrated BW) are not quantified; further investigations are being suggested.

5. Conclusion and Future Outlook

This study presented a new conceptual route of integrating anaerobic digestion, composting, and pyrolysis for the proficient valorization of FW and feces/concentrated BW organic waste. It was proposed that a mixture of the waste streams be subjected to anaerobic digestion for simultaneous biodegradation of the mixture of waste streams via consortia of microbial communities to generate energy and stabilized digestates for farming. The high moisture content digestate can be composted directly for utilization as a soil conditioner before being subjected to the pyrolysis process. Anaerobic digestion will produce bioenergy and digestate as a biofertilizer product. The digestate liquor can be utilized to replace freshwater and nutrients in algae cultivation. The digestate is characterized by high water content, hence the need to compost before pyrolysis. The composted substrate will avert the need for further drying and heating during the pyrolysis process. The pyrolyzed digestates will produce biochar and associated biofuel materials. The biochar can be directly used as a soil conditioner or added as an additive to the anaerobic digester to increase energy production and reactor stability. The proposed route’s feasibility indicates the potential for enhancing product yield from individual and combined processes suitable for agronomy and energy production. At the same time, the amount of heat generated could fulfill the energy demand for coupling the technology.

The amount of money saved by processing one ton of date palm waste (another form of FW) through the pyrolysis unit was about $259.58 in Saudi Arabia. Approximately 345,000 tons of date palm waste are processed through the pyrolysis unit each year, and the gross income from the sale of the pyrolysis products made from one ton of date palm waste is $556.8, while the cost of producing these pyrolysis products is $297.22 [120]. In order to assess the economic viability of constructing a small-scale biogas plant, Al-Wahaibi et al. [121] generated biogas from a range of FW. Economic analysis indicated that the break-even point occurred at $0.2944/m³, and all prices above that point produced a positive net present value. FW composting plants in Taiwan, under China’s
jurisdiction, reported that composting of FW may yield the most net benefit compared to other applications today; and the production cost of compost ranges from NTS 2897–23,117/tonne [122]. In the present report, the integrated technologies’ energy utilization and economic feasibility were not elucidated for the DWW and FW valorization. Establishing an assessment system for the economic and energy implications demand for the coupled technologies and SWOT analysis is suggested to be further investigated.

The other route proposed is storing both mixtures (DWW and FW) in a sub-surface storage tank and further degrading them in anaerobic digestion to generate energy and stabilize the digestate. The proposed routes lacks long pipeline sewerage systems and transportation, offering a decentralized waste treatment approach. However, this peculiar route with a subsurface storage tank will be most appropriate for rural areas, while for cities, this technique will not be recommended for implementation. Studies are suggested to comprehend the characteristics or properties of the sub-surface storage substrates in an anaerobic or aerobic tank for one or two years. The effects on biogas generation after storage and the quality of the digestates during anaerobic digestion, composted digestate quality, and the biochar generated from the pyrolysis process should be studied further. It is feasible in a real-life context that the integrated technological routes proposed in this review are capable of valorizing DWW and FW for maximal resource recovery and sustainable development. However, a comprehensive techno-economic analysis needs to be investigated.

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